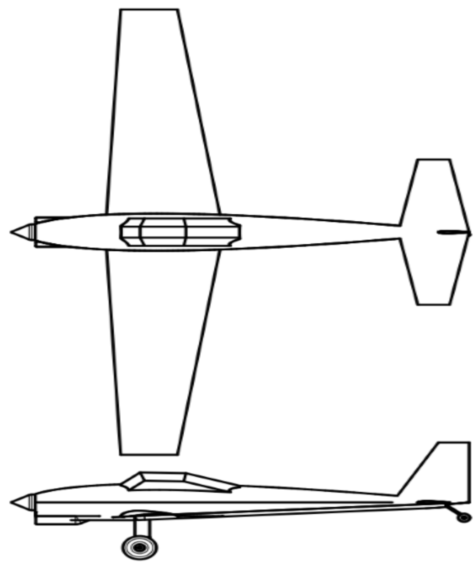
Ceres AG-1
Agricultural Aircraft



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EXECUTIVE SUMMARY

The Ceres AG-1, developed by Cupertino Aerospace, represents an innovative approach to advancing agricultural aviation. Designed to address the industry's critical challenges—enhancing safety, improving efficiency, and reducing environmental impact—this agricultural aircraft incorporates state-of-the-art technologies and design principles. Key objectives include minimizing pilot exposure to hazardous chemicals, improving field reparability, and enabling dual functionality for diverse applications such as wildfire suppression and glider towing.

The development process utilized advanced computational tools and analytical methods to optimize weight distribution, aerodynamic efficiency, and structural integrity. The design integrates a high-capacity hopper, field-repairable systems, and a taildragger landing gear configuration to meet operational demands. Powered by the Pratt & Whitney PW127XT engine, the aircraft achieves superior performance metrics, including a 16.9-hour endurance, a 2,168-mile range, and a 1,500-foot takeoff distance over a 50-foot obstacle. Cost analysis revealed a projected unit cost of $15.2 million, making it competitive within its market segment.

This project sets a new benchmark in agricultural aviation, offering a versatile, sustainable, and high-performing solution to meet current and future industry demands.

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3. NOMENCLATURE

a_g	= acceleration in the ground roll
AR	= Aspect Ratio (span^2/reference area, applied to wings and tails)
α_{eff}	= effective angle of attack of the propeller blade
B	= number of propeller blades
β_0	= pitch added to the propeller blades by rotating them
c	=propeller blade chord as a function of radius
c_{BHP}	= specific fuel consumption in pounds per horsepower-hour
C_L	= Lift Coefficient
C_{Lmax}	= Maximum Wing Lift Coefficient
C_{LTO}	= Wing Lift Coefficient on takeoff
C_D	= Drag Coefficient
C_{D0}	= Zero-lift Drag Coefficient
CAD	= Computer-Aided Design
CFD	= Computational Fluid Dynamics
cg	= Center of Gravity (mass)
D	= Drag force
DATCOM	= Data Compendium (USAF aerodynamics methodology report)
E	= Endurance
g	= Gravitational acceleration
γ_{min}	= Minimum glide angle
h_{OBS}	= Obstacle height
k	= Span efficiency factor
L/D	= Lift-to-Drag Ratio
L	= Length of the Fuselage
M	= Mach Number
Operating Speed	=the velocity at which crop dusting runs can be carried out
mph	= Miles per hour
Φ	= Ground effect parameter
$\Phi + \alpha_i$	= Differential angle of attack
P_{req}	= Engine power required to turn the propeller
RoC	= Rate of Climb
ρ	= Air density
S	= Reference wing area
S_G	= Distance traveled in the ground roll
S_R	= Distance traveled during rotation
S_{Air}	= Distance traveled during climb over the obstacle
XFLYR 4	= Aerospace vehicle design software
V_0	= True Airspeed
$\mathrm{V}_{\mathrm{L/Dmax}}$	= Velocity for maximum lift-to-drag ratio
V_{LOF}	= Liftoff velocity
V_r	= The velocity imparted to the air by the propeller
V_{eff}	= Effective air velocity over the propeller
V_{max}	= Level flight top speed

V_{Pmin}	= Flight velocity for minimum power required
V_T	= Velocity of the propeller tip
V_{ymin}	= Minimum sink rate
T	= Produced thrust
T_0	= Desired thrust
T/W	= Thrust-to-weight ratio
W/S	= Wing loading (weight/area)
W_e	= Empty Weight
W_f	= Final weight
W_i	= Initial weight
W_0	= Takeoff Weight
ω	= Rotational velocity
ROP	= Document containing the tasked design requirements
lb	= Pounds
hp	= Horsepower
ft	= feet
hr	= hour
SHOTS	= Safe High Operational Tempo Sprayer

4. INTRODUCTION

Cupertino Aerospace has partially completed its contracted effort for the Safe High Operational Tempo Sprayer (SHOTS) Agricultural Aircraft. In the previous months, a preliminary design has been developed to meet the requirements outlined in the ROP. The research done has impacted the design of the proposed aircraft Ceres AG-1 allowing Cupertino Aerospace to develop an answer to the advancing agricultural industry's demand for a high-volume long endurance sprayer.

The outer mold line of the Ceres AG-1 was refined last month to meet the ROP specifications. The aircraft's airfoils have been selected to provide a balanced flying experience catering to the performance and stability necessary within the agriculture industry. The engines have been researched and selected, giving the Ceres AG-1 the thrust-to-weight ratio needed to allow for quick take-off lengths and long endurance times.

5. BACKGROUND[1]

Agricultural aviation plays a critical role in maintaining and enhancing the nation's food supply chain. Each year, over 127 million acres of cropland in the United States are treated using agricultural aircraft, contributing approximately $37 billion to the national economy. These aircraft are essential for applying fertilizers, pesticides, and other chemicals to improve crop yields, control invasive species, and mitigate pest-related losses. However, agricultural aviation operations face significant challenges despite their longstanding utility, including high accident rates and operator exposure to hazardous substances.

Data from a 28-year retrospective study highlights the inherent dangers of agricultural aviation. During this period, aircraft operating under 14 CFR 137 regulations experienced 3,726 accidents, with nearly 10% being fatal. Human error, engine or fuel issues, and collisions with objects account for a substantial percentage of these incidents. Additionally, agricultural pilots and operators are frequently exposed to chemicals classified as poisons, carcinogens, and mutagens, further compounding safety and health risks.

To address these challenges, a new generation of agricultural aircraft that prioritizes safety and operational efficiency is needed. The proposed Safe High Operational Tempo Sprayer (SHOTS) aircraft seeks to redefine industry standards by reducing pilot exposure to hazardous substances, minimizing accident risks, and doubling the operational tempo compared to current market-leading agricultural aircraft. This next-generation design must enhance safety and efficiency and ensure economic viability and adaptability to emerging needs in agricultural and non-agricultural markets.

The Ceres AG-1 aircraft represents Cupertino Aerospace's response to this need, incorporating advanced safety features, innovative design principles, and sustainable technologies. With a targeted entry into service by 2028, this aircraft aims to set new benchmarks in agricultural aviation, offering superior performance, reduced environmental impact, and extended versatility.

6. Ethics

The Ceres AG-1, a large-capacity agricultural plane capable of carrying 8,000 pounds of fertilizer, is an ethical and impactful innovation in modern farming. Ethically, the Ceres AG-1 promotes sustainability and efficiency by reducing the number of trips required for fertilizer distribution, thereby minimizing fuel consumption and carbon emissions. This eco-friendly approach helps mitigate climate change and supports environmental stewardship.

Culturally, Ceres AG-1 can significantly influence global agriculture. This plane can transform agricultural practices in regions where farming is a cornerstone of the economy. By ensuring timely and uniform fertilizer distribution, the Ceres AG-1 optimizes crop yields, enhancing food security and fostering prosperity in local communities. This technological advancement empowers farmers with superior tools, nurturing a culture of innovation and resilience.

Furthermore, the introduction of the Ceres AG-1 can inspire educational initiatives and training programs, enhancing the skills of the workforce and promoting continuous learning and adaptation. This shift towards embracing advanced technology can generate broader cultural impacts, leading to more innovative solutions and collective efforts toward sustainable agriculture.

In essence, the Ceres AG-1 is a technological marvel and a catalyst for ethical practices and cultural transformation, driving a more sustainable and prosperous future for farming communities worldwide.

7. STATEMENT OF THE PROBLEM

This research study addresses the fundamental problem of identifying and implementing the technical means to design an agricultural aircraft capable of meeting the Safe High Operational Tempo Sprayer (SHOTS) specifications outlined in the ROP. This includes achieving enhanced operational safety and minimizing human exposure to toxic chemicals while ensuring compliance with regulatory and environmental standards.

The first problem that must be addressed is the safety of the pilot. The aircraft must lower the pilot's exposure rate to toxic chemicals. Repeat exposure to the chemicals commonly used in the agricultural industry has a long-known impact on human health and has been the subject of many legal cases. Decreasing the exposure to these chemicals will help reduce the elevated mortality rate of the agricultural pilot profession.

The next problem was designing an aircraft that was field repairable. Within the agricultural industry, only a small window of time is allotted for chemical applications. The Ceres AG-1 must be field repairable so that the pilot can meet this critical time window. By removing the need for repairs done at specialized facilities, the aircraft can be fixed quicker and will not have to require expensive fees related to transportation of the damaged aircraft.

The final problem is implementing dual functionality of the aircraft so it can be used during the off-season for other purposes, such as wildfire suppression. Offering dual functionality will allow the owner to profit from their investment during agricultural downtimes.

8. APPROACH

A. Initial Sketch

The initial conceptual design for the aircraft was created from a discussion between four concept sketches. Two sketches favored a biplane design, and two a monoplane. All four sketches contained a tail dragger landing gear configuration and twin turboprops. After discussing the concept sketches, the monoplane configuration was selected. The twin turboprop design was reduced to a single propeller after weight and power estimations were made, as one propeller was sufficient for the power requirements, and the added weight was determined to be unnecessary.

B. Weight Estimation and Power Loading

To begin sizing the plane from the sketches, a weight estimation and power loading calculation must be performed. These calculations were carried out in Excel to facilitate easy visualization of changes, which was particularly useful during the early design stages when adjustments occurred rapidly.

The initial weight estimation includes the crew, payload, fuel, and empty weight. The mission parameters determine crew and payload weights, while the empty weight is estimated using historical data. Fuel estimation is conducted using a fractional buildup method, where the mission profile is divided into segments, and the proportion of fuel required for each segment is calculated.

The final weight estimation is then used to plot power loading curves, which are essential for plane sizing. Power loading is evaluated using coplotted curves incorporating factors such as stall speed, maximum speed, sustained turn, takeoff performance, rate of climb, and service ceiling. Stall speed provides a vertical line on the multiplot, representing a constraint the plane cannot pass. This constraint significantly influenced subsequent wing sizing and weight distribution decisions. Maximum speed and sustained turn are key flight characteristics derived from the mission profile. High speeds are not critical for a crop duster, which is reflected in the plots. However, sustained turns are crucial for the tight maneuvers required during dusting, creating a lower bound for the thrust-to-weight ratio. The takeoff and rate of climb are also influenced by the mission profile's takeoff conditions, with takeoff being the more impactful of the two.

C. Fuselage and Wing Sizing

One fundamental requirement in the design of agricultural aircraft is the capacity to carry and distribute significant payloads efficiently. Thus, fuselage design must consider the maximum weight capacity. The fuselage length was calculated using Eq. (1), which determines the fuselage length based on its weight and the type of aircraft:

$$L = aW_0^C \tag{1}$$

The calculation resulted in a fuselage length of 37.7 feet, according to Raymer[2], using the constants a = 4.04 and C = 0.23, which are specific to agricultural aircraft, and the W_0 = 16,500 lbs. (Total weight).

The design of the cockpit is predicated on the average dimensions of both the control panel and the pilot to ensure sufficient space for controls and adequate headroom and visibility. From this, the width is estimated to be between 30 and 34 inches (2.5-2.833 feet) and the height between 43 and 49 inches (3.5833-4.0833 feet). These estimates are based on research on agricultural aircraft with similar performance specifications (Air Tractor-802A[3]).

The ratio between the weight and wing area is set using the design point selected on the power loading curves. Using the weight estimation, the necessary S can now be determined. This led to challenges. Given the maximum stall speed specified in FAR Part 23 and the required mission payload weight, a large wing area was necessary. This presented two undesirable options: wings with a span of about 80 feet or wings with a very low aspect ratio, neither ideal for crop-dusting missions. We resolved these issues by slightly exceeding the maximum allowable stall speed, though this approach will require special certification from regulators.
We estimated a tail volume coefficient using historical data to size the rear stabilizers. Then, a length ratio was chosen to determine the stabilizer's position relative to the wing. With the wing areas and fuselage length defined, the aspect and taper ratios for the wing and control surfaces complete the initial wing sizing and geometry.

D. Center of Gravity

To determine the weight of each component of the aircraft, the general aviation method, Cessna estimation method, and the Toren Beek estimation method have been used using all the components properties previously obtained, namely W_0 = 16,500 lbs, and assuming an ultimate load factor of 4.4 for general aviation aircraft (according to CFR part 23). The fuselage has a top section shape close to an airfoil shape; therefore, its aerodynamic center is assumed to be at 25% of its main chord from the datum. Each component's average weight found using these methods has then been computed. The outlier obtained for whichever component has been omitted from the equation.

The moment arm of each component was then determined using the CAD model, which was designed based on the initial sizes and locations of each component (from the Initial Weight step and Wing-Tail selection step). The moment for each component and the sum of all of them were then computed.

Using Eq. (2), the position of the center of gravity has been determined, and it is its position from the datum line in ft. The datum line here has a position x=0 and is at the tip of the fuselage.
To find the empty weight center of gravity, the weight of the hopper, fuel tank, and payload have been brought down to 0.
The desired center of gravity position is between 15% and 30% of the wing's MAC.

$$x_{cg} = \frac{\Sigma W_i x_{cgi}}{\Sigma W_i} \tag{2}$$

E. Landing Gear

The landing gear for the Ceres AG-1 was developed with detailed consideration of the runway conditions required for both takeoff and landing. The design requirements for the Ceres AG-1 aircraft specify operation on grassy, wet, and muddy runways, conditions typical for agricultural aviation. A taildragger configuration was selected for this purpose, as it provides several key advantages suited to the mission profile of the Ceres AG-1.

The Cupertino Aerospace design uses a Type III tire measuring 11.0 x 12 inches, which, according to the Goodyear Aviation Databook 20224, also suits agricultural aircraft operating on grass, muddy, or wet runways due to its superior flotation, cushioning, and self-cleaning capabilities.

Additionally, the landing gear utilizes an oleo strut, a pneumatic air-oil hydraulic shock absorber, to cushion the impact of landings and dampen vertical oscillations. The oleo strut consists of an oil-filled cylinder with a hollow, perforated piston, where oil is forced into the piston during compression, providing effective shock absorption. This comprehensive design ensures that the Ceres AG-1 can reliably operate under the demanding conditions often encountered in agricultural aviation.

F. Aerodynamics

The Drag for the Ceres AG-1 was calculated piecewise, with the C_{d0} of each part of the aircraft being summed to get the total C_{d0} of the aircraft. The Drag Build-Up[5] document was referenced for the methods of drag estimation. The drag for the landing gear, canopy, fuselage, empennage, wings, and sprayer was calculated using these methods. Multiple methods were used to solve the lift of the Ceres AG-1. Xflyr was used to find the wings' lift and validate the drag found using previously outlined methods.

Oswald's Efficiency Factor for the wing was calculated using the method in the Drag Build-Up[5] document and averaged with the Douglas and Straight-Wing methods.

G. Engine and Propeller

The engine that best meets this requirement is the 2750 horsepower PW127XT[6]. A propeller must be affixed to transform all that power into propulsive thrust. The first parameter is its radius, acquired by limiting the tip speed. To avoid shockwaves and maintain structural integrity, V_T is set to Mach 0.8. Pratt & Whitney[6] gives maximum rotational velocity as 40π, and expecting maximum velocity of 150% of optimal dusting velocity gives 264 feet per second. Research into propellers for this engine produced only defunct companies and unanswered emails, leaving no choice but to design a propeller in-house. The first step is approximating V_r, the velocity added to the airflow through the action of the propeller, by guessing thrust T_0 and utilizing Momentum Theory with the formula

$$V_r = \sqrt{\left(\frac{V_0^2}{4}\right) + \frac{T_0}{2\Pi\rho r^2}} - \frac{V_0}{2} \tag{3}$$

Now, Blade Element Method analysis may begin. Selecting the Clark Y airfoil for its commonality with other propellers, its maximum C_L/C_D occurs around 4° Angle of Attack, with approximately

C_L = 0.8125 and C_D = 0.0093. Crop dusters operate very close to stall speed at very low altitudes, so the interests of safety dictate a design speed of V_0 = 135 ft/s with sea-level density. To keep a constant Angle of Attack at this takeoff/stall recovery setting, the Angle of Twist should match the change in Angle of Attack over the length of the blade using

$$\Phi + \alpha_i = \tan^{-1}\left(\frac{V_0 + V_r}{\omega r}\right) \tag{4}$$

From prior research, Hamilton Standard 6-bladed propellers are used by the ATR 72 for its PW100-series engines[7], so this propeller will also use B = 6. Affixing a spinner to match the nose puts r_{hub} at 20 inches and V_{eff} can be calculated from its normal component $V_0 + V_r$ and rotational component ωr. Now the following integral for power required can be solved to ensure the thrust calculation can be produced by the PW127. To ensure the engine can operate at a given flight condition and propeller setting, the Power Required cannot exceed the 2750 maximum power of the PW127XT. This requires a complex integral multiplying the aerodynamic forces resisting rotation over the length of the propeller blades by the rotational velocity shown in Eq. 5.

$$P_{req} = \frac{B\rho\omega}{2} \int_{r_{hub}}^{r_{tip}} V_{eff}^2\, cr[C_L \sin(\Phi + \alpha_i) + C_D \cos(\Phi + \alpha_i)]dr \tag{5}$$

Then, iterating Eq. 5 with Eq. 6 below, a chord function over the length of the blade, c, can be experimented with to maximize thrust while remaining within power limits. Through this iterative process, a bulged ellipse proved to be the best shape for generating thrust.

$$T = \frac{B\rho}{2} \int_{r_{hub}}^{r_{tip}} V_{eff}^2\, c[C_L \cos(\Phi + \alpha_i) - C_D \sin(\Phi + \alpha_i)]dr \tag{6}$$

At which point Eq. 3 through 6 must be iterated through until T_0 = T and P_{req} = 2750 hp. The torque produced is then P_{req} divided by rotational velocity ω. With the propeller thus designed, introducing approximations for the aerodynamic coefficients and effective Angle of Attack allows thrust and power to be calculated across the flight envelope. Due to obtaining these values, Tv/P_{req} is always used rather than propeller efficiency η_P.

$$\alpha_{\mathrm{eff}} = \tan^{-1}\left(\frac{252.1069669}{40\Pi \mathrm{r}}\right) - \tan^{-1}\left(\frac{\mathrm{V_0} + \mathrm{V_r}}{\omega \mathrm{r}}\right) + \beta_0 \tag{7}$$

$$\boldsymbol{C_L} = 4.5\alpha_{eff} + 0.5 \tag{8}$$

$$\mathrm{C_D} = 0.07684\alpha_{\mathrm{eff}} + .00394 \tag{9}$$

In Eq. 7, the effective Angle of Attack calculation, β_0 represents additional pitch allowed by the nature of a constant-speed propeller, effectively fixed at 4° for takeoff and increasing to optimize other flight settings. Through repeated execution of these calculations, the thrust and power required, and thereby the fuel consumed, can be found. This, in turn, allows mathematical calculations of aircraft performance.

H. Performance

The first stage of flight is takeoff, and FAR part 23 requires calculations of ground roll and climb to 50 feet. First, Gudmundsson[8] provides a chart on page 358 based upon leading-edge sweep and wing taper ratio, which gives C_{Lmax} as approximately 0.88 times the maximum lift coefficient of our airfoil, or 2.112. Then,

$$V_{LOF} = 1.15\sqrt{\frac{2W}{\rho S C_{Lmax}}} \tag{10}$$

The lift coefficient on takeoff $C_{LTO} = C_{Lmax}/1.32 = 1.6$. then, with the distance between the wing and the ground in the takeoff roll h_w,

$$\Phi = \frac{1 + \left({}^{16h_w}/_{b}\right)^2}{2\left({}^{16h_w}/_{b}\right)^2} \tag{11}$$

Now to find acceleration on the ground a_g, which also requires runway friction. On hard turf, $\mu = 0.05$.

$$a_g = g\left[\left(\frac{T}{W} - \mu\right) - \frac{(C_{D0} + \Phi k C_{LTO}^2 - \mu C_{LTO})\rho S V_{LOF}^2}{2W}\right] \tag{12}$$

With the acceleration known, kinematics can be used to find S_G. Assuming rotation time is three seconds due to high takeoff weight, Rotation Distance $S_R = 3V_{LOF}$. Then the distance required to climb over the obstacle S_{Air}

$$S_{Air} = \frac{V_{LOF}^2 \sin\left[\cos^{-1}\left(1 - \frac{0.2h_{OBS}}{V_{LOF}^2}\right)\right]}{0.2g} \tag{13}$$

Adding S_G, S_R, and S_{Air} gives the total distance to clear a fifty-foot obstacle, calculated for maximum takeoff and empty weights. Then, the best climb will occur at the minimum power required V_{Pmin},

$$V_{Pmin} = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{k}{3C_{D0}}}} \tag{14}$$

Then, the Rate of Climb follows at the best climb angle achievable at this setting. The best cruise then occurs where the lift-to-drag ratio is maximized, and this velocity can be found with

$$V_{\frac{L}{D}max} = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{k}{C_{D0}}}} \tag{15}$$

By setting thrust equal to drag and iterating through the Power Required calculations outlined earlier, the engine and propeller can be set to minimize fuel consumption. Then, the endurance of the aircraft is given by

$$E = \frac{550T}{2\sqrt{kC_{D0}}c_{BHP}P_{req}} \ln\left[\frac{W_i}{W_f}\right] \tag{16}$$

This endurance was found at 8000 feet for the ferry mission with the FAA-mandated 30-minute reserve and the hopper used as an extra fuel tank. The range is simply Eq. 15 multiplied by Eq. 16.

$$V_{max} = \sqrt{\frac{T + \sqrt{T^2 - 4W^2kC_{D0}}}{\rho SC_{D0}}} \tag{17}$$

Iterating through Eq. 19 and the Blade Element Method, as thrust and velocity are mutually dependent, can yield maximum level speed.

For power-off descent, the minimum glide angle γ_{min}, which occurs at $V_{L/Dmax}$, is calculated by Eq. 21.

$$\gamma_{min} = \sin^{-1}\left[2\sqrt{kC_{D0}}\right] \tag{18}$$

Velocity for minimum sink rate is given by Eq. 22

$$V_{ymin} = 4\sqrt{kC_{D0}}\sqrt{\frac{2W}{\rho S}}\left(\frac{k}{27C_{D0}}\right)^{\frac{1}{4}} \tag{19}$$

I. Cost Analysis

The cost calculations were completed using RDT&E, as well as production costs for general aviation, GAA. Our cost analysis largely followed the outlined process of the GAA method, with a few variables of note being changed. The plane was assumed to fall under FAR Part 23 for calculating various F factors, such as the certification cost factors. It was assumed the plane would be made of approximately 80 percent composites for the composites F factor. The aircraft does not require a pressurized cabin, so the pressurization F factor was left at one. We assumed a production rate of 1 aircraft per month, which, for the first 100 aircraft, we feel gives a reasonable 2 years of initial production.

9. RESULTS

The results of the research conducted by Cupertino Aerospace have helped create substantial innovative progress in the development of a SHOTS agricultural aircraft. The outcomes are divided into three sections: System Requirements, Design Concept, Design Analysis, and Cost Effectiveness.

Task 1: System Requirements

The design requirements for Cupertino Aerospace's Ceres AG-1 aircraft aim to enhance safety, efficiency, and market competitiveness in agricultural aviation. A primary focus is on improving operational safety by reducing pilot exposure to hazardous chemicals by at least 50% compared to current operations and minimizing accidents during critical flight phases such as maneuvering, application, and landing. The aircraft must incorporate field-repairable structures and swappable powerplants to ensure reliability and ease of maintenance.

Performance objectives include doubling the operational tempo of leading agricultural aircraft, measured using the Agricultural Aircraft Utility Metric (AAUM). The design must demonstrate optimized performance across configurations for operational weight, wingspan, and speeds, ensuring the capability to spray 400 acres permission at two gallons per acre. The aircraft must accommodate human pilots for ferry missions while supporting autonomous operations during spraying, providing flexibility. It must also integrate safety systems to meet stringent hull loss and fatality probability thresholds.

The aircraft is required to operate reliably within a wide temperature range, from -20°F to 180°F in storage and 32°F to 150°F during operations, and power plants compatible with sustainable aviation fuel (SAF) are used. Its geometry must allow it to fit within a conventional T-hangar when folded. The design must also meet strict ground and airspace constraints, with a ground run length of 1,000 feet and a total field length of 1,500 feet over a 50-foot obstacle, operable on hard-packed dirt or grass runways.

Speaking to crop duster pilots also provided valuable insight into optimizing the design. Chemicals are best dispersed at different altitudes and velocities, but 120 mph suits even the most stringent mission profile. The need for air conditioning for the pilot, corrosion prevention for the airframe, and a powerful engine were also impressive.

In addition to agricultural applications, the aircraft must be adaptable for alternative revenue-generating uses such as wildfire suppression, glider towing, and military operations. A comprehensive life cycle cost analysis, including potential insurance cost reductions from safety enhancements, is required. The aircraft is expected to enter service by 2028, with a projected operational lifespan of 30 years and 220 agricultural service days annually.

Mission profiles include a ferry mission with a 600-nmi range and an operational mission radius of 50 nmi. The design must ensure efficiency, focusing on hopper capacity, turnaround times, and optimal performance for various mission scenarios. These requirements address current challenges in agricultural aviation while positioning the Ceres AG-1 as a safety, efficiency, and versatility leader.

Task 2: Design Concept

From these requirements, an initial design concept was prepared as shown in Fig. 1.

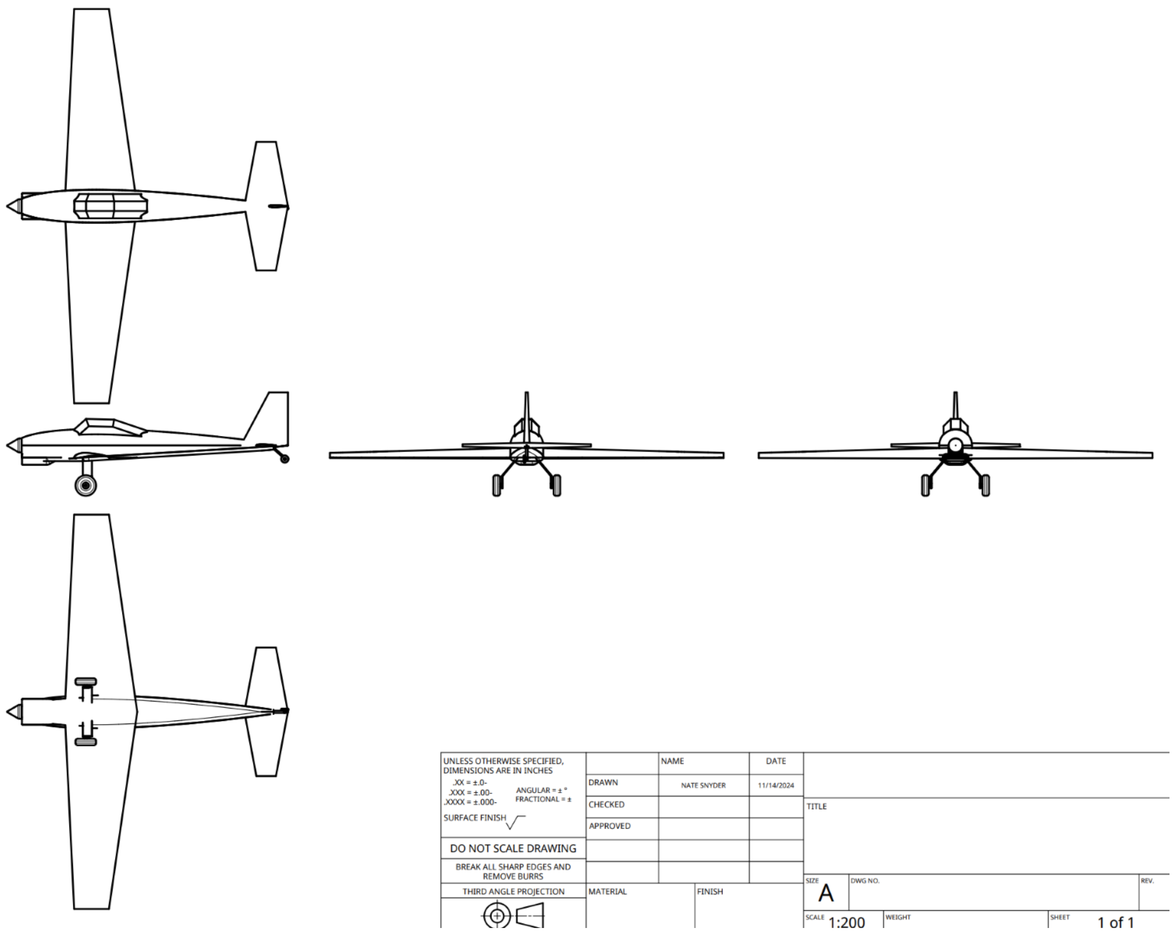

Figure 1. Vehicle Arrangement Five-View

Our fuselage is designed to be 37.7 feet long, 30–34 inches wide, and 43–49 inches tall, resulting in a fineness ratio of 6. It will feature a tadpole-shaped structure and will be mounted using a spar box under the cabin floor. The fuselage will primarily be constructed from composite materials, chosen for their lighter weight compared to metal and the cost efficiency of shaping composites for the tadpole design. Additionally, the fuselage will have a slight downward tilt to reduce upwash effects induced by the wing.

The selected engine is the Pratt & Whitney 127, which produces 2,750 horsepower. It weighs 1,060 pounds and has a fuel consumption rate of 0.459 pounds per horsepower per hour.

The wing has been designed to meet the dimensional constraints of a standard T-hangar. Its span will be 54 feet, with a root chord of 10 feet and a tip chord of 4.8 feet, resulting in a total wing area of 393 square feet and an aspect ratio of 7.5.

The empennage also adheres to the T-hangar constraints. The horizontal tail will have an 18.7-foot span, a root chord of 6.5 feet, a tip chord of 2.9 feet, and an aspect ratio of 4. The vertical tail will span 7.4 feet, with a root chord of 6.6 feet, a tip chord of 2.6 feet, and an aspect ratio of 1.5.

Table 1. Design Data

Parameter	Horizontal Tail		Vertical Tail		Wing		Fuselage		
Area	87.5	[ft2]	33.8	[ft^2]	393	[ft^2]	Length	37.7	[ft]
Span	18.7	[ft]	7.4	[ft]	54.29	[ft]	Width	36	[in]
Aspect Ratio	4		1.6		7.5		Height	49	[in]
Taper Ratio	0.45		0.45		0.45		Fineness Ratio	6	
Root Chord	6.5	[ft]	6.6	[ft]	10	[ft]	Fuselage Weight	9000	[lb]
Tip Chord	2.9	[ft]	2.6	[ft]	4.8	[ft]			
MAC	4.9	[ft]	4.9	[ft]	7.5	[ft]			
Airfoil	NACA 0012		NACA 0012		S1223				

Task 3: Design Analysis

A. Power Loading Curves

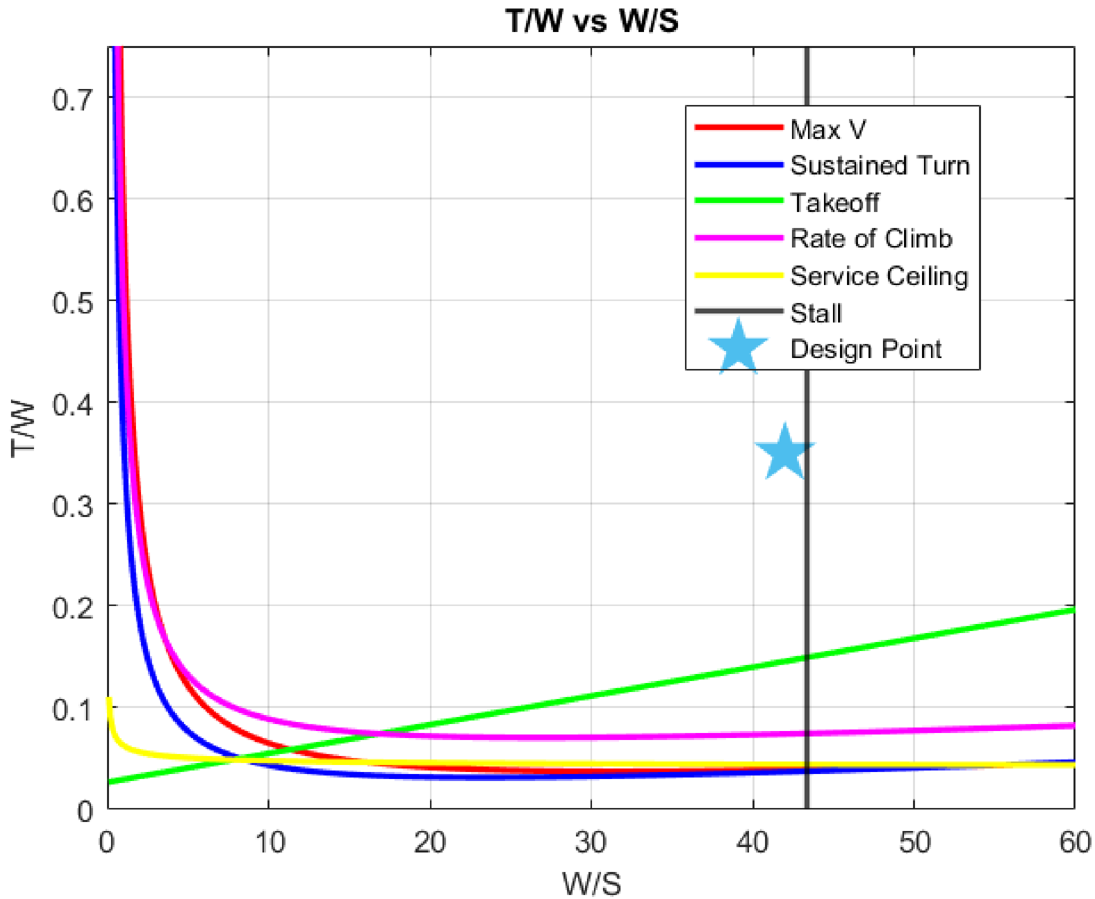

Figure 2. Matching Plot for Thrust, Weight and Wing Area

The design area for the power loading curves is to the left of the stall line and above the other curves. The optimal point would be at the intersection between takeoff and stall. The Pratt & Whitney 127 was found to be the closest to this optimum point, but during the engine selection process, a higher T/W ratio was eventually selected.

B. Wing Design

Table 2. Wing and Empennage Design Criteria

Plane		
Weight	W	16500
Fuselage Length	L	37.7
Wing		
Aspect Ratio	AR	7.5
Taper Ratio	λ	0.45
Wing Area	S	393
Tail		
Horizontal		
Aspect Ratio	AR	4
Taper Ratio	λ	0.45
Volume Coefficient	cht	0.5
Length Ratio	lh	0.6
Vertical		
Aspect Ratio	AR	1.6
Taper Ratio	λ	0.4
Volume Coefficient	cvt	0.03
Length Ratio	lv	0.5

Table 3. Wing And Empennage Design Measurements

Wing		
Area	S	393
Span	b	54.22176685
Aspect Ratio	AR	7.5
Taper Ratio	λ	0.5
Root Chord	cr	9.97181919
Tip Chord	ct	4.487318636
MAC	cbar	7.576290212
	Ybar	11.84153529
Horizontal Tail		
Area	S	65.64778433
Span	b	16.20466406
Aspect Ratio	AR	4
Taper Ratio	λ	0.45
Root Chord	cr	5.587815193
Tip Chord	ct	2.514516837
MAC	cbar	4.245454992
Length	lh	22.62
Vertical Tail		
Area	S	33.82747895
Span	b	7.356899232
Aspect Ratio	AR	1.6
Taper Ratio	λ	0.4
Root Chord	cr	6.568660029
Tip Chord	ct	2.627464011
MAC	cbar	4.879576021
Length	lv	18.85

The results of these calculations seem reasonable compared to historical data. The wing area is larger than most crop dusters have been historically, but this is due to the significant increase in hopper capacity.

C. Weight

Table 4. CG Position at Maximum weight

	Weight (lbs)	Location (ft)	Moment (ft*lbs)	Contribution % to total moment
Wings	1488.803903	9.48	14113.861	8.829565803
Horizontal tail	210.4284066	33.63	7076.707314	4.427155184
Vertical tail	104.9102377	33.63	3528.131294	2.207182529
Fuselage	981.6815871	9.44	9267.074182	5.797438511
Landing gear	494.6572413	9.021	4462.302974	2.791595988
Flight control system	213.3755526	6.404	1366.457039	0.854849169
Cargo/payload	3000	11.5	34500	21.58303955
Fuel	1400	9.48	13272	8.302901477
Hopper	7000	9.5	66500	41.60209073
fuel system	85	9.48	805.8	0.504104733
Electrical system	442.2	5.404	2389.6488	1.494953176
Furnishing	47.56	9.425	448.253	0.280424992
sprayer equipment	150	13.45	2017.5	1.262138617
engine	1000	0.1	100	0.062559535
total	16618.61693	total moment:	159847.7356	
CG Position at max weight (ft)	9.618594393			

Table 5. CG position at empty weight

	Weight (lbs)	Location (ft)	Moment (ft*lbs)	Contribution % to total moment
Wings	1488.803903	9.48	14113.861	30.96792803
Horizontal tail	210.4284066	33.63	7076.707314	15.52735731
Vertical tail	104.9102377	33.63	3528.131294	7.741249257
Fuselage	981.6815871	9.44	9267.074182	20.33335076
Landing gear	494.6572413	9.021	4462.302974	9.790962043
Flight control system	213.3755526	6.404	1366.457039	2.998211704
Cargo/payload	0	11.5	0	0
Fuel	0	9.48	0	0
Hopper	0	9.5	0	0
fuel system	85	9.48	805.8	1.768046065
Electrical system	442.2	5.404	2389.6488	5.2432479
Furnishing	47.56	9.425	448.253	0.983534317
sprayer equipment	150	13.45	2017.5	4.426697613
engine	1000	0.1	100	0.219414999
total	5218.616928	total moment:	45575.7356	
CG Position at empty weight (ft)	8.733297774			

Looking at the results in Tables 4 and 5, the main contributors to the CG position of the aircraft are the payload and the hopper weight. In the previous calculations, the payload center of gravity is assumed to be at the pilot seat, which is not true. It has been kept there to keep the airplane stable. The next step worth looking into is changing the position of the wing, which will push the center of gravity a little bit aft, which will allow us to place the payload behind the pilot seat, which will make more sense.

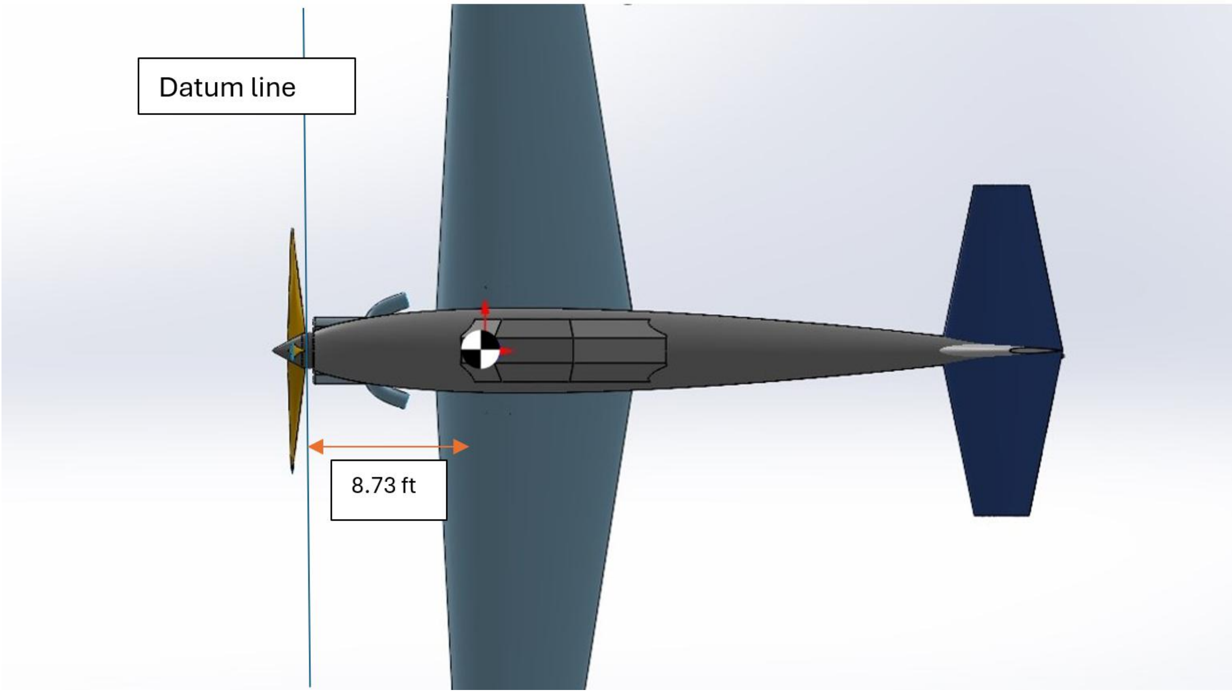

Figure 3. Empty weight center of gravity location

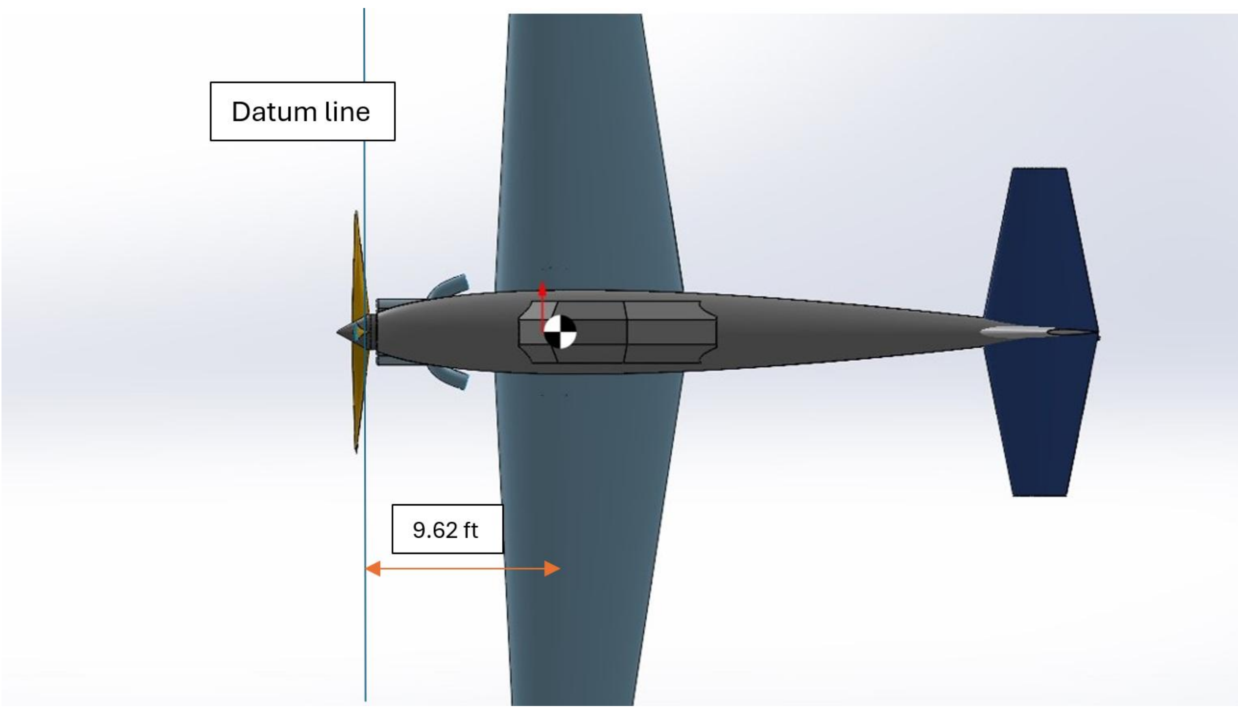

Figure 4. Max weight center of gravity location

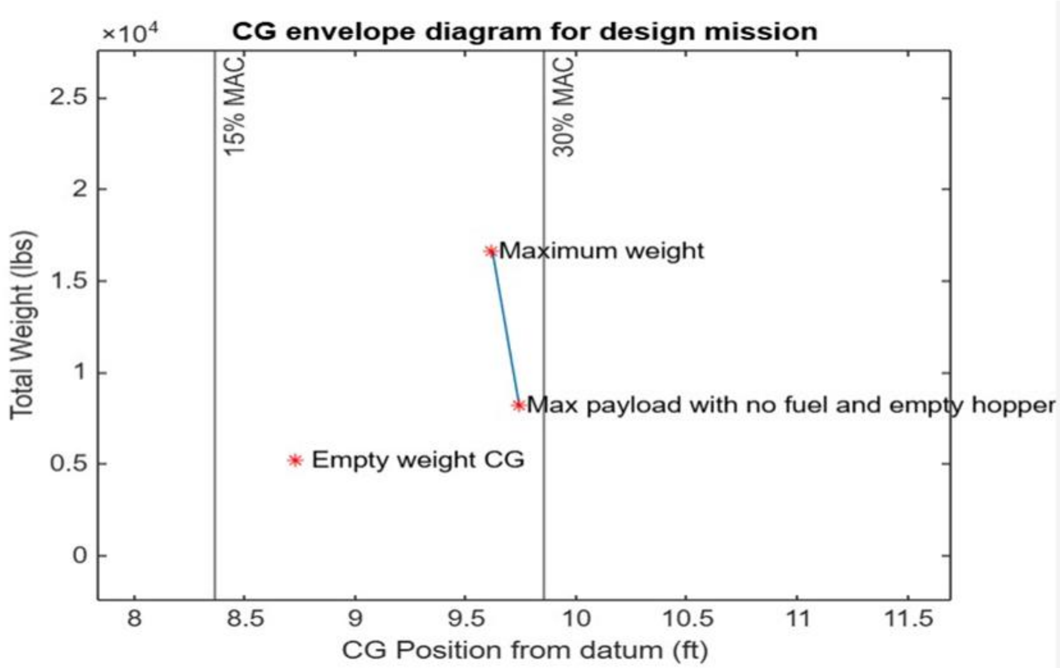

Figure 5. CG envelope for design mission

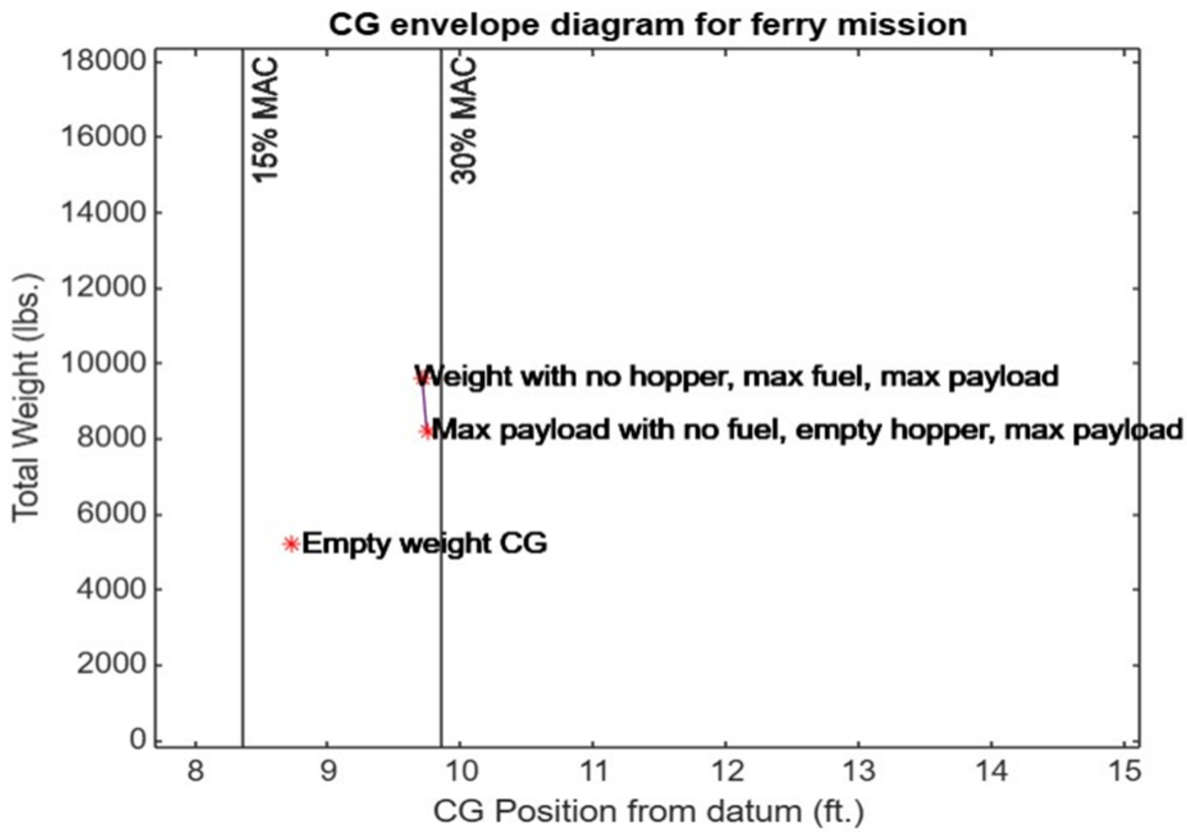

Figure 6. CG envelope for ferry mission

D. Drag

Table 6. Total Drag of Aircraft by Components

Drag Chart								Total	Total
α	Fuselage	Landing Gear	Sprayer	Wing	Empanage	Cockpit	Sprayer	Cd	Cd0
0	0.00265	0.00300	0.00481	0.00361	0.00578	0.00935	0.00005	0.02926	0.02436
1	0.00268	0.00300	0.00481	0.00361	0.00578	0.00935	0.00005	0.02930	
2	0.00277	0.00300	0.00481	0.00361	0.00578	0.00935	0.00005	0.02938	
3	0.00293	0.00300	0.00481	0.00362	0.00578	0.00935	0.00005	0.02955	
4	0.00320	0.00300	0.00481	0.00362	0.00578	0.00935	0.00005	0.02982	
5	0.00360	0.00300	0.00481	0.00362	0.00578	0.00935	0.00005	0.03022	
6	0.00417	0.00300	0.00481	0.00363	0.00578	0.00935	0.00005	0.03079	
7	0.00491	0.00300	0.00481	0.00363	0.00578	0.00935	0.00005	0.03154	
8	0.00587	0.00300	0.00481	0.00363	0.00578	0.00935	0.00005	0.03250	
9	0.00707	0.00300	0.00481	0.00363	0.00578	0.00935	0.00005	0.03370	
10	0.00854	0.00300	0.00481	0.00364	0.00578	0.00935	0.00005	0.03517	

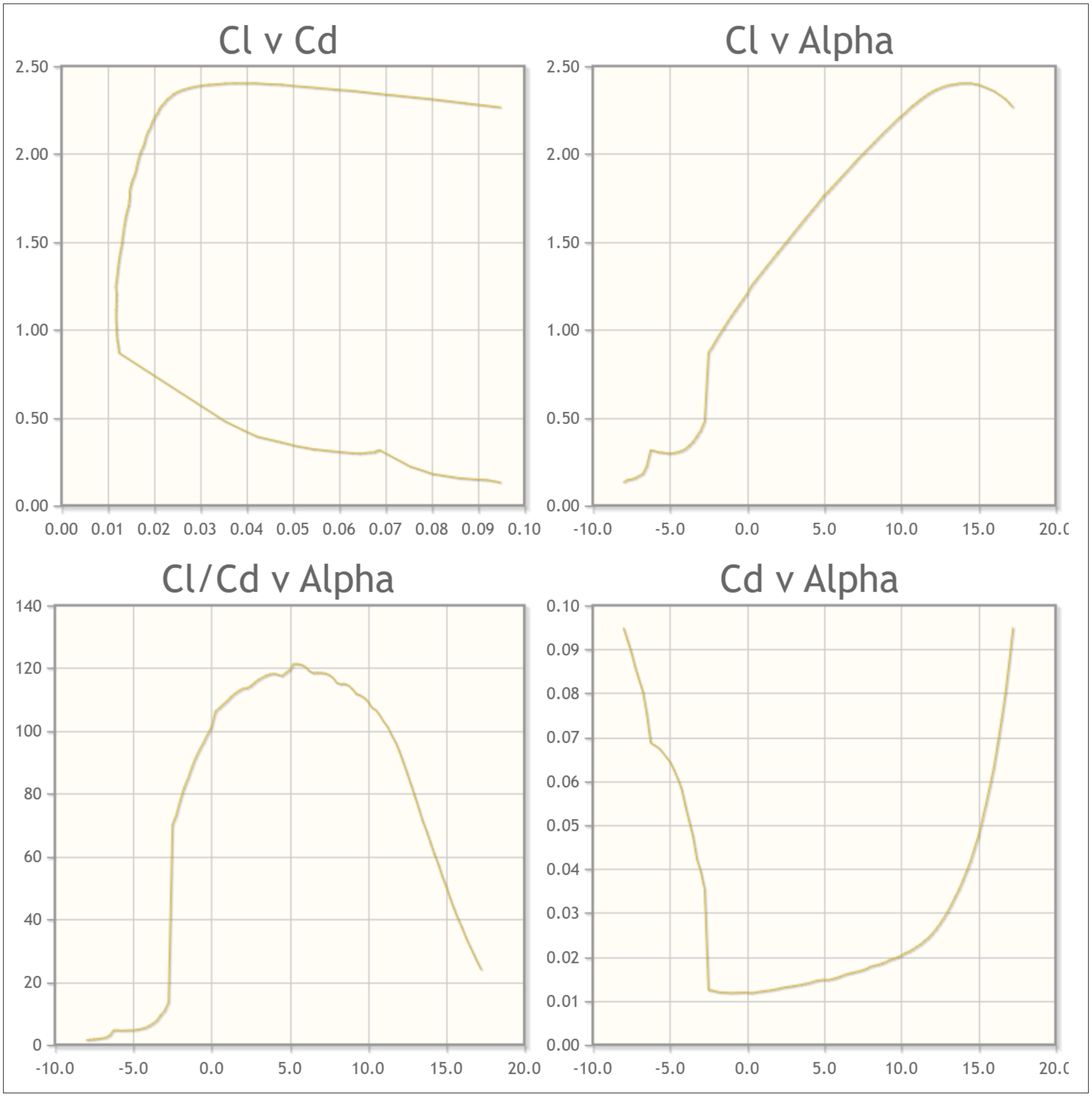

Figure 77. Polars of S1223 Airfoil

The Ceres AG-1's drag approximations align with those of similar agricultural aircraft, such as the AT-802A3. With a Cd0 of 0.0244, the Ceres AG-1 has a slightly smaller drag coefficient than most agricultural planes' typical 0.03-0.05. This indicates that the aircraft will be more efficient during flights.

E. Performance

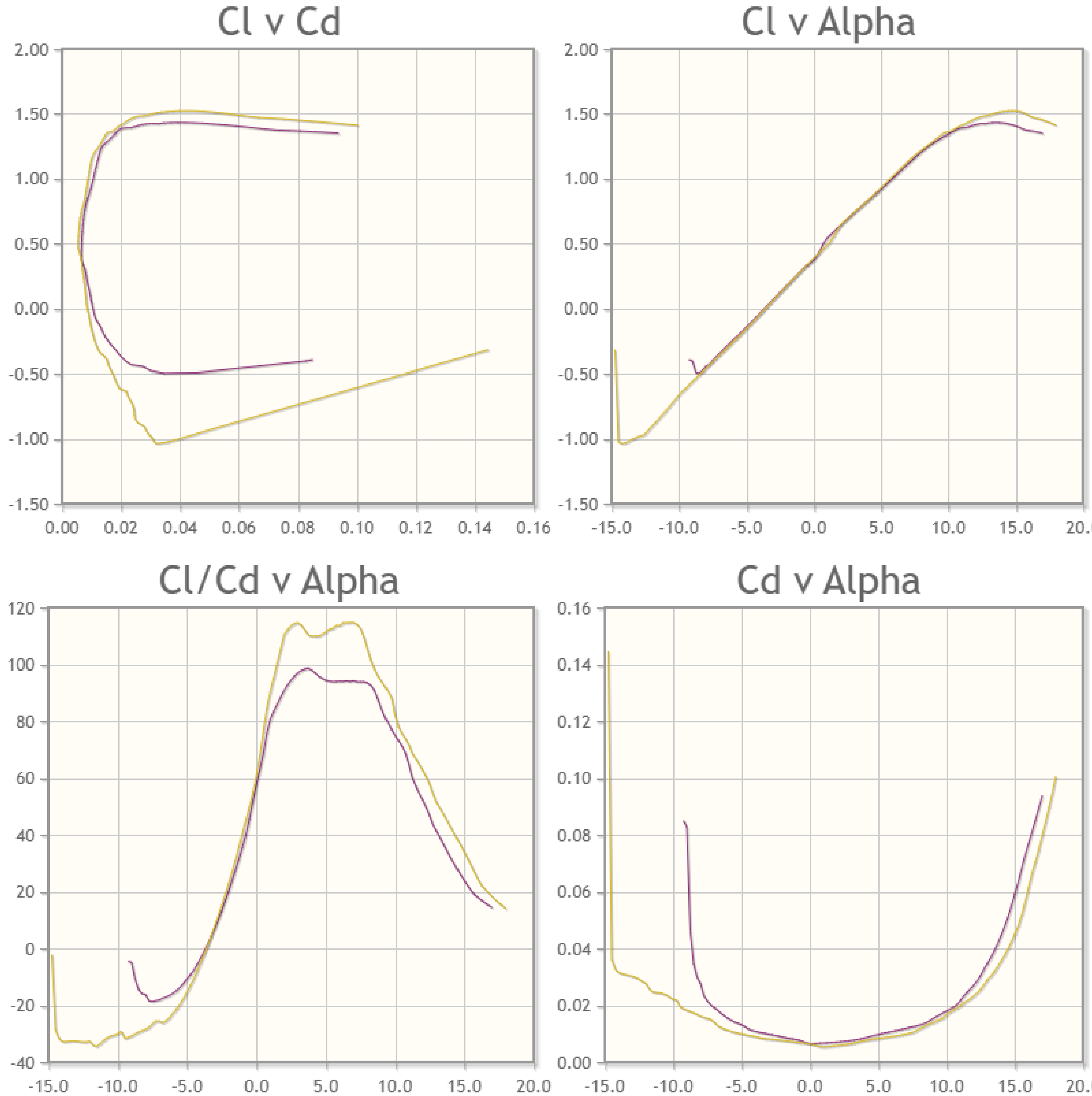

Figure 8. Propeller Airfoil (Clark Y) Polars

Table 7. Propeller Statistics

tip radius	6.5 ft		
Chord function			
	Thrust	Power Required	Torque
Takeoff	5800 lbs	2750 hp	12005 ft-lbs
Best Cruise	1276 lbs	862.5 hp	
Max Speed	2480 lbs	2750 hp	

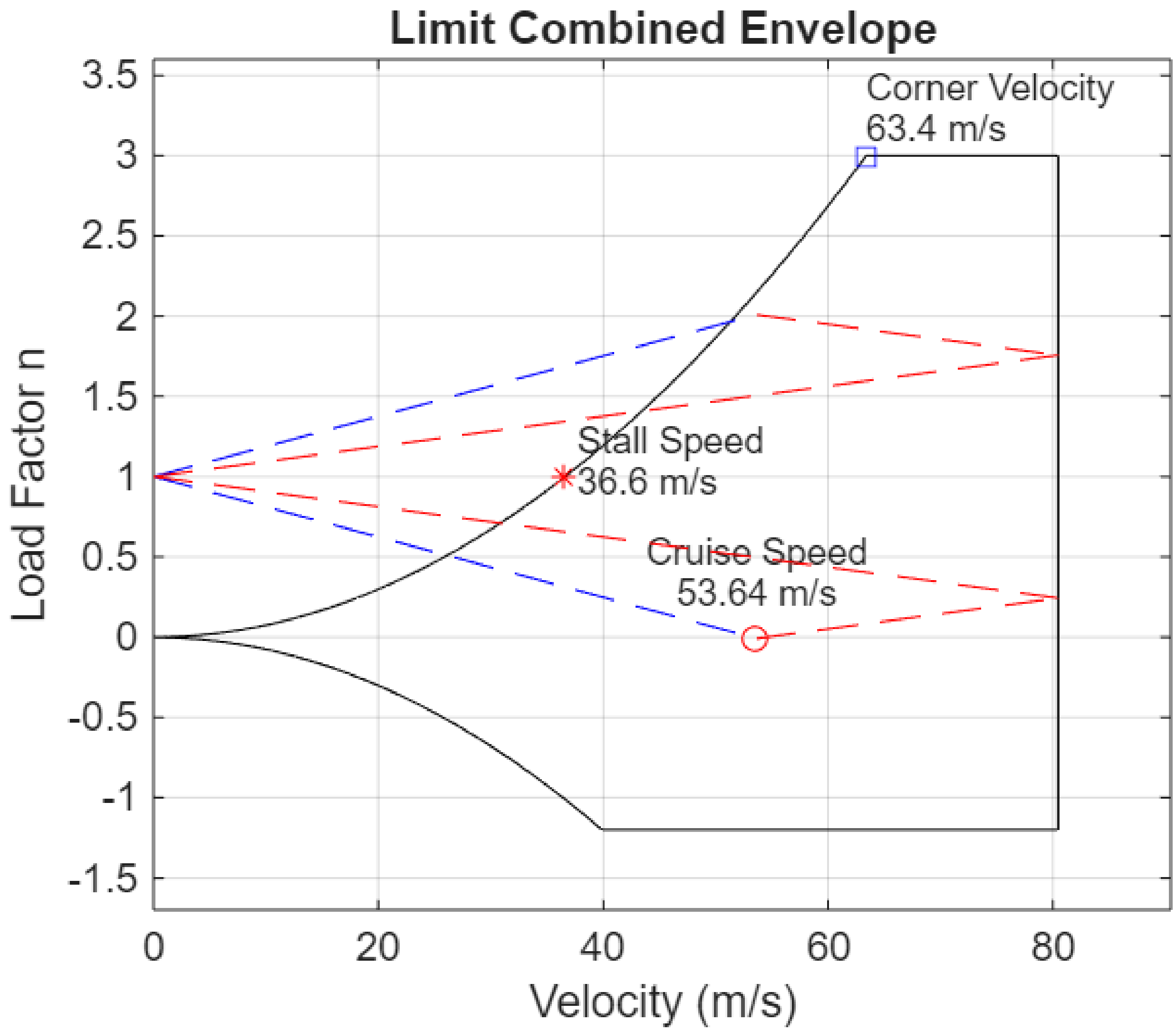

Figure 8. V-N Diagram

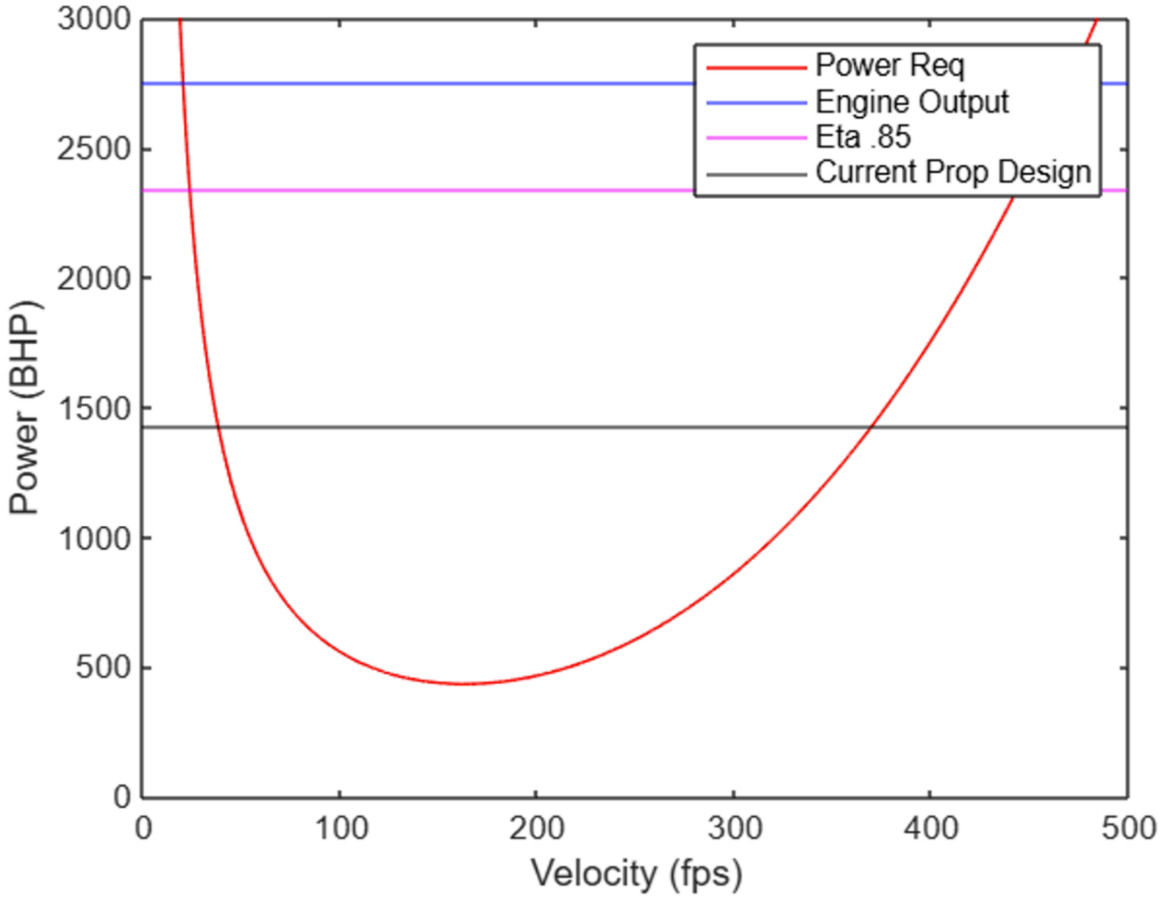

Figure 90. Flight Power Required vs Power Available

Table 8. Performance Statistics

Takeoff Performance			
	Max TOW	Empty(9000lb)	
Ground Roll	1208.027 ft	306.119 ft	
Rotation Distance	426.978 ft	315.211 ft	
Transition Distance	584.226	411.200 ft	
Total Distance	2219 ft	1033 ft	
V_{LOF}	101 mph	75 mph	
Climb Performance			
V_y	111 mph	V_x	110 mph
Best Rate of Climb	2208.221 ft/min		
Climb to 8000 ft	3.489 minutes		
Cruise Performance (8000 ft)			
Cruise Speed	164 mph		
Breguet Endurance	16.93 hours	Breguet Range	2168 miles
Sea-level Top Speed	279 mph		
Glide Performance			
Minimum Glide Angle	146 mph	Glide Ratio13.1:1	
Minimum descent rate	877 ft/min		

Task 4: Cost-Effectiveness

The airframe is assumed to be the first to be delivered in 2035. Therefore, all numbers below are given in 2035 dollars, with a CPI of 1.894 from 2012. Engine cost was not estimated using the GAA formulas and, therefore, is omitted below; however, the engine selected, the PW100 series, has a cost of around 300,000-400,000 dollars. The cost per unit of over 15 million is high compared to similar airframes in production. However, no new company has entered the market recently, and all current companies are established. Considering that this number includes all the project's startup costs in 2035 dollars, we believe that this is not an unreasonable price.

Table 9. Cost Analysis Breakdown

Costs	
Engineering (C_{ENG})	\$386,679,018.01
Tooling (C_{TOOL})	\$149,220,542.08
Manufacturing (C_{MFG})	\$461,065,864.54
Develop Support (C_{DS})	\$26,987,268.91
Mfg. Material (C_{MAT})	\$30,087,694.78
Quality Control (C_{QC})	\$136,257,135.11
Flight Test (C_{FT})	\$3,340,825.42
Certification Cost (C_{CERT})	\$566,227,654.42
Total	\$1,759,866,003.26
Cost per Unit	\$15,171,258.65

10. SUMMARY & CONCLUSIONS

The Ceres AG-1 project successfully demonstrates the feasibility of a next-generation agricultural aircraft designed to meet stringent operational, safety, and environmental criteria. Cupertino Aerospace has developed an aircraft that prioritizes pilot safety, operational efficiency, and versatility, addressing key industry challenges such as chemical exposure and limited operational capabilities. The aircraft achieves exceptional performance metrics through rigorous design and analysis, positioning it as a transformative asset for agricultural and multipurpose aviation.

The Ceres AG-1's innovative features, including its advanced aerodynamic profile, sustainable fuel compatibility, and adaptability for off-season applications, highlight its potential to redefine industry standards. While the project entails significant development and production costs, its long-term economic and operational benefits underscore its value proposition. Cupertino Aerospace is confident in the Ceres AG-1's ability to enhance agricultural productivity, promote sustainability, and ensure financial viability for operators in diverse markets.

11. REFERENCES

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