

# Preliminary Design of the ECHO Aircraft

“Conquering Climate Change”



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**List of Symbols**

<b><u>Symbol</u></b>	<b><u>Description</u></b>	<b><u>Units</u></b>
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AR	Aspect Ratio	lb <sub>f</sub>
b	Wingspan	ft
c <sub>p</sub>	Brake Specific Fuel Consumption	lb <sub>f</sub> /hp-hr
C <sub>D</sub>	Drag Coefficient	(~)
C <sub>D0</sub>	Zero-Lift Drag Coefficient	(~)
C <sub>L</sub>	Coefficient of Lift	(~)
C <sub>n</sub>	Yawing Moment Coefficient	(~)
D	Drag	lb <sub>f</sub>
h	Altitude/Ceiling	ft
L	Lift	lb <sub>f</sub>
M <sub>ff</sub>	Mission Fuel Fraction	(~)
MTOW	Maximum Takeoff Weight	lb <sub>f</sub>
R	Range	ft
RC	Rate of Climb	ft/min
S	Wing Area	ft <sup>2</sup>
T	Thrust	lb <sub>f</sub>
V	Velocity	ft/s
W	Weight	lb <sub>f</sub>
W/SWing Loading	lb <sub>f</sub> /ft <sup>2</sup>	

<b><u>Greek Symbol</u></b>	<b><u>Description</u></b>	<b><u>Units</u></b>
$\alpha$	Angle of Attack	(deg)
$\beta$	Sideslip Angle	(deg)
$\delta$	Deflection Angle	(deg)
$\eta$	Efficiency	(~)
$\xi$	Damping Ratio	(~)
$\Delta$	Change In	(~)

<b><u>Subscript</u></b>	<b><u>Description</u></b>	<b><u>Units</u></b>
A	Aircraft	(~)
crew	Crew	(~)
e	Empty	(~)
f	Fuel	(~)
fused	Fused	(~)
fTO Fraction of Takeoff	(~)	
h	Horizontal Tail	(~)
L	Landing	(~)

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max	Maximum	(~)
oe	Operating Empty	(~)
p	Propellor	(~)
P	Phugoid	(~)
pl	Payload	(~)
r	Roll	(~)
r	Rudder	(~)
res	Reserve	(~)
SP	Short Period	(~)
tent	Tentative	(~)
TO	Takeoff	(~)
wf	Wing Fuselage	(~)
2S	Double in Spiral	(~)

<b><u>Acronyms</u></b>	<b><u>Description</u></b>	<b><u>Units</u></b>
AIAA	American Institute of Aeronautics and Astronautics	(~)
AEO	All Engines Operative	(~)
AO	Ancillary Objective	(~)
AOW	Ancillary Objective Weight	(~)
APU	Auxiliary Power Unit	(~)
Config	Configuration	(~)
ConOps	Concept of Operations	(~)
CFR	Code of Federal Regulations	(~)
CG	Center of Gravity	(~)
EIS	Entry Into Service	(~)
ECHO	Efficient Climate High-altitude Operations	(~)
FAR	Federal Aviation Regulations	(~)
FL	Flight Level	(~)
IFR	Instrument Flight Rules	(~)
L/D	Lift to Drag Ratio	(~)
O	Objective	(~)
OEI	One Engine Inoperative	(~)
OW	Objective Weight	(~)
R	Requirement	(~)
RAT	Ram Air Turbine	(~)
RFP	Request For Proposal	(~)

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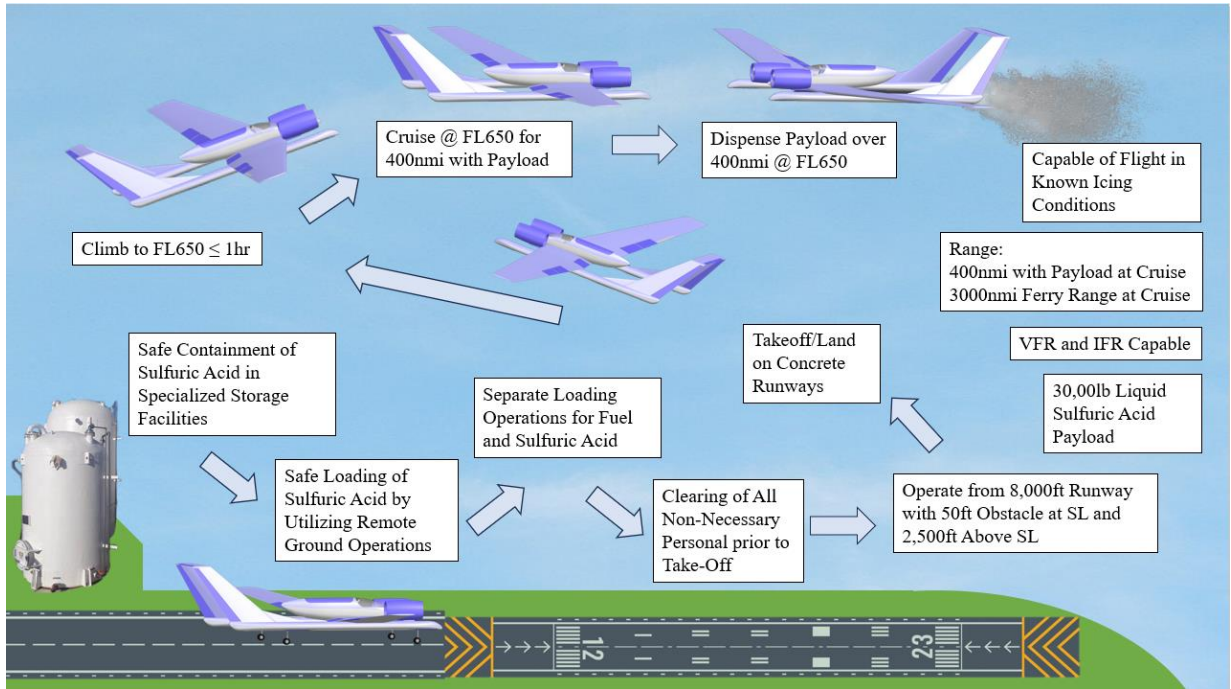
SL	Sea Level	(~)
SPD	Stratospheric Payload Delivery	(~)
SRM	Solar Radiation Management	(~)
STAMPED	Statistical Time and Market Predictive Engineering Design	(~)
T/W	Thrust to Weight Ratio	(~)
VFR	Visual Flight Rules	(~)



**1 Introduction, General Concept of Operations, Mission Specification and Profile**

To mitigate the effects of global warming, Solar Radiation Management (SRM) has been proposed as a modern solution to cool the planet. The unconventional approach of dispensing liquid sulfuric acid into the stratosphere to reflect solar radiation away from the Earth to decrease the core temperature has been proposed [1].

There are a few requirements needed to complete the stratospheric payload mission. First, a concept of operations (ConOps) was developed to outline the necessary procedures for the stratospheric payload delivery aircraft, also known as the Efficient Climate High-altitude Operations (ECHO) aircraft, as shown in Figure 1.1 [2] [3] [4].



**FIGURE 1.1: CONOPS FOR THE ECHO AIRCRAFT**

Table 1.1, Table 1.2, and Table 1.3 outline the mission specifications as detailed in the RFP.

**TABLE 1.1: DESIGN MISSION SPECIFICATION FOR THE ECHO AIRCRAFT**

Design Requirements	
<b>Payload</b>	Must be able to transport and dispense 30,000lb liquid sulfuric acid payload in appropriate tank.



	Must dispense payload over 400nmi.
<b>Propulsion</b>	Engine/propulsion system must have an EIS by 2030.

**TABLE 1.2: PERFORMANCE MISSION SPECIFICATION FOR THE ECHO AIRCRAFT**

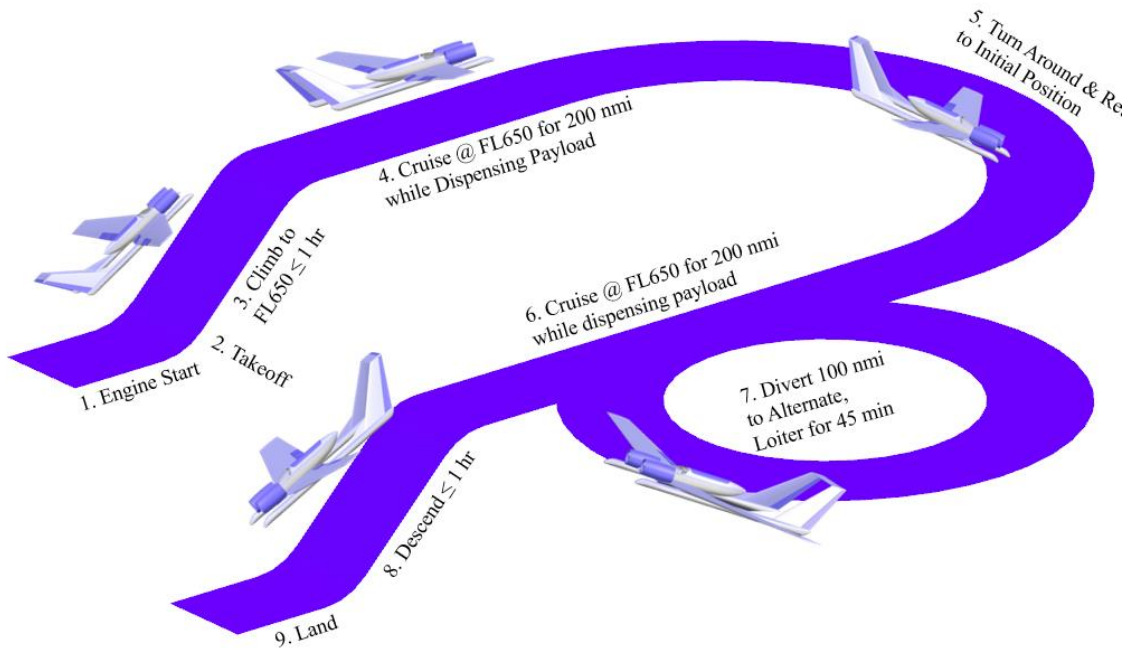
<b>Performance Requirements</b>	
<b>Range</b>	3,000nmi without payload for ferry mission. 400nmi with payload for payload dispense mission.
<b>Altitude</b>	Cruise altitude of 65,000ft for payload dispense mission. No required altitude for ferry mission.
<b>Speed</b>	Cruise Mach of 0.5. No required speed for ferry mission.
<b>Takeoff</b>	Takeoff from 8,000ft concrete runway with 50ft obstacle.
<b>Landing</b>	Land on 8,000ft concrete runway with 50ft obstacle.
<b>Climb/Descend</b>	Climb to cruise in $\leq$ 1hr. Descend from cruise altitude in $\leq$ 1hr.

**TABLE 1.3: OPERATION MISSION SPECIFICATION FOR THE ECHO AIRCRAFT**

<b>Operation Requirements</b>	
<b>Airspace</b>	Capable of flight in controlled and uncontrolled airspace with necessary systems.

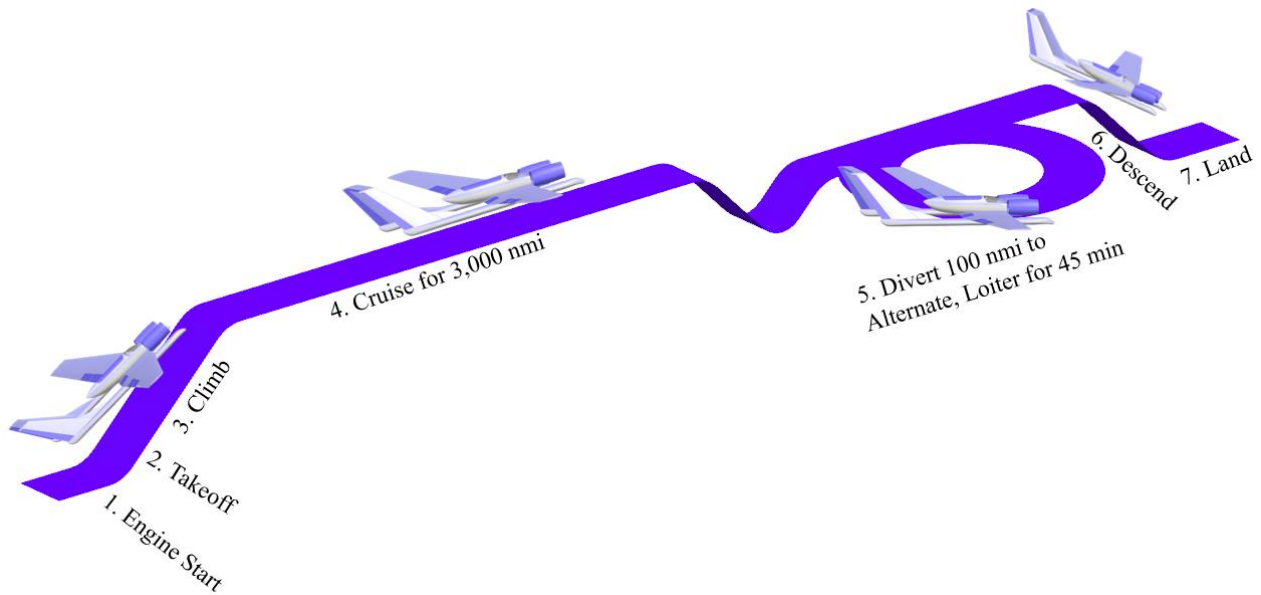
For the ECHO aircraft, there are two mission profiles the aircraft must be able to perform. The first mission profile is the payload dispensing mission. The aircraft must dispense the liquid sulfuric acid payload at 65,000 ft over 400 nmi. At 200 nmi, it must turn around and return to the initial position. The aircraft must also reach the required cruise altitude in less than 1 hr. The mission profile is detailed in Figure 1.2.





**FIGURE 1.2: PAYLOAD DISPENSE MISSION PROFILE**

The second mission profile required is the ferry mission. In this mission, the aircraft must cruise over 3,000 nmi with no payload. There is no specified speed or altitude, so the performance will be considered to select the most efficient speed and altitude for the mission. The takeoff and landing requirements remain the same as the payload dispensing mission. The mission profile is detailed in Figure 1.3.



**FIGURE 1.3: FERRY MISSION PROFILE**



The main design objective for the ECHO aircraft is to minimize the cost of dispensing the payload. This allows for the aircraft to dispense the required 3 million metric tons per year at a reasonable cost. It is important to focus on minimizing the cost to allow the ECHO fleet to fly as long as necessary to begin to reverse the catastrophic effects of global warming.

## 2 **Historical Review, Competition in the Market**

This section reviews similar aircraft to the ECHO aircraft and analyzes a possible market.

### 2.1 **Historical Review**



**FIGURE 2.1.1: CLOUD SEEDING AIRCRAFT**

Throughout history, there have been many attempts to mitigate the effects of climate change. One example includes aerial cloud seeding, as shown in Figure 2.1.1 [5]. The effects of climate change often bring severe weather events including droughts. To decrease the severity of the droughts, cloud seeding is performed to influence weather patterns that promote rain [6].

The first example of cloud seeding was performed in the late 1940s by Vincent Schaefer. After Schaefer's initial experiments proved successful, many scientists continued to try new methods of cloud seeding. The most popular method is to inject silver iodine or potassium iodine particles into clouds to promote ice-crystal formation [6].

Many types of aircraft have been used and modified to perform cloud seeding missions. Fixed-wing aircraft, turboprop aircraft, helicopters, and UAVs are all examples of aviation used to perform cloud seeding [6].

To supplement cloud-seeding, the proposed ECHO aircraft focuses more on climate change mitigation. The sulfuric acid released in the stratosphere is intended to reflect solar radiation back into space. However, the ECHO aircraft has significantly different requirements to perform the necessary tasks compared to the low-altitude aircraft used in cloud seeding.



**2.2 Relevant Aircraft Markets and Missions**

**2.2.1 Relevant Market**

The mission of the ECHO aircraft is to reduce the negative effects of climate change by reflecting the sun’s harmful radiation back into space. Many countries are heavily invested in positive climate change policies. Shown below are the top 10 leaders in reducing carbon emissions as of 2023 [7]:

**TABLE 2.2.1: TOP 10 COUNTRIES LEADING IN DECARBONIZATION, RANKED**

<b>1</b>	Sweden	<b>6</b>	Finland
<b>2</b>	Norway	<b>7</b>	United Kingdom
<b>3</b>	Denmark	<b>8</b>	New Zealand
<b>4</b>	Switzerland	<b>9</b>	France
<b>5</b>	Austria	<b>10</b>	Iceland

The ECHO aircraft does pose a problem: due to the nature of sulfuric acid, an accident could have catastrophic effects and possibly loss of life. To reduce the severity of this problem, the ECHO aircraft would be best suited to perform the payload dispensing mission above water instead of above land. Many of the countries listed above border the ocean and have smaller islands, meaning the ECHO could perform payload dispensing missions from a remote island and ferry to mainland as needed.

**2.2.2 Relevant Mission**

To meet the specifications of the RFP for the ECHO aircraft, three major types of aircraft will be discussed.

**2.2.3 Subsonic, High-Altitude Aircraft**

The RFP specifies that the ECHO aircraft must be capable of flying at 65,000ft, and must have a Mach  $\geq$  0.5. Therefore, examples of subsonic, high-altitude aircraft will be discussed.

The first aircraft of this type was the WB-57F Canberra. This aircraft has a ceiling above 60,000ft and can carry up to 6,000lb of payload. The WB-57F was used to test for nuclear debris in the upper atmosphere. The WB-57F began service in 1951 but ended its military service in 1974. The WB-57F remains in service by NASA, however, to this day [8].



**FIGURE 2.2.1: WB-57F**





**FIGURE 2.2.2: U-2S**

Another widely used high altitude aircraft is the Lockheed U-2S Dragon Lady. The U-2S has a ceiling above 70,000ft and a maximum payload of 5,000lb. The U-2S has a range greater than 6,000mi, and it can support multiple different missions with state-of-the-art sensors and instrumentation to collect and analyze data taken at high altitudes. The U-2S is equipped with a single turbofan engine. The first variant of the U-2 flew in 1955 and the aircraft continues to fly to this day [9].

An example of an unmanned high-altitude aircraft is the Teledyne Ryan AQM-91 Firefly/Compass Arrow. The AQM-91 had a ceiling of 78,000ft and a max speed of Mach 0.8, with a range of 2000nmi. The aircraft was powered by a single turbojet engine and did not have a designated payload. The AQM-91 began service in 1968, only to be retired in 1973 due to the political relationship between the United States and China [10].



**FIGURE 2.2.3: AQM-91**



**FIGURE 2.2.4: RQ-4**

Another unmanned aircraft capable of high-altitude flight is the RQ-4 Global Hawk. The RQ-4 can fly up to 60,000ft with a payload of 3,000lb and a maximum fuel capacity of 17,300lb. The RQ-4 can support a range of 12,300nmi with a single turbofan engine. The Global Hawk has been in service since 2001 and continues to fly to this day [11].

Another manned, high-altitude aircraft is the M-55 Geophysica. The M-55 has a similar mission to the Lockheed U-2S but was fitted with two turbojet engines instead of one. The M-55 had a make ceiling of 70,500ft with a crew of one.



**FIGURE 2.2.5: M-55**

The aircraft also had a range of 3,000 miles and could carry 24,200lb of payload (including fuel). The first flight of the M-55 was in 1988, and it remains in service with the Russian Air force [12].



**FIGURE 2.2.6: MQ-20**

The final aircraft is the unmanned MQ-20 Predator C Avenger. The MQ-20 can carry a total of 6,500lb of payload with a ceiling above 50,000ft. The aircraft also has the capacity for multiple types of payloads.



The MQ-20 has a single turbofan engine, and it can travel for up to 20 hr. The MQ-20 first flew in 2016 and has remained in service [13] [14].

#### 2.2.4 Bomber/Cargo Transport Aircraft

Since the RFP specifies a payload of 30,000lb of sulfuric acid, bomber and cargo aircraft will be studied to understand how the payload can affect the performance of the aircraft.

The first example of a bomber aircraft is the B-47 Stratojet. The B-47 had a service ceiling of 40,500ft and a maximum payload of 20,000lb. Using six turbojet engines, the aircraft could fly around 3,500nmi. The B-47 began service in 1947 and the last variant was retired in 1977 [15] [16].



**FIGURE 2.2.7: B-47**

The next example of a bomber aircraft is the B-52H Stratofortress. The B-52H had a maximum ceiling of 50,000ft and could carry 70,000lb of payload. The aircraft used eight turbofan engines for flight. The aircraft had a maximum range around 7,700nmi. The B-52H went into service in 1952 and remains in service to this day [17].



**FIGURE 2.2.8: B-52H**



**FIGURE 2.2.9: A400M**

An example of a heavy cargo aircraft is the Airbus A400M Atlas aircraft. The A400M has a maximum range of 4,800nmi and can carry up to 74,000lb of payload. The A400M operates at a maximum ceiling of 37,000ft, but for special operations the ceiling can increase to 40,000ft. The A400M has 4 turbofan engines and can cruise up to Mach 0.72 [18] [19].

The final example of a cargo aircraft is the C-17 Globemaster III. The C-17 can carry up to 170,000lb of payload at a ceiling of 45,000ft. The C-17 had four turbofan engines and it can reach a maximum speed of Mach 0.74. The C-17 was deployed in 1993 and it remains in service to this day [20].



**FIGURE 2.2.10: C-17**



### 2.2.5 Flying Wing Aircraft

Due to the nature of the RFP, flying wing aircraft pose a unique solution with the lack of fuselage and high lift to drag ratios. Therefore, examples of flying wing aircraft will be discussed.



The first flying wing aircraft is the Northrop N-9M. This aircraft was a one-third scale prototype that eventually led to the development of the YB-35. The N-9M featured 2 turbofan engines and had a maximum ceiling of 21,500ft. The aircraft was not designed to carry a payload and had a range of 500mi. The N-9M was in service from 1942 until it was quickly retired in 1949 after the YB-35 program was cancelled [21] [22].

**FIGURE 2.2.11: N-9M**

The second flying wing aircraft is the Northrop XB-35/YB-35. The XB-35 had a similar configuration to the N-9M, with an additional two turboprop engines. The XB-35 had a service ceiling of 40,000ft with a range of 8,000mi. The XB-35 was designed as a bomber and could store up to 120,000lb (including fuel). The XB-35 began service in 1946 but was quickly retired in 1949 once the program was cancelled [23] .



**FIGURE 2.2.12: XB-35**



**FIGURE 2.2.13: YB-49**

Another example of a flying wing is the Northrop YB-49. This aircraft was developed from a modified YB-35 and equipped with eight turbojet engines. The ceiling of the aircraft reached 42,000ft and was designed to carry 16,000lb worth of payload. The YB-49 was also able to travel 4,000mi with 10,000lb of payload. The aircraft, however, suffered issues with stability and was eventually retired in 1950 after only being serviced in 1947 [24].

The final example of a flying wing aircraft is the B-2 Spirit. The B-2 Spirit is a high-altitude stealth bomber capable of carrying up to 40,000lb



**FIGURE 2.2.14: B-2**



of payload. The B-2 has a ceiling of 50,000ft and runs with four embedded turbofan engines. The B-2 entered service in 1997 and is still in service today [25].

### 3 Design Philosophy & Configuration Constraint Establishment

The design philosophy for the ECHO aircraft is to prioritize the safety of the ground and flight crew. To ensure safe operations of the ECHO aircraft, a few configuration constraints must be applied. The configuration constraints are shown below in Figure 3.1 [2]. To decrease the risk of exposing the sulfuric acid to the fuel, the fuel and sulfuric acid will have separate tanks and separate loading points.

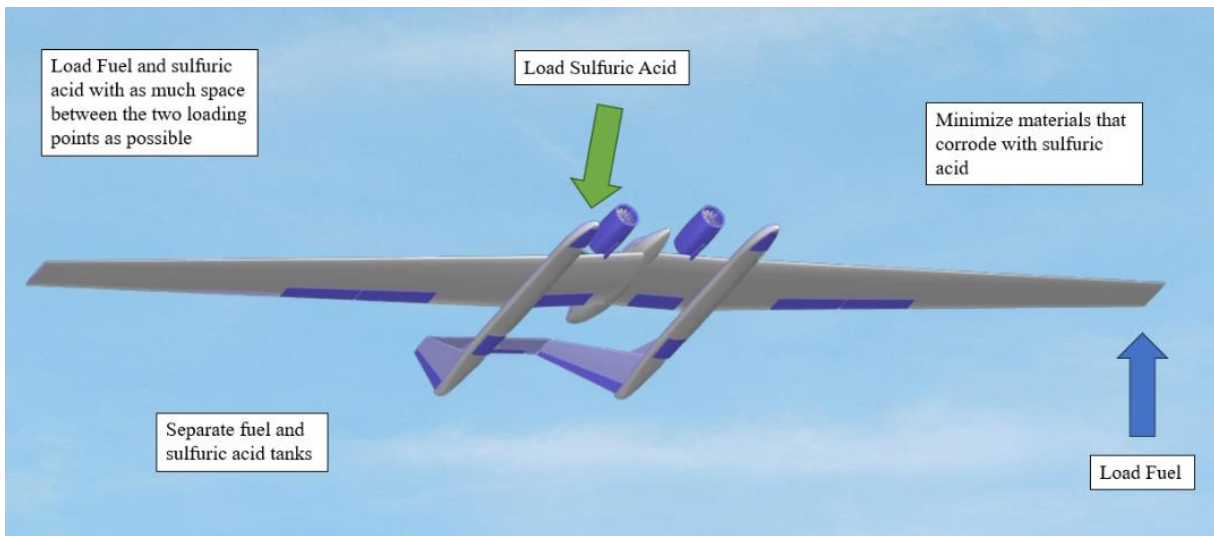


FIGURE 3.1: CONFIGURATION CONSTRAINTS FOR THE ECHO AIRCRAFT

### 4 Objectives, Requirements, and Design Optimization Function

To develop an appropriate optimization function, the requirements, ancillary requirements, objectives, and ancillary objectives are compiled in Table 4.1 through Table 4.3.

Table 4.1 details the requirements outlined by the RFP. Each requirement can either score a one or a zero, depending on whether the requirement is met [1].

TABLE 4.1: REQUIREMENTS FOR DESIGN OPTIMIZATION

Req. #	Requirement	Function
$R_1$	Take-off and landing from concrete runways	$R_1 = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$
$R_2$	Cruise Mach $\geq 0.5$	$R_2 = \begin{cases} 1 & \text{if Mach} \geq 0.5 \\ 0 & \text{if Mach} < 0.5 \end{cases}$
$R_3$	VFR and IFR capable	$R_3 = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$



$R_4$	Flight in known icing conditions	$R_4 = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$
$R_5$	Engine/propulsion system EIS date of 2030	$R_5 = \begin{cases} 1 & \text{if EIS of 2030} \\ 0 & \text{if No EIS of 2030} \end{cases}$
$R_6$	Flight crew of 4	$R_6 = \begin{cases} 1 & \text{if Crew} = 4 \\ 0 & \text{if Crew} \neq 4 \end{cases}$
$R_7$	Capable of handling 30,000lb of sulfuric acid payload	$R_7 = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$
$R_8$	Capable of dispensing payload over 400nmi	$R_8 = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$
$R_9$	Time to climb $\leq$ 1hr	$R_9 = \begin{cases} 1 & \text{if Climb} \leq 1\text{hr} \\ 0 & \text{if Climb} > 1\text{hr} \end{cases}$
$R_{10}$	Cruise altitude of 65,000ft for payload mission	$R_{10} = \begin{cases} 1 & \text{if Cruise} = 65,000\text{ft} \\ 0 & \text{if Cruise} \neq 65,000\text{ft} \end{cases}$
$R_{11}$	Capable of using landing field length of 8,000ft with 50ft obstacle	$R_{11} = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$
$R_{12}$	Capable of 3,000nmi range with no payload	$R_{12} = \begin{cases} 1 & \text{if Capable} \\ 0 & \text{if Not Capable} \end{cases}$
$R_{13}$	FAA 14 CFR Part 25 Certifiable	$R_{13} = \begin{cases} 1 & \text{if FAR 25 Certifiable} \\ 0 & \text{if Not FAR 25 Certifiable} \end{cases}$

Table 4.2 details the objectives developed for the design optimization of the ECHO aircraft. These objectives are not considered requirements, but the ECHO aircraft will be designed with these objectives in mind. Each objective is weighted based on how important it is for the objective to be met [1].

**TABLE 4.2: OBJECTIVES FOR DESIGN OPTIMIZATION**

Obj. #	Objective	Obj. Weight	Function
$O_1$	Time to climb $\leq$ 45 min	$OW_1=2$	$O_1 = \begin{cases} \frac{60 - RC}{15} & \text{if } 45\text{min} < RC \leq 60\text{min} \\ 1 & \text{if } \leq 45\text{min} \end{cases}$
$O_2$	Ferry range $\geq$ 3,500nmi	$OW_2=1$	$O_2 = \begin{cases} \frac{R_{ferry} - 3000}{500} & \text{if } 3000\text{nmi} \leq R_{ferry} \leq 3500\text{nmi} \\ 0 & \text{if } Mach < 0.5 \end{cases}$



Table 4.3 details the ancillary objectives developed for the design optimization of the ECHO aircraft. The ancillary objectives are set to focus on objectives that either minimize or maximize specific traits the aircraft has. The ancillary objectives are weighted, based on the importance the aircraft follows the objectives.

**TABLE 4.3: ANCILLARY OBJECTIVES FOR DESIGN OPTIMIZATION**

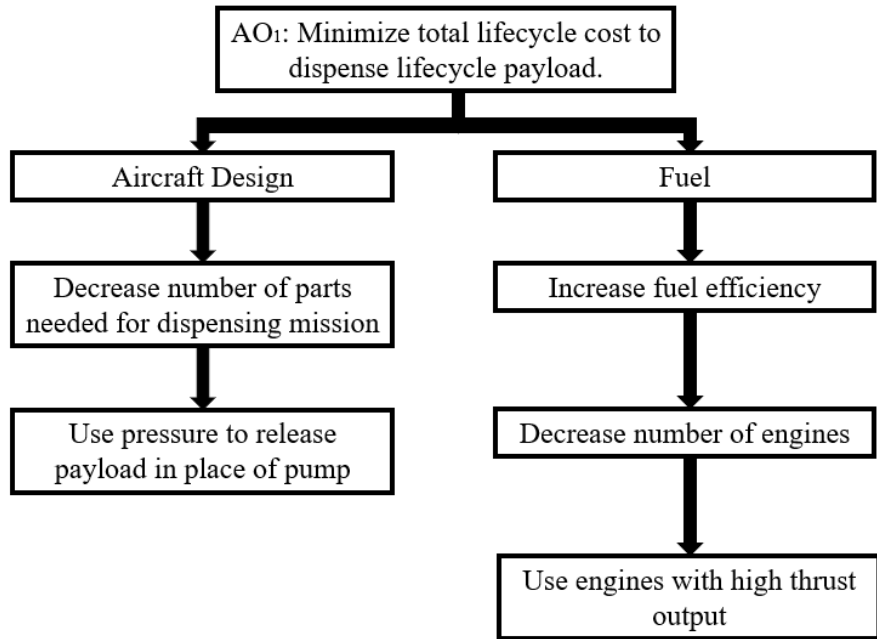
A.O. #	Ancillary Objective	A.O. Weight	Function
$AO_1$	Minimize total lifecycle cost to dispense lifecycle payload.	$AOW_1 = 3$	$AO_1 = \begin{cases} 1 & \text{if minimized} \\ 0 & \text{if not} \end{cases}$
$AO_2$	Minimize required ground crew.	$AOW_2 = 3$	$AO_2 = \begin{cases} 1 & \text{if minimized} \\ 0 & \text{if not} \end{cases}$
$AO_3$	Maximize distance between refueling points.	$AOW_3 = 3$	$AO_3 = \begin{cases} 1 & \text{if maximized} \\ 0 & \text{if not} \end{cases}$
$AO_4$	Minimize amount of corrosion susceptible material used in aircraft.	$AOW_4 = 4$	$AO_4 = \begin{cases} 1 & \text{if minimized} \\ 0 & \text{if not} \end{cases}$

The final optimization function is compiled into Eq. 4.1 below. The aircraft must meet all requirements to receive a score, and the objectives and ancillary objectives are weighted.

$$OF = \left[ \prod_{n=1}^{13} R_n \right] \times \left[ \sum_{i=1}^2 O_m \times OW_m \right] \times \left[ \sum_{j=1}^4 AO_j \times AOW_j \right] \quad \text{EQ. 4.1}$$

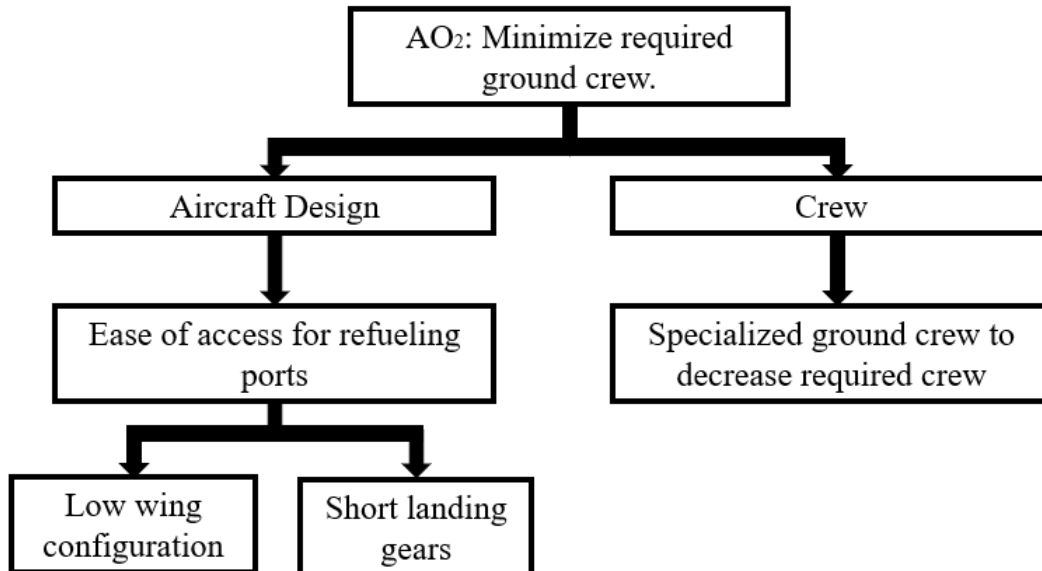
To aid in the design process, a flowdown chart was constructed for each of the ancillary objectives. The first ancillary objective is to minimize the total lifecycle cost to dispense lifecycle payload. Reducing the total cost allows for the dispensing mission to be completed more often.





**FIGURE 4.1: ANCILLARY OBJECTIVE 1**

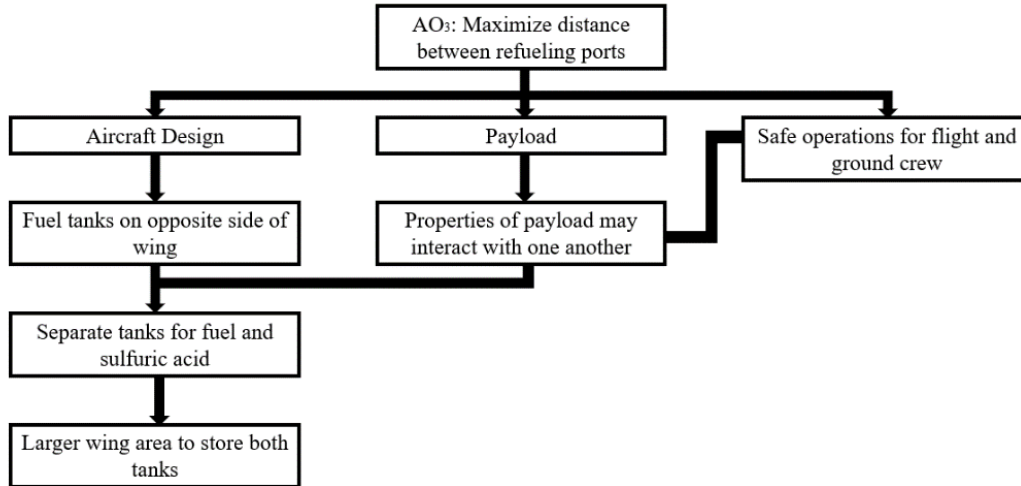
The second ancillary objective is to minimize the required ground crew. Sulfuric acid is dangerous to handle and could become catastrophic if it encountered the fuel. Reducing the number of required ground crew members is important in case of an accident.



**FIGURE 4.2: ANCILLARY OBJECTIVE 2**

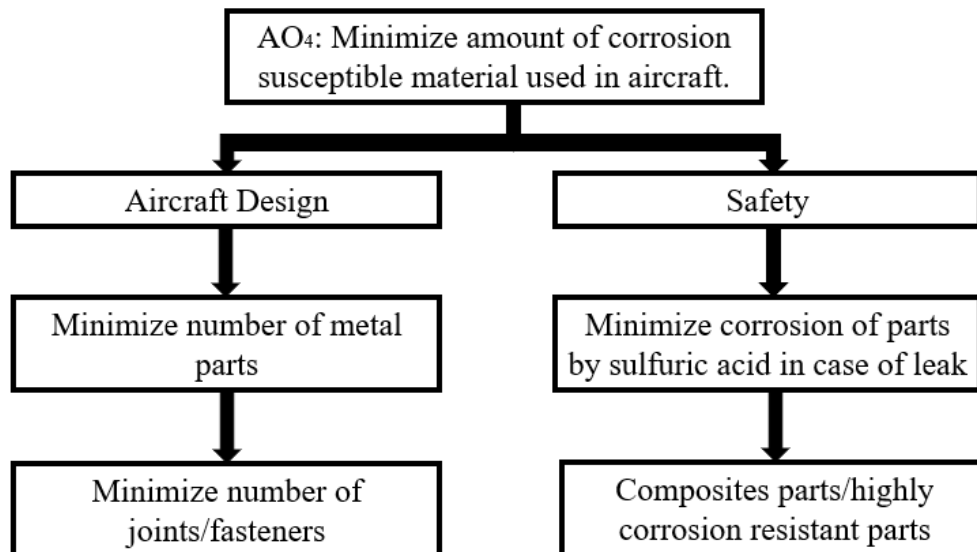


The third ancillary objective is to maximize distance between refueling points. Due to the possibility of the fuel reacting with sulfuric acid, it is incredibly important to have separate refueling points for each.



**FIGURE 4.3: ANCILLARY OBJECTIVE 3**

The final ancillary objective is to minimize the amount of corrosion susceptible material used in aircraft. Since sulfuric acid is corrosive, it could cause materials to corrode rapidly if in contact. Since sulfuric acid is being deployed, the chance of contact is high. To reduce the damage done by corrosion, materials not susceptible to corrosion will be used.



**FIGURE 4.4: ANCILLARY OBJECTIVE 4**



**5 Statistical Time and Market Predictive Engineering Design (STAMPED) Analysis**

To develop an understanding of the ECHO aircraft’s performance characteristics, a table of similar aircraft and the performance characteristics was developed to analyze the trends associated with each type of aircraft. Note in Table 5.1 a few aircraft have propellor engines, so the thrust per engine was converted from power using Eq. 5.1 below. The efficiency value was assumed to be a conservative 0.75.

$$T = \frac{P}{nV} \tag{EQ. 5.1}$$

**TABLE 5.1: AIRCRAFT PERFORMANCE CHARACTERISTICS**

Aircraft	W <sub>e</sub> (lb)	MTOW (lb)	W <sub>pl</sub> (lb)	T per Engine(lb)	V <sub>max</sub> (ft/s)
WB-57F [8]	~	72,000	9,700	15,500	692
U-2S [9]	16,000	40,000	5,000	17,000	794
AQM-91 [10]	3,800	5,500	~	5270	774
RQ-4 [11]	15,000	32,250	3,000	7,600	559
M-55 [12]	23,800	48,000	3,300	22,000	684
MQ-20 [13] [14]	10,200	18,200	6,500	4,700	675
B-47 [15] [16]	80,800	198,000	20,000	6,000	887
B-52H [17]	185,000	488,000	70,000	17,000	924
A400M [18] [19]	154,000	311,000	81,600	11,400	711
C-17 [20]	277,000	585,000	171,000	40,400	760
N-9M [21] [22]	5,900	14,000	~	534	378
XB-35 [23]	90,000	209,000	51,000	3,820	576
YB-49 [24]	88,400	194,000	16,000	4,000	723
B-2 [25]	158,000	376,000	40,000	17,000	924

The next set of performance characteristics for each aircraft are shown in Table 5.2 below. Note the aspect ratio of each aircraft was found using Eq. 5.2 below.

$$AR = \frac{b^2}{S} \tag{EQ. 5.2}$$

**TABLE 5.2: AIRCRAFT PERFORMANCE CHARACTERISTICS CONT.**

Aircraft	Wingspan, b (ft)	Wing Area, S (ft <sup>2</sup> )	Aspect ratio, AR (~)	Range, R (nmi)	Ceiling, h (ft)
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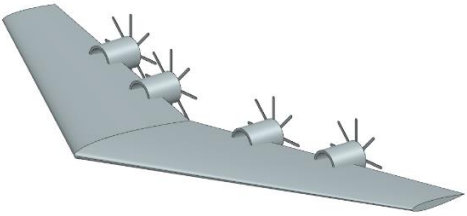


<b>WB-57F [8]</b>	122.5	2,000	7.5	2,200	60,000
<b>U-2S [9]</b>	105	1,000	11	6,100	78,500
<b>AQM-91 [10]</b>	34	128	9.0	1,750	78,700
<b>RQ-4 [11]</b>	131	690	25	12,300	60,000
<b>M-55 [12]</b>	123	1,580	9.6	2,600	70,500
<b>MQ-20 [13] [14]</b>	66	1,140	3.8	~	50,000
<b>B-47 [15] [16]</b>	116	1,430	9.4	3,500	40,500
<b>B-52H [17]</b>	185	4,000	8.5	7,650	50,000
<b>A400M [18] [19]</b>	139	2,500	7.7	4,800	40,000
<b>C-17 [20]</b>	170	3,800	7.6	2,450	45,000
<b>N-9M [21] [22]</b>	60	525	6.3	450	21,500
<b>XB-35 [23]</b>	171	4,200	7.0	7,100	40,000
<b>YB-49 [24]</b>	172	4,200	7.0	3,500	42,000
<b>B-2 [25]</b>	172	5140	5.8	6,000	50,000

**6 Candidate Configuration Matrix Establishment**

To select the appropriate configuration for the ECHO aircraft, multiple configurations were developed and analyzed. The first configuration is a flying wing with four pusher turboprop engines, as shown in Figure 6.1 and detailed in Table 6.1.

**TABLE 6.1: CONFIGURATION 1**

<b>FLYING WING, FOUR ENGINES</b>		
<b>Pros</b>	<b>Cons</b>	
+ All surfaces are lifting surfaces	- No camber/lower $C_{L,max}$	<b>FIGURE 6.1: FLYING WING, FOUR ENGINES CONFIGURATION</b>
+ Lightweight configuration	- 4 engines increase weight/fuel weight	
+ 4 engines provide higher thrust		

The second configuration is a flying wing with two pusher turboprop engines, as shown in Figure 6.2 and detailed in Table 6.2.

**TABLE 6.2: CONFIGURATION 2**



FLYING WING, TWO ENGINES	
Pros	Cons
+ All surfaces are lifting surfaces	- No camber/lower $C_{L,max}$
+ Lightweight configuration	- No directional stability
+ 2 engines provide lower fuel weight	

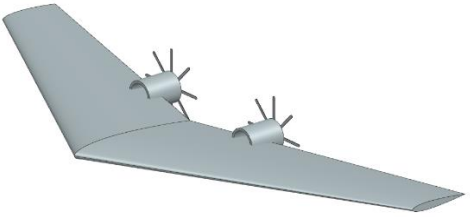


FIGURE 6.2: FLYING WING, TWO ENGINES CONFIGURATION

The third configuration is a zagi configuration with four pusher turboprop engines, as shown in Figure 6.3 and detailed in Table 6.3.

**TABLE 6.3: CONFIGURATION 3**

ZAGI, FOUR ENGINES	
Pros	Cons
+ All surfaces are lifting surfaces	- 4 engines increase weight/fuel weight
+ Lightweight configuration	- No camber/lower $C_{L,max}$
+ 4 engines provide higher thrust	- 4 engines increase weight/fuel weight

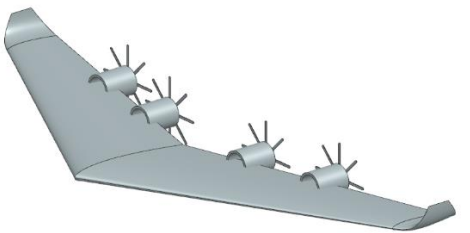


FIGURE 6.3: ZAGI, FOUR ENGINES CONFIGURATION

The fourth configuration is a zagi configuration with two pusher turboprop engines, as shown in Figure 6.4 and detailed in Table 6.4.

**TABLE 6.4: CONFIGURATION 4**

ZAGI, TWO ENGINES	
Pros	Cons
+ All surfaces are lifting surfaces	- No camber/lower $C_{L,max}$
+ Lightweight configuration	- Lower thrust output
+ 2 engines provide lower fuel weight	

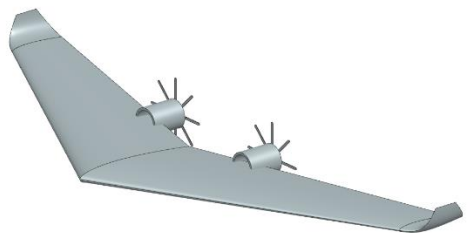


FIGURE 6.4: ZAGI, TWO ENGINES CONFIGURATION

The fifth configuration is a twin fuselage configuration with four turbofan engines, as shown in Figure 6.5 and detailed in Table 6.5.



**TABLE 6.5: CONFIGURATION 5**

TWIN FUSELAGE, FOUR ENGINES	
Pros	Cons
+ Separate fuselage for fuel/sulfuric acid	- Increased weight
+ Crew separate from sulfuric acid	- Lateral instability after payload dispensed
	- Need wider runways and more landing gears

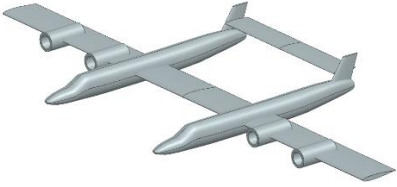


FIGURE 6.5: TWIN FUSELAGE, FOUR ENGINES CONFIGURATION

The sixth configuration is a tailboom configuration with two turbofan engines, as shown in Figure 6.6 and detailed in Table 6.6.

**TABLE 6.6: CONFIGURATION 6**

TAILBOOM, TWO ENGINES	
Pros	Cons
+ Lower weight due to shorter fuselage	- Aft CG
+ Increased distance for loading fuel/sulfuric acid	- Foreign object damage if engine is compromised

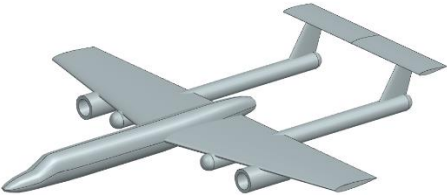


FIGURE 6.6: TAILBOOM, TWO ENGINES CONFIGURATION

The seventh configuration is a conventional configuration with two turbofan engines, as shown in Figure 6.7 and detailed in Table 6.7.

**TABLE 6.7: CONFIGURATION 7**

CONVENTIONAL, TWO ENGINES	
Pros	Cons
+ Stable	- No redundant engine
+ Separation of fuel and payload	- Payload dispensing from wings would corrode empennage
+ Fuselage allows for storage of fuel or payload	

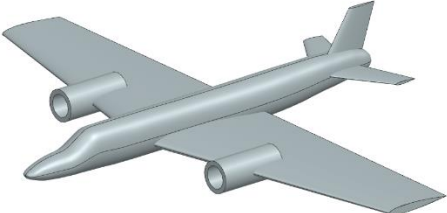


FIGURE 6.7: CONVENTIONAL, TWO ENGINES CONFIGURATION

The eight configuration is a conventional configuration with two vertical tails and two turbofan engines, as shown in Figure 6.8 and detailed in Table 6.8.



**TABLE 6.8: CONFIGURATION 8**

TWO VERTICAL TAILS, TWO ENGINES	
Pros	Cons
+ Stable	- No redundant engine
+ Separation of fuel and payload	- Increased weight from additional vertical tail
+ Fuselage allows for storage of fuel or payload	- Payload dispensing from wings would corrode empennage

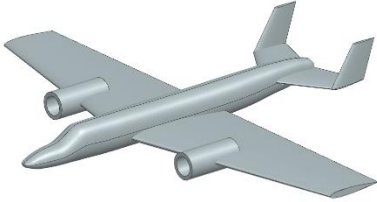


FIGURE 6.8: TWO VERTICAL TAILS, TWO ENGINES CONFIGURATION

The ninth configuration is a conventional configuration with a T-tail and two turbofan engines, as shown in Figure 6.9 and detailed in Table 6.9.

**TABLE 6.9: CONFIGURATION 9**

T-TAIL, TWO ENGINES	
Pros	Cons
+ Stable	- No redundant engine
+ Separation of fuel and payload	- T-tail more prone to stalling
+ Fuselage allows for storage of fuel or payload	- Payload dispensing from wings would corrode empennage

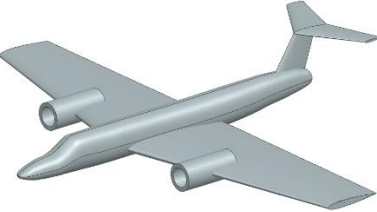


FIGURE 6.9: T-TAIL, TWO ENGINES CONFIGURATION

The tenth configuration is a conventional configuration with a V-tail and two turbofan engines, as shown in Figure 6.10 and detailed in Table 6.10.

**TABLE 6.10: CONFIGURATION 10**

V-TAIL, TWO ENGINES	
Pros	Cons
+ Stable	- No redundant engine
+ Separation of fuel and payload	- reduced directional and lateral stability
+ Fuselage allows for storage of fuel or payload	- Payload dispensing from wings would corrode empennage

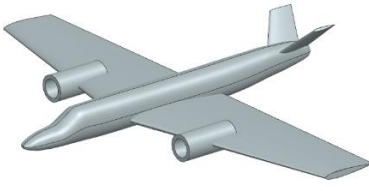


FIGURE 6.10: V-TAIL, TWO ENGINES CONFIGURATION

The eleventh configuration is a conventional configuration with a V-tail and one turbofan engine, as shown in Figure 6.11 and detailed in Table 6.11.



**TABLE 6.11: CONFIGURATION 11**

V-TAIL, ONE ENGINE	
Pros	Cons
+ Separation of fuel and payload	- Aft CG
+ Fuselage allows for storage of fuel or payload	- Engine failure catastrophic
	- Payload dispensing from wings would corrode empennage

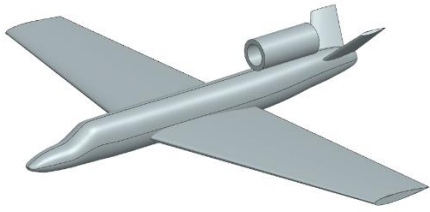


FIGURE 6.11: V-TAIL, ONE ENGINE

The final configuration is a conventional configuration with two vertical tails and one turbofan engine, as shown in Figure 6.12 and detailed in Table 6.12.

**TABLE 6.12: CONFIGURATION 12**

TWO VERTICAL TAILS, ONE ENGINE	
Pros	Cons
+ Separation of fuel and payload	- Aft CG
+ Fuselage allows for storage of fuel or payload	- Engine failure catastrophic
	- Payload dispensing from wings would corrode empennage

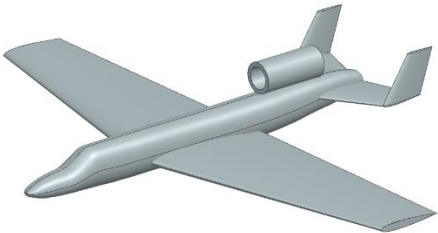


FIGURE 6.12: TWO VERTICAL TAILS, ONE ENGINE

**7 Application of Optimization Function and Requirements Flowdown Charts to Configurations and Downselection**

To downselect to the best configuration for the ECHO aircraft, Eq. 4.1 is used for each configuration. An assumption that each aircraft can fulfil all requirements is made, since the ECHO aircraft will be designed with these requirements. For the objectives and ancillary objectives, each configuration is given a score from 1-10 with ten being the best score. The configuration with the highest total score will be selected. Table 7.1 details the process below.

**TABLE 7.1: APPLICATION OF OPTIMIZATION FUNCTION**

Objective	Config 1 Score	Config 2 Score	Config 3 Score	Config 4 Score	Config 5 Score	Config 6 Score
$O_1$	7	7	7	7	8	8
$O_2$	7	7	7	7	8	8
<b>Sum:</b>	7	14	14	14	16	16
<b>Weighted Sum:</b>	21	21	21	21	24	24
$AO_1$	7	7	7	7	5	7



$AO_2$	8	8	8	8	5	7
$AO_3$	8	8	8	8	10	8
$AO_4$	8.5	9	8.5	9	5	7
<b>Sum:</b>	7.875	8	7.875	8	6.25	7.25
<b>Weighted Sum:</b>	25.75	26.25	25.75	26.25	20	23.5
<b>Total Score:</b>	46.75	47.25	46.75	47.25	44	47.5
<b>Objective</b>	<b>Config 7 Score</b>	<b>Config 8 Score</b>	<b>Config 9 Score</b>	<b>Config 10 Score</b>	<b>Config 11 Score</b>	<b>Config 12 Score</b>
$O_1$	8	8	8	8	6	6
$O_2$	8	8	8	8	7	7
<b>Sum:</b>	16	16	16	16	13	13
<b>Weighted Sum:</b>	24	24	24	24	19	19
$AO_1$	7	7	7	7	8	8
$AO_2$	7	7	7	7	5	5
$AO_3$	8	8	8	8	8	8
$AO_4$	6	6	6	6.5	6	6
<b>Sum:</b>	7	7	7	7.125	6.75	6.75
<b>Weighted Sum:</b>	22.5	22.5	22.5	23	21.75	21.75
<b>Total Score:</b>	46.5	46.5	46.5	47	40.75	40.75

The selected configuration is configuration 6, or the tailboom configuration with two turbofan engines.

## 8 Weight Sizing

To determine the preliminary weight of the aircraft, the STAMPED weight estimation can be used. The weight will be estimated assuming the payload dispense mission, except that the sulfuric acid payload remains the same the entire trip. This conservative assumption is made in case the mission cannot be performed so that the aircraft has enough fuel to complete the mission without dispensing the payload. The weight fractions for each portion of flight are shown in Table 8.1.

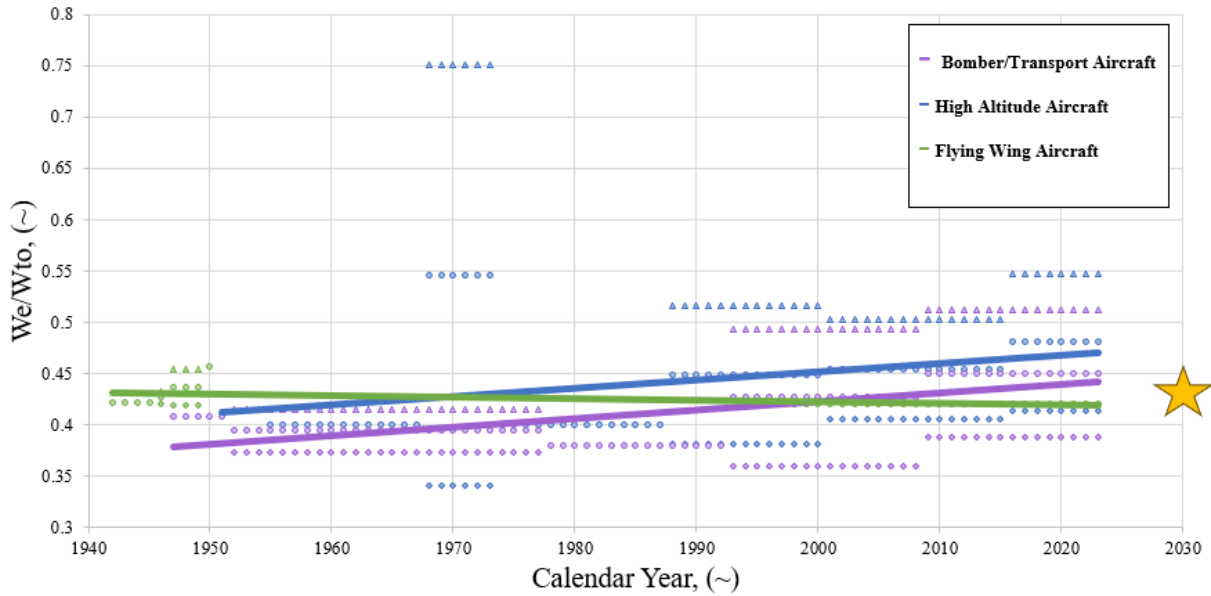
**TABLE 8.1: MISSION WEIGHT FRACTIONS**

<b>Mission Weight Fraction (~)</b>	<b>Value (~)</b>	<b>Section of Flight</b>
$W_1/W_{T0}$	0.99	Engine Start, Warmup
$W_2/W_1$	0.99	Taxi
$W_3/W_2$	0.995	Takeoff



$W_4/W_3$	0.98	Climb
$W_5/W_4$	0.988	Cruise for 400 nmi
$W_6/W_5$	0.990	Loiter 45 min
$W_7/W_6$	0.997	Divert to Alternate
$W_8/W_7$	0.99	Descend
$W_9/W_8$	0.992	Landing, Taxi

To determine the desired empty weight to take-off weight ratio, the STAMPED method is utilized. The aircraft studied in Chapter 2 are compared to determine an appropriate ratio. As shown in Figure 8.1, the selected  $W_e/W_{TO}$  is 0.43.



**FIGURE 8.1: WE/WTO STAMPED ANALYSIS**

With the  $W_e/W_{TO}$  ratio selected, the empty weight, takeoff weight, and fuel weights are calculated. The lift to drag ratio,  $L/D$ , is assumed to be 25. The final values for the weights are shown in Table 8.2.

**TABLE 8.2: FINAL WEIGHT VALUES**

Aircraft Weight	Weight, W (lb)
Empty Weight, $W_e$	27,950
Takeoff Weight, $W_{TO}$	65,000
Fuel Weight, $W_{fuel}$	5,997



9 **V-n Diagram**

A V-n diagram is used to determine the necessary velocity needed under certain load conditions. For a FAR 25 aircraft, the minimum required load an aircraft must be able to endure is +2.5 to -1.0 g's. As well as this, the aircraft must maintain an airspeed that does not cause the aircraft to stall. The segment of flight analyzed for the V-n diagram is climb. The aircraft is most likely to encounter high gusts during cruise and must be able to maneuver and respond appropriately to gusts. Figure 9.1 details the response to a gust of 20 m/s, or 38.9 KEAS. A 20m/s gust has a  $10^{-5}$  chance of occurring between 3,000 ft and 25,000ft, and a  $10^{-6}$  chance of occurring between sea level and 50,000 ft [26]. This magnitude of gust is classified as “severe” [27]. At a gust of 20 m/s, the maximum amount of g's that could occur close to 4 g's and -2 g's. To withstand the severe magnitude of gusts, the aircraft will be designed with a design g force of 4 g's and -2 g's.

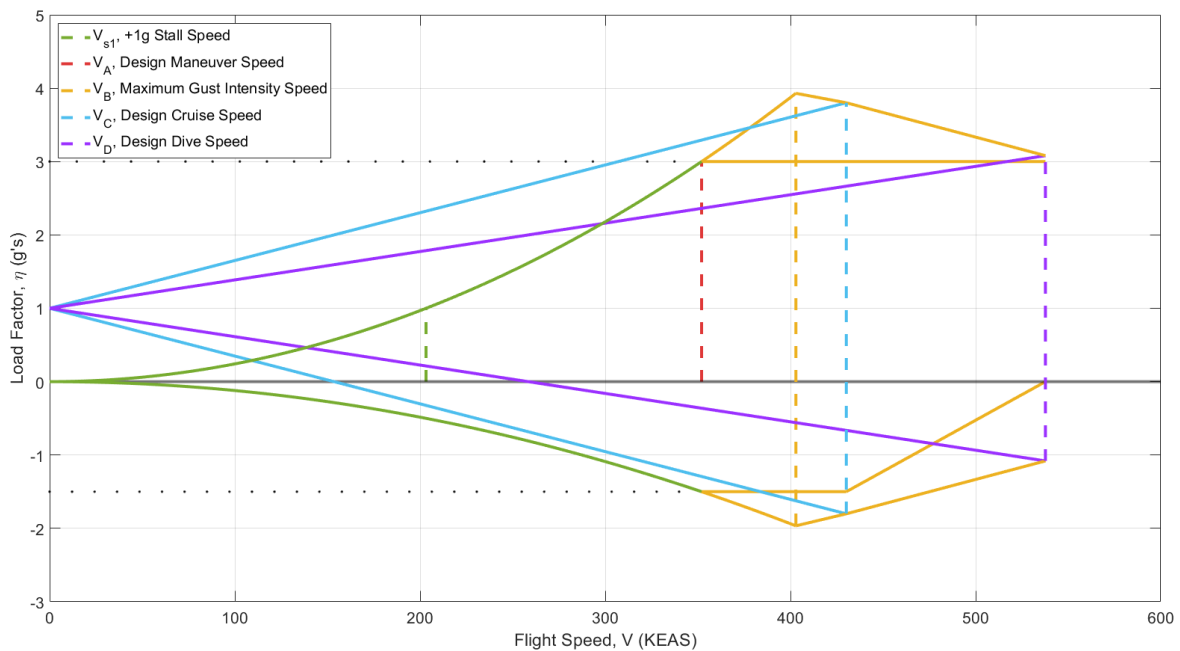


FIGURE 9.1 V-N DIAGRAM

10 **Wing and Powerplant Sizing**

To size the aircraft wing and powerplant, the desired thrust-to-weight ratio and wing loading must be selected. To determine both values, a few factors must be considered. The first factor is the climbing rate. Near and at an altitude of 65,000 ft, more thrust is required to maintain a steady climb rate. A climb rate of 100 ft/min is



selected at 65,000 ft. This allows for a lower thrust to weight ratio, which decreases the number of engines needed. The aircraft will have a higher rate of climb at sea level and in the troposphere to allow the aircraft to climb to altitude in less than one hour.

It is important to calculate the maximum wing loading that can be obtained at cruise altitude. To do so, a cruise velocity and cruise  $C_L$  is estimated. The cruise velocity is selected at 726.075 ft/s (or Mach 0.75) and a  $C_L$  at cruise of 0.6. The  $C_L$  of 0.6 is chosen due to the selected airfoils being designed for a  $C_L$  of 0.6. The maximum wing loading that can occur at altitude is 28 lb/ft<sup>2</sup>.

The next limiting flight conditions are related to takeoff and landing. Values of  $C_{L,max,L}$  were selected at 2.0, 2.2, and 2.4, and  $C_{L,max,TO}$  values of 1.8, 2.0, and 2.2. The selected thrust to weight ratio can achieve much lower values of takeoff and landing  $C_{L,max}$ .

There are some FAR 25 requirements associated with takeoff and landing with one engine inoperative (OEI) and all engines operative (AEO) that must be considered. Table 10.1 details the relevant sections of FAR 25.

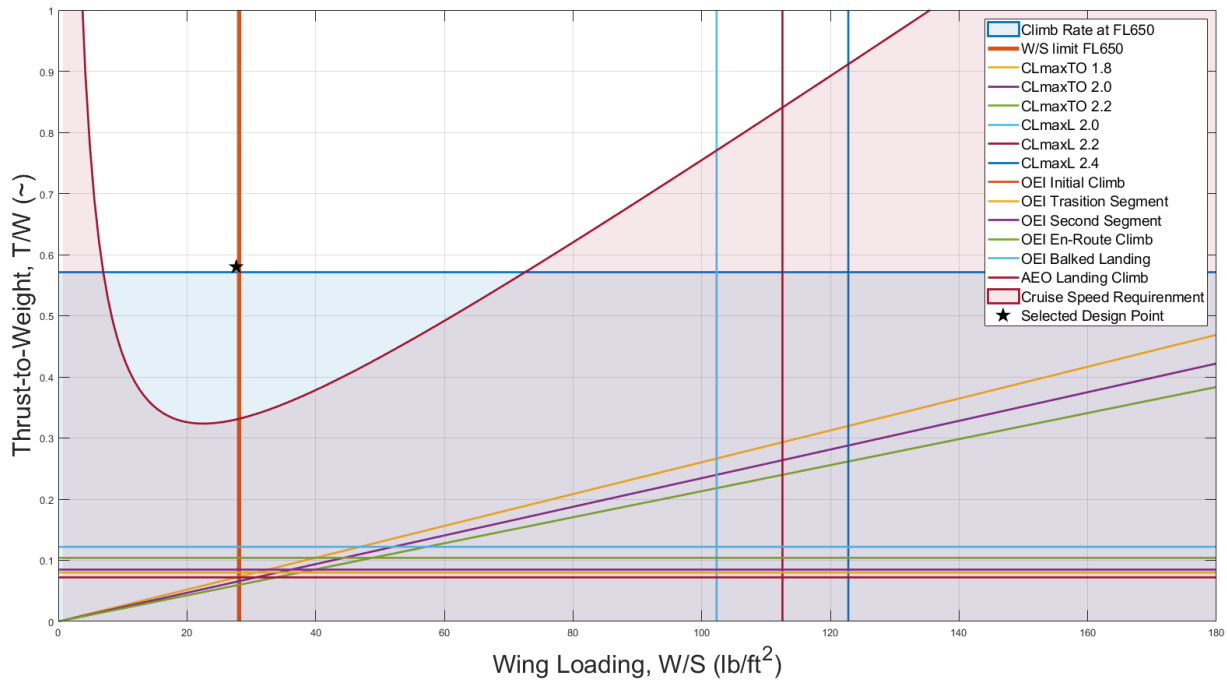
**TABLE 10.1: FAR 25 CLIMB REQUIREMENTS**  
**FAR 25 Climb Requirements**

FAR 25 Climb Requirements	
<b>FAR 25.111 OEI</b>	Initial Climb Segment
<b>FAR 25.121 OEI</b>	Transition Segment Climb
<b>FAR 25.121 OEI</b>	Second Segment Climb
<b>FAR 25.121 OEI</b>	En-route Climb
<b>FAR 25.119 AEO</b>	Landing Climb
<b>FAR 25.121 OEI</b>	Balked Landing Climb

The aircraft can meet each of the FAR 25 requirements, as shown in Figure 10.1.

The final requirements needed to select an appropriate thrust to weight ratio is the cruise speed requirements. The cruise speed requirement determines the curve that relates to the altitude, temperature, density, and other conditions as well as speed and aspect ratio. The cruise speed requirement is a function of wing loading and is shown in Figure 10.1.





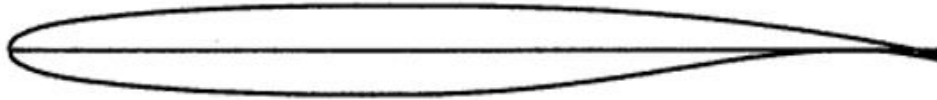
**FIGURE 10.1: THRUST TO WEIGHT RATIO VS WING LOADING**

As shown in Figure 10.1, the selected thrust to weight ratio and wing loading meets all the requirements listed above. The selected thrust to weight ratio is 0.58 and the selected wing loading is 27.7 lb/ft<sup>2</sup>. With the selected wing loading, the wing area,  $S$ , is chosen to be 2350 ft<sup>2</sup> and an aspect ratio,  $AR$ , of 20. Due to the low air density, low-bypass engines were selected. The F118-100 engines were selected for the ECHO. The F118-100 engines are also used for the U-2 and the B-2 [9] [25] to provide high-thrust in high-altitude conditions.

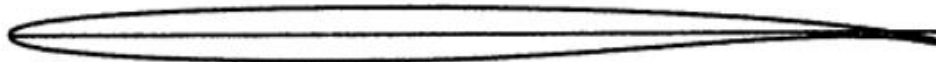
With a wing loading of 27.7 lb/ft<sup>2</sup> and a wing area of 2,350 ft<sup>2</sup>, other features of the wing can be decided. Since the aircraft will be experiencing transonic speeds of Mach 0.75, a supercritical airfoil has been selected, as shown in Figure 10.2. This will increase the critical Mach number and decrease the chances of local shockwaves occurring at any point on the wing. The sweep angle of the wing was selected at 5 degrees, and the wing has an inner dihedral of 0 degrees and an outer dihedral 2.5 degrees. The inner portion of the wing occurs between the tailbooms, and the outer portion of the wing occurs aft of the tailbooms. Other geometric features of the wing include an incidence angle of 1 degree, a taper ratio of 0.46, and a wingspan of 216.8 ft.



**Table XII. Coordinates of 10-Percent-Thick Supercritical Airfoil SC(2)-0610  
Designed for 0.6 Lift Coefficient**



**Table VII. Coordinates of 6-Percent-Thick Supercritical Airfoil SC(2)-0606  
Designed for 0.6 Lift Coefficient**



**FIGURE 10.2: SUPERCRITICAL AIRFOILS**

The selected engine for the aircraft is the F118-100 engine. This engine is a low-bypass, non-afterburning turbofan engine with a maximum thrust of 19,000 lb [28]. This engine increases the ceiling of aircraft as well as providing sufficient thrust.



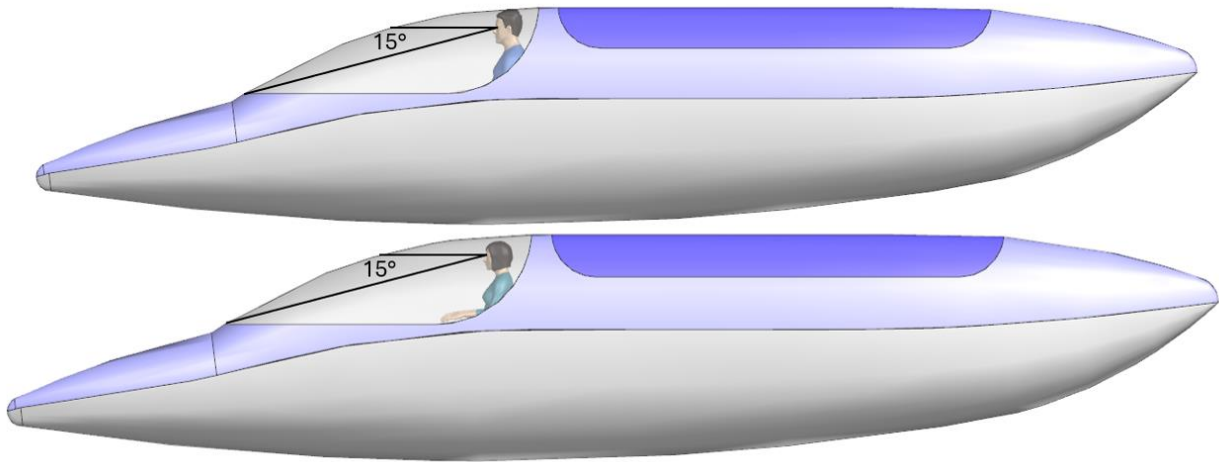
**FIGURE 10.3: F118 ENGINE**

**11 Fuselage/Cockpit/Tailboom Sizing**

The fuselage is designed to house the four required crew members for the mission. To decrease the wetted area, the crew is seated in tandem. The aircraft will be manned by a pilot and three mission specific crew members that will oversee the operations of the aircraft and the sulfuric acid deployment. The fuselage design considers the 95% percentile male and a 20% percentile female, as shown in Figure 11.1. For each pilot, the pilot



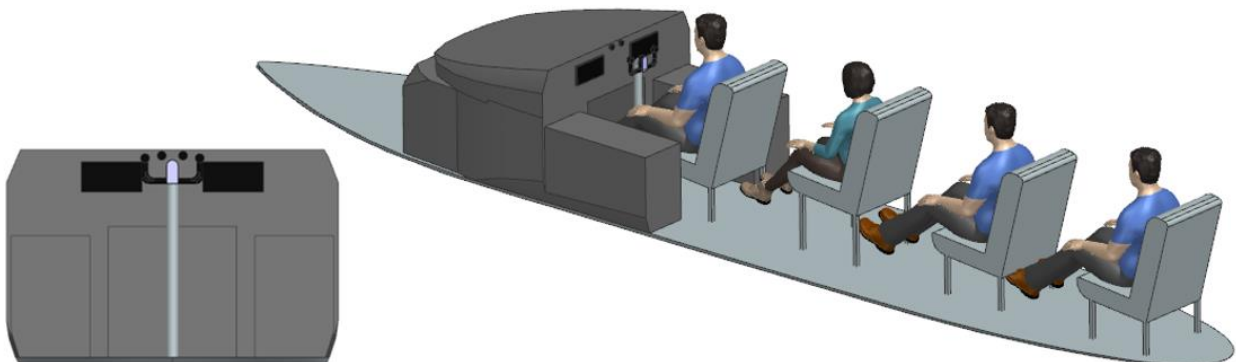
seat can be adjusted to the required height needed for the pilot to have a 15-degree field of vision. As well as this, the pedals and wheel can be adjusted for comfort and accessibility. The nose of the fuselage also allows for better visibility.



**FIGURE 11.1 95% PERCENTILE MALE AND 20% PERCENTILE FEMALE**

The length of the fuselage spans 30 ft, and has a maximum width of 4.75 ft and a maximum height of 5.58 ft. The fuselage also extends downward to account for the space needed for the wing connection and to allow for a continuous front and aft spar.

The cockpit is continuous throughout the fuselage, since there are only 4 crew members on board. For the control panel, the newest technology will be used to assure the pilot can successfully fly and maneuver the aircraft. A simplified control panel is shown in Figure 11.2.



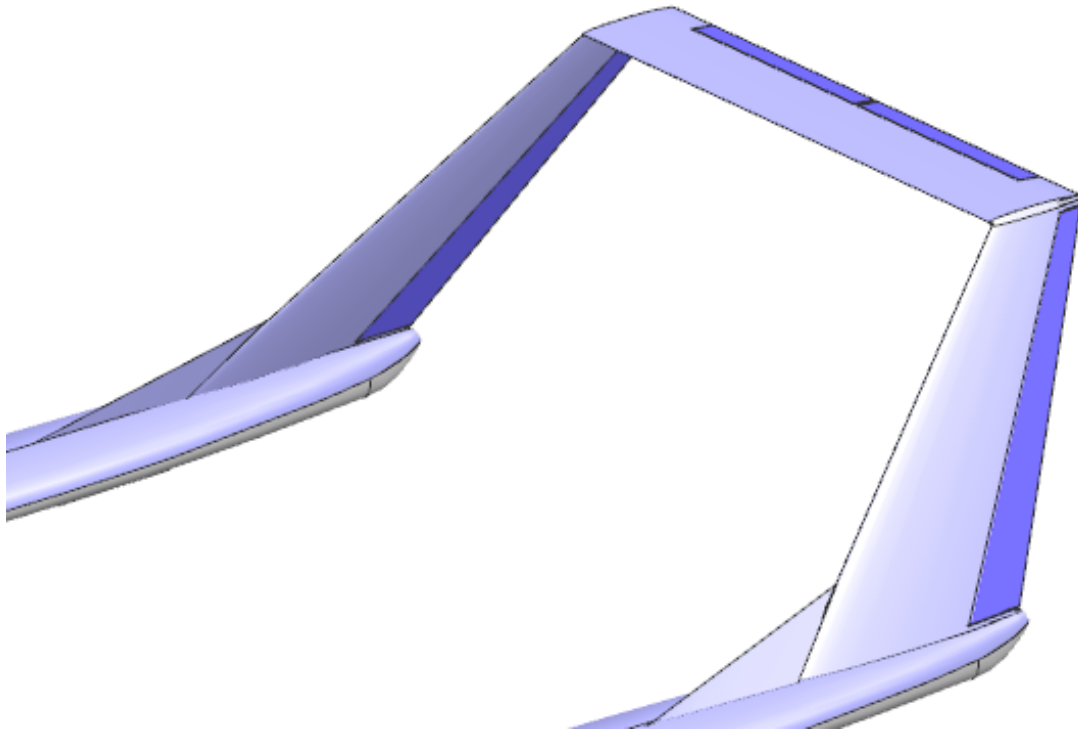
**FIGURE 11.2: COCKPIT LAYOUT**



The tailboom is sized to hold the sulfuric acid and the landing gear. The tailboom has a length of 49.3 ft, a width of 5 ft and a height of 2 ft. The tailbooms are 35 ft apart.

## 12 Empennage Sizing

The empennage is sized around the tailbooms and engine. Since the tailbooms are longer than the fuselage, a twin-boom tail configuration is selected. The horizontal tail is placed on the tip of the two vertical tails to generate an end-plate effect, which increases lift. As well as this, the vertical tails are placed at a dihedral to decrease the wetted area. The empennage is also placed 5 degrees away from the exhaust of the engine to avoid jet wash and reduce fatigue on the empennage. Finally, spin strakes are placed on the empennage to help with stabilization in spiral mode. The final design of the empennage is shown in Figure 12.1.



**FIGURE 12.1: EMPENNAGE DESIGN**



**13 Landing Gear Sizing**

The landing gear was sized based on the tailboom sizing. The aircraft has a quad-landing gear layout to allow for deck-level takeoff. The deck-level takeoff reduces the amount of slosh that occurs for the fuel and sulfuric acid, which will decrease any CG excursions that could occur during takeoff. The landing gear has a diameter of 1.5 ft and has two wheels per gear. The landing gear will fall into Class II characteristics, which includes a high-pressure wheel with the capability to take off and land on concrete runways. As well as this, the landing gear is configured to be statically and dynamically stable to prevent incidents with landing. The forward and aft landing gears are over 15 degrees from the center of gravity location to avoid longitudinal tip-over. As well as this, the quad gear provides lateral stability to avoid lateral tip-over. The aft landing gear includes a 15 degree space in case the aircraft needs to rotate, though a standard takeoff will not include rotation. Finally, the landing gears will retract forward. This allows the to lock the landing gear in place if the landing gear does not initially retract in

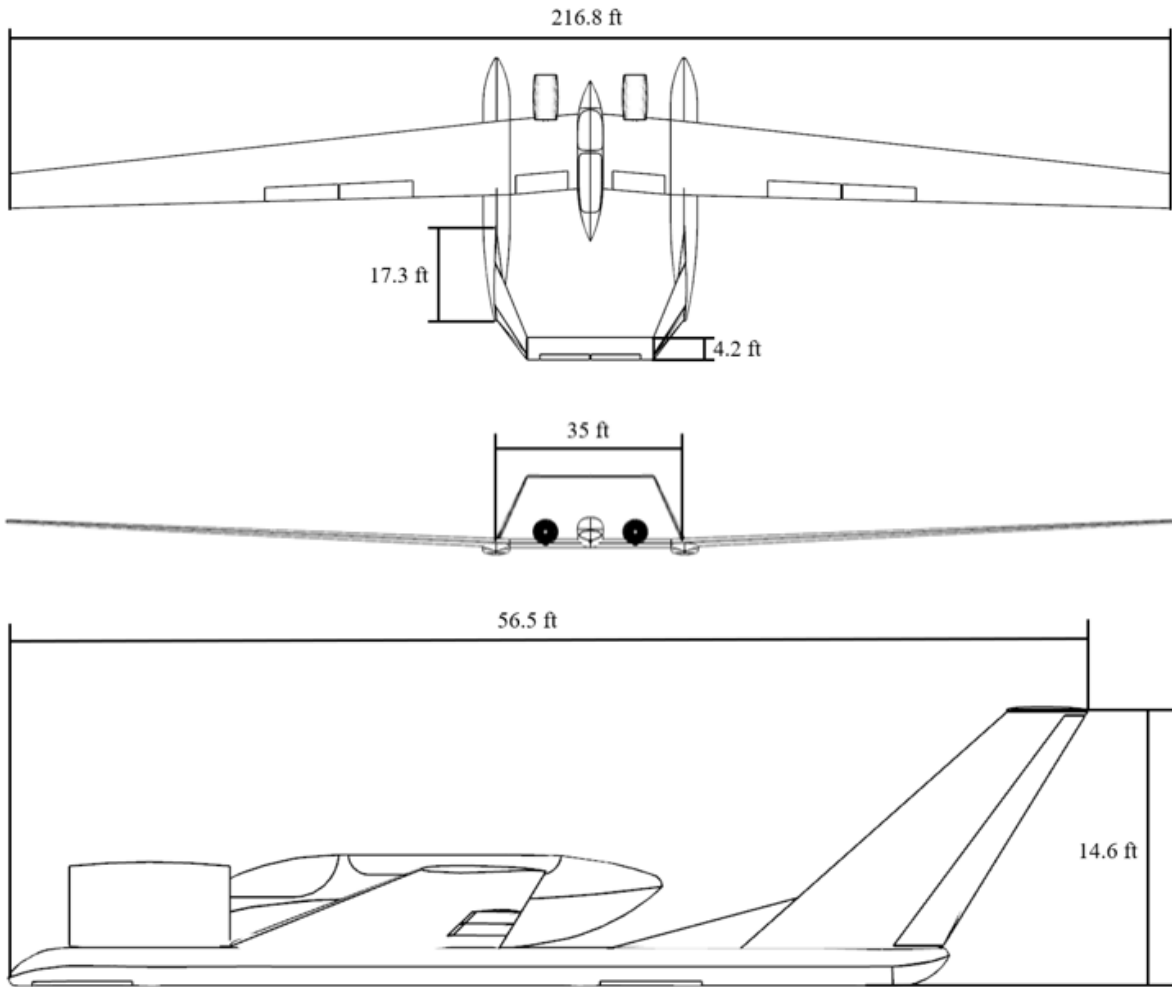


**FIGURE 13.1:** airflow  
**LANDING GEAR** place.

**14 Aircraft Three-View and List of Salient Characteristics**

Figure 14.1 details the three-view of the ECHO and the length characteristics associated with the aircraft.





**FIGURE 14.1: THREE-VIEW OF THE ECHO AIRCRAFT**

Table 14.1 details the salient characteristics of the ECHO aircraft.

**TABLE 14.1: SALIENT CHARACTERISTICS**

	Wing	Horizontal Tail	Vertical Tail	Units
Area, S	2,350	189.2	182.1	ft <sup>2</sup>
Span, b	216.8	23.4	17.6	ft
Mean Geometric Chord, mgc	11.4	4.22	7.88	ft
Aspect Ratio, AR	20	2.9	1.7	(~)
Sweep Angle,	5	0	50	deg
Taper Ratio,	0.46	1.0	0.4	(~)
Thickness Ratio	0.10, 0.06	0.06	0.06	(~)



<b>Root Airfoil</b>	SC2-0610	SC2-0606	NACA0006	(~)
<b>Tip Airfoil</b>	SC2-0606	SC2-0606	NACA0006	(~)
<b>Root Dihedral Angle</b>	0	0	65	deg
<b>Tip Dihedral Angle</b>	2.5	0	65	deg
<b>Control Chord Ratio</b>	0.25	0.25	0.25	(~)
<b>Control Span Ratio</b>	0.34	0.79	0.86	(~)
	<b>Fuselage</b>	<b>Tailboom</b>	<b>Aircraft</b>	<b>Units</b>
<b>Maximum Length</b>	30	49.3	56.5	ft
<b>Maximum Height</b>	5.58	2	14.6	ft
<b>Maximum Width</b>	4.75	5	216.8	ft

## 15 Weight and Balance

To determine the anticipated weights and CG excursion, each portion of the aircraft is given a weight fraction [26]. To do so, data from Roskam's Part V is used to estimate each weight fraction [26]. Adjustments are made as necessary to incorporate each structure. As well as this, the empty weight to takeoff weight fraction, 0.43, is incorporated and met. Once each weight fraction is analyzed, the CG location of each structure is found [29]. Each CG location can be added or removed from the CG location analysis to determine each excursion. The empty weight, operating empty weight, and the operating empty weight with crew, fuel, and payload are all found and plotted as a function of the mean geometric chord, as shown in Figure 15.1. The maximum flight CG excursion is 4.16%, which is an aft CG excursion.



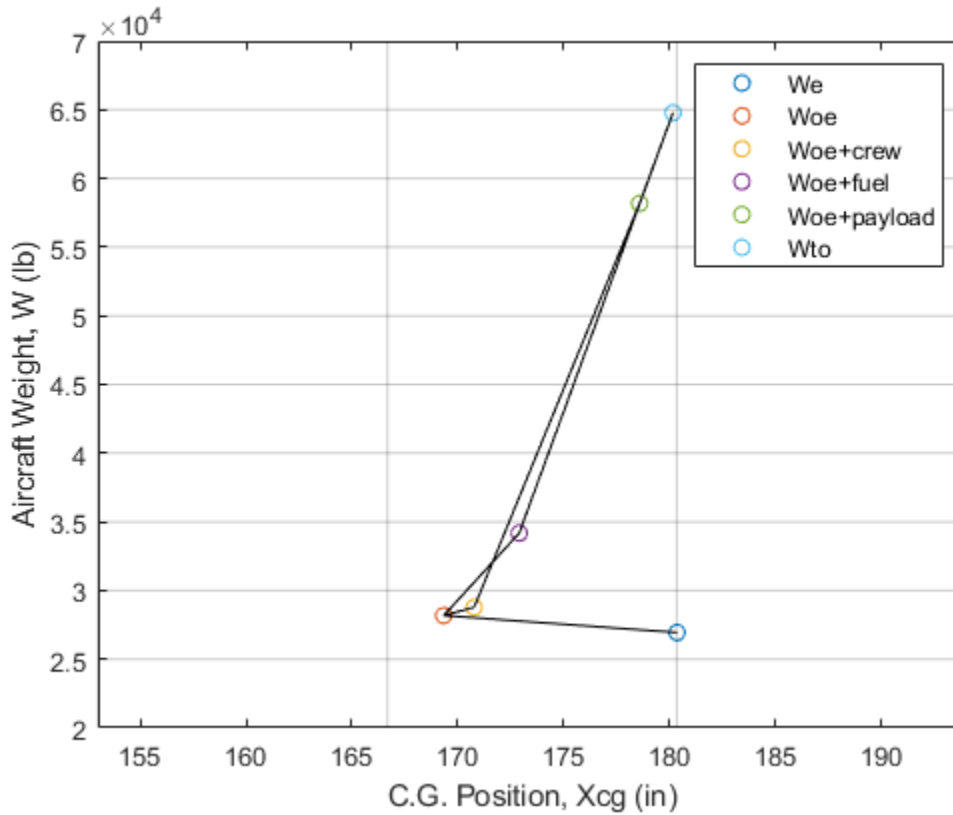


FIGURE 15.1: CG EXCURSION DIAGRAM

16 Stability and Control

In this section, class I and class II stability and control will be discussed.

16.1 Class I Stability and Control

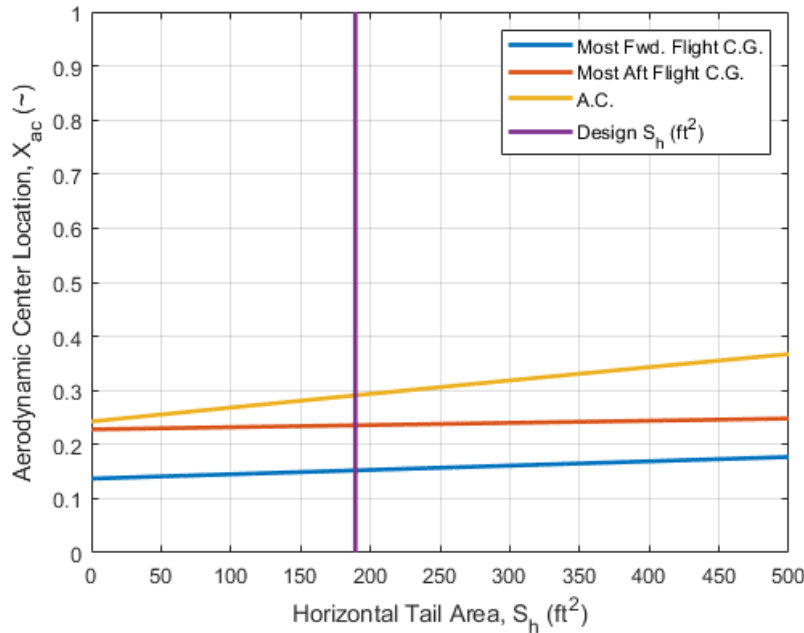
In order to establish class I longitudinal and directional stability, it is necessary to determine the aerodynamic center of the aircraft. To determine the aerodynamic center of the aircraft, Eq. 16.1 must be solved.

$$\bar{X}_{ac,A} = \frac{\bar{X}_{ac,wf} C_{L,\alpha wf} + C_{L,\alpha h} \left(1 - \frac{d\varepsilon_h}{d\alpha}\right) \frac{S_h}{S} \bar{X}_{ac,h}}{C_{L,\alpha wf} + C_{L,\alpha h} \left(1 - \frac{d\varepsilon_h}{d\alpha}\right) \frac{S_h}{S}} \quad \text{EQ. 16.1}$$

The variable  $C_{L,\alpha h}$  can be found using the Polhamus equation and extrapolated from data from Roskam’s Part VI [30]. Next, the  $C_{L,\alpha wf}$  can be found using an equation from chapter 8 of Part VI [30]. The locations of the aerodynamic center of the horizontal tail can be found by measuring the distance between the quarter chord of the horizontal tail’s mean geometric chord to the leading edge of the wing mean geometric curve. The downwash,  $d\varepsilon_h/d\alpha$  can be estimated using another equation from chapter 8 of Part VI [30]. To find the location of the



aerodynamic center of the wing fuselage combination, the aerodynamic center of the wing can be added to the estimated Munk shift. To estimate the Munk shift, a Multhopp integration is performed. Finally, the aerodynamic center of the aircraft can be found as a function of the horizontal tail area, as shown in Figure 16.1.



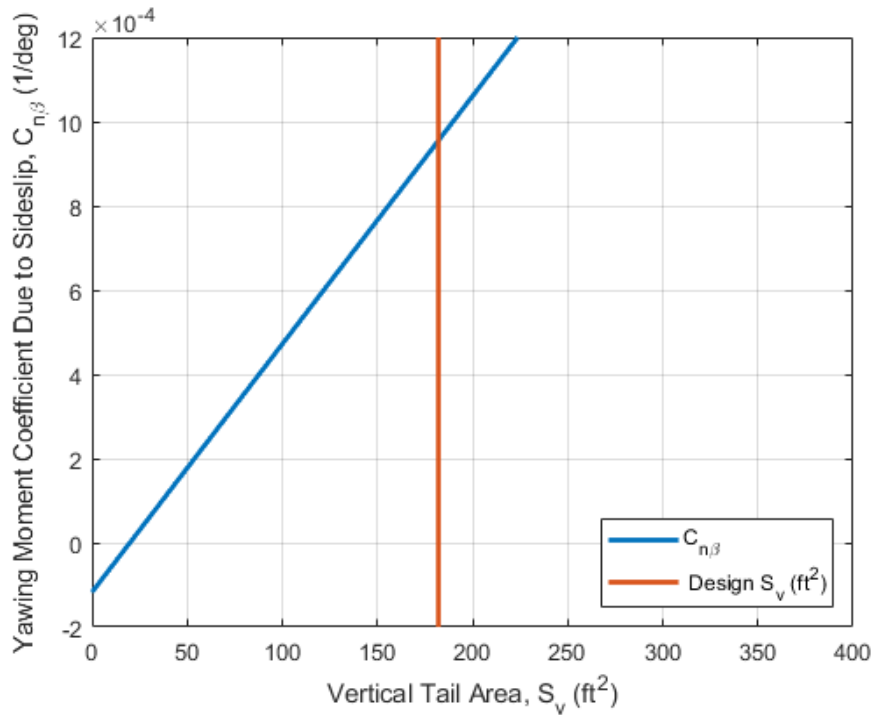
**FIGURE 16.1: LONGITUDINAL STABILITY**

The desired static margin is around 10% forward, so the aircraft is marginally stable. The maximum static margin is determined to be 13% forward, which is slightly higher than anticipated, but within a reasonable range, as the center of gravity will shift during the dispensing mission. The next step in determining stability is to calculate directional stability. To determine directional stability, the  $C_{n\beta}$  of the aircraft must be found as a function of the vertical tail area. For the ECHO, there are two vertical tails, so the total area will be added together. The equation to find  $C_{n\beta}$  is shown in Eq. 16.2.

$$C_{n\beta} = C_{n\beta, wf} + C_{L\alpha, v} \left( \frac{S_v}{S} \right) \left( \frac{x_v}{b} \right) \quad \text{EQ. 16.2}$$

Due to the end-plating effect produced by the empennage, the  $C_{L\alpha, v}$  is assumed to be  $2\pi$  /rad. The  $C_{n\beta, wf}$  can be found using information from Part VI [30]. Finally, the  $C_{n\beta}$  line is shown as a function of the total vertical tail area, as shown in Figure 16.2.





**FIGURE 16.2: DIRECTIONAL STABILITY**

The desired level of stability for the aircraft is a value of 0.0010 /deg for  $C_{n\beta}$ . At the selected vertical tail area, the value is 0.00095 /deg, which is very close to the desired value.

The final step in determining the functionality and stability of the ECHO is to determine the maximum rudder deflection in the case of an engine-out. To counteract the critical engine-out yawing moment, the required rudder deflection can be calculated by using Eq. 16.3.

$$\delta_r = \frac{N_D + N_{t,crit}}{\bar{q}_{mc} S b C_{n\delta r}} \quad \text{EQ. 16.3}$$

In the instance of a critical engine-out, the maximum rudder deflection is -24.7 degrees, which is less than the desired  $\pm 25$  degrees. This is the maximum rudder deflection of the rudder nearest to the failed engine and does not account for the opposite rudder deflection. The rudder deflection will be shared between the two rudders and will decrease the maximum overall rudder deflection.

### 16.2 Class II Stability and Control

For Class II stability and control, the handling qualities of the aircraft are considered. Due to the complexity of the mission, it is important to meet level I handling qualities. The requirements for longitudinal stability for each handling quality is shown in Table 16.1 and Table 16.2.



**TABLE 16.1: PHUGOID STABILITY REQUIREMENTS**

Handling Qualities	Phugoid Stability Requirement
Level 1	$\xi_P > 0.04$
Level 2	$\xi_P > 0$
Level 3	$T_2 > 55 \text{ sec}$

**TABLE 16.2: SHORT PERIOD STABILITY REQUIREMENTS**

Handling Qualities	Category A and C Flight Phases	Category B Flight Phases
Level 1	$0.35 < \xi_{SP} < 1.30$	$0.30 < \xi_{SP} < 2.00$
Level 2	$0.25 < \xi_{SP} < 2.00$	$0.20 < \xi_{SP} < 2.00$
Level 3	$0.15 < \xi_{SP}$	$0.15 < \xi_{SP}$

For the lateral stability handling requirements, the aircraft must meet level 1 requirements for each flight phase. The handling requirements for roll and spiral mode are shown in Table 16.3 and Table 16.4.

**TABLE 16.3: ROLL STABILITY REQUIREMENTS**

Flight Phase	Class	Level I	Level II	Level III
A	I, II, III, IV	$T_r < 1.0 \text{ sec}$	$T_r < 1.4 \text{ sec}$	
		$T_r < 1.4 \text{ sec}$	$T_r < 3.0 \text{ sec}$	
B	All	$T_r < 1.4 \text{ sec}$	$T_r < 3.0 \text{ sec}$	$T_r < 10 \text{ sec}$
C	I, II-L, II-C, C, IV	$T_r < 1.0 \text{ sec}$	$T_r < 1.4 \text{ sec}$	
		$T_r < 1.4 \text{ sec}$	$T_r < 3.0 \text{ sec}$	

**TABLE 16.4: SPIRAL STABILITY REQUIREMENTS**

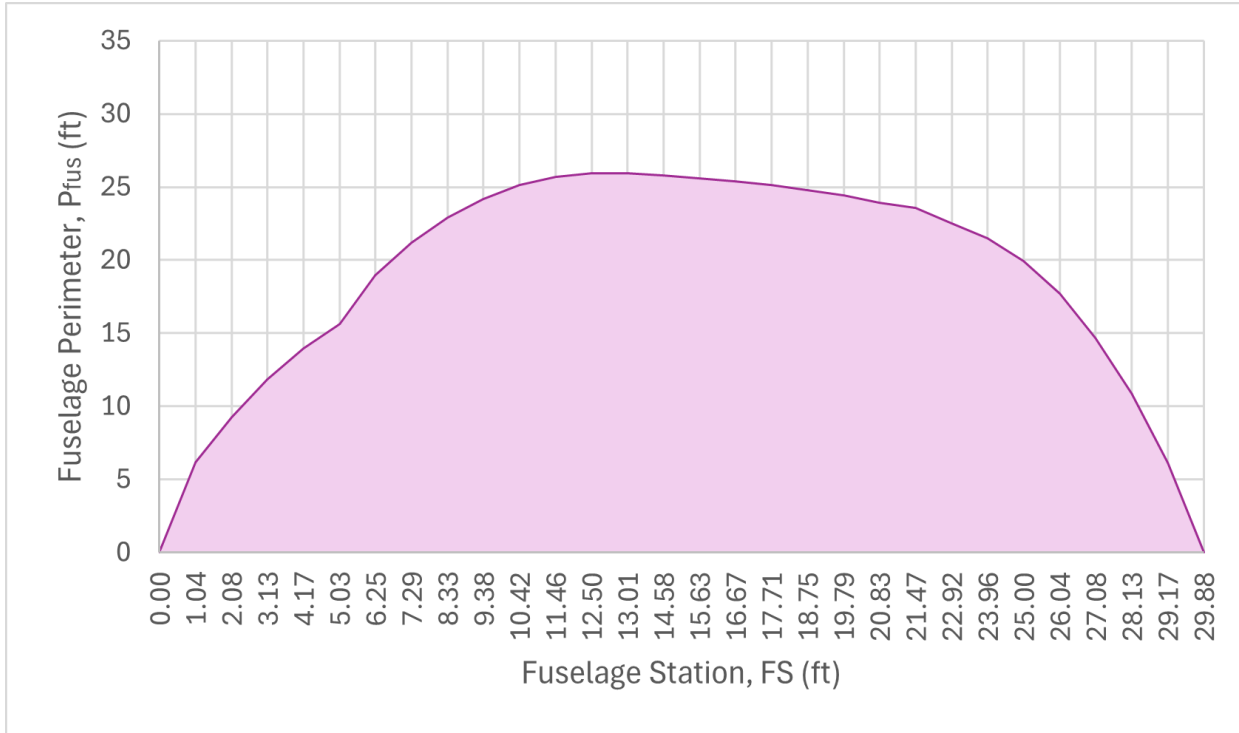
Flight Phase and Category	Level I	Level II	Level III
A and C	$T_{2S} > 12 \text{ sec}$	$T_{2S} > 8 \text{ sec}$	$T_{2S} > 4 \text{ sec}$
B	$T_{2S} > 20 \text{ sec}$	$T_{2S} > 8 \text{ sec}$	$T_{2S} > 4 \text{ sec}$

**17 Drag Polars**

A few steps must be taken to determine the class I drag polars. The first step is to estimate the  $\Delta C_{D_0}$  and the Oswald efficiency factor,  $e$ . To do so, Roskam’s Part I is used. The  $\Delta C_{D_0}$  and the Oswald efficiency factor are found for the clean, takeoff and landing flaps, and the gear down conditions. Once this is found, the next step is to determine the wetted area of each component of the aircraft. The wetted area for the wing, engines, and



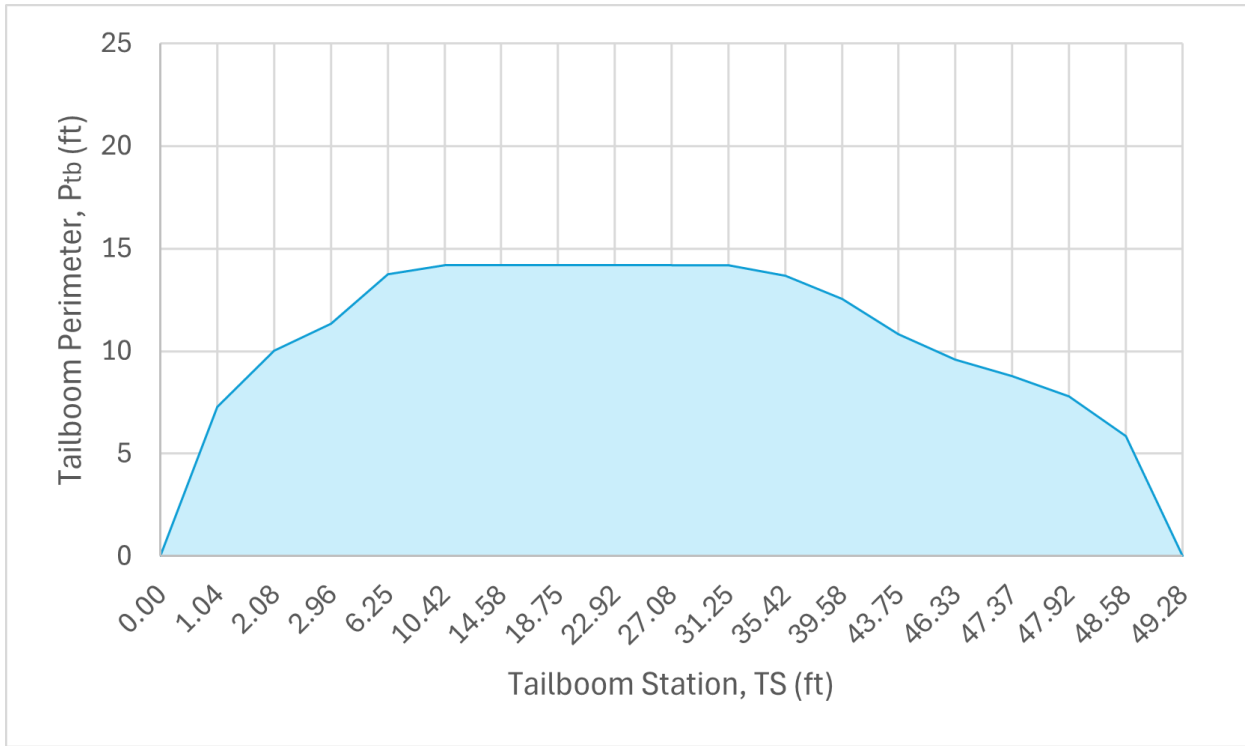
empennage are found using the software NX. For the fuselage and the tailbooms, the wetted area is found by developing a perimeter plot for each. This is to guarantee the wetted area calculations are more accurate than the NX values due to the complex geometry. To develop the perimeter plot, fuselage/tailboom stations are measured and the perimeter of each section is found. The perimeter is then plotted as a function of area and the wetted area can be found. In Figure 17.1, the perimeter plot of the fuselage is shown.



**FIGURE 17.1: FUSELAGE PERIMETER PLOT**

The highlighted area underneath the curve represents the wetted area of the fuselage. The fuselage has a streamlined shape, and the perimeter plot details the location where the cabin and the nose of the fuselage meet. As well as this, the fuselage tapers off as the length increases, similar to the design of the fuselage. Figure 17.2 represents the wetted area of the tailbooms.





**FIGURE 17.2: TAILBOOM PERIMETER PLOT**

The tailboom’s perimeter remains constant in the middle portion and begins to taper off both horizontally and vertically toward the empennage. The tailboom also has a lower wetted area than the fuselage due to the decreased height.

The wetted area of the aircraft was determined to be 6496.27 ft<sup>2</sup>. This value is reasonable due to the two tailbooms and the large wing area. Using Roskam’s Part I, the parasite area is estimated to be 30 ft<sup>2</sup>. The final drag polars of the aircraft are found, as shown in Figure 17.3.



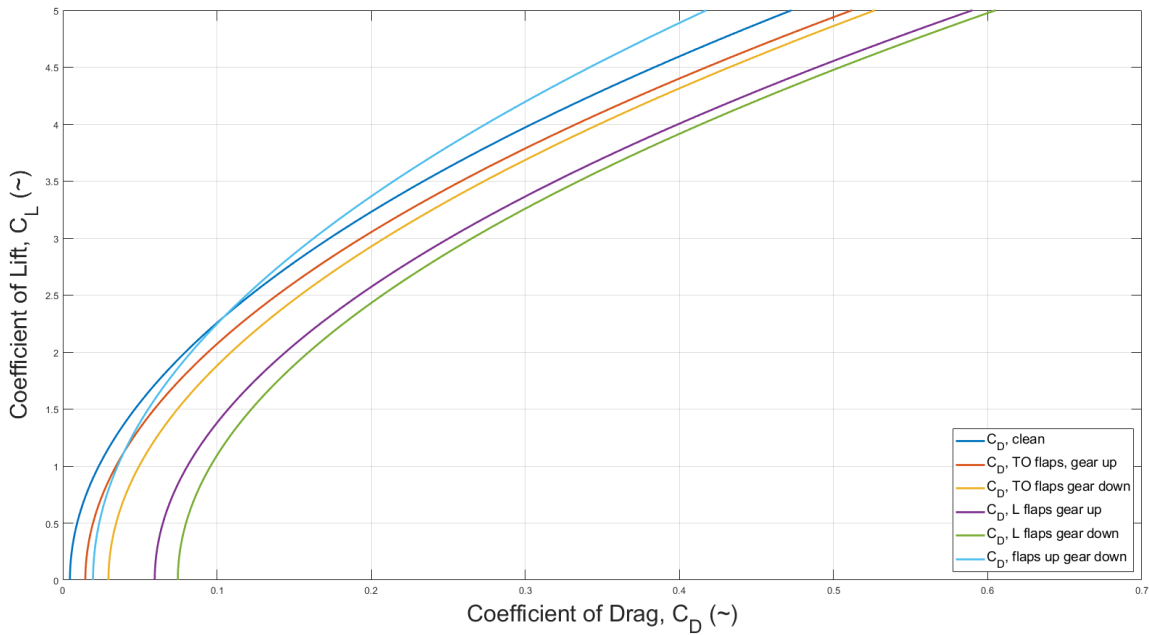


FIGURE 17.3: CLASS I DRAG POLARS

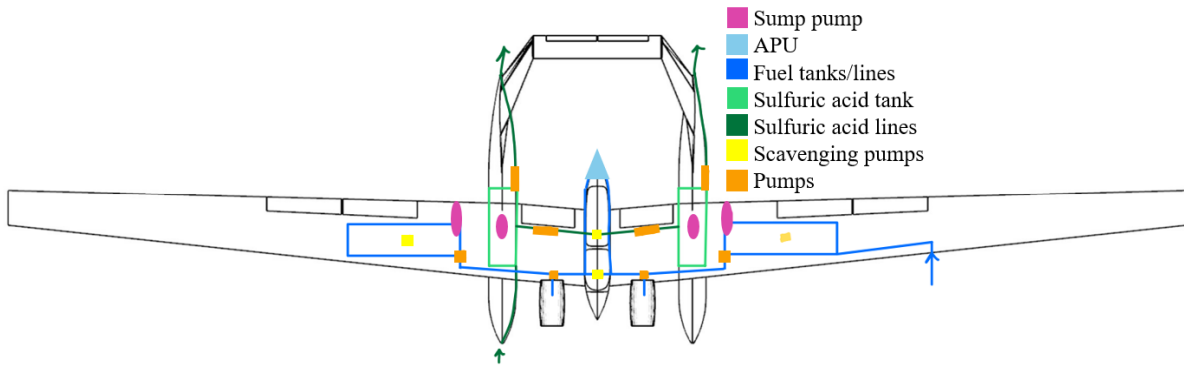
## 18 System Integration

There are many systems needed to successfully complete the required missions associated with the ECHO aircraft. The required systems are discussed in this section.

### 18.1 Fuel System/Sulfuric Acid Systems

When developing the fuel and sulfuric acid tank systems, it is important to recognize the importance of keeping the fuel and sulfuric acid separate. Sulfuric acid is highly corrosive and reactive, and any interaction between the two substances can cause catastrophic damage. To avoid this, the sulfuric acid and fuel will be stored in separate tanks and loaded into the aircraft separately. The sulfuric acid will be loaded in the front of the left tailboom and will fill both tanks. Once the sulfuric acid is loaded, a scavenging pump will be utilized to empty the line connecting the two tanks. The line will also be closed after the loading process to avoid any left-over sulfuric acid under the fuselage. Once the pre-flight checks that the sulfuric acid is loaded safely, the fuel can be loaded. The fuel is loaded on the right wing and connects to the fuel tank on the left wing. The fuel tanks are placed in the outboard of the wing to produce a dry bay in between the tailbooms. This prevents the aircraft from igniting under the wing in case of an engine fire. The layout of the tanks is shown in Figure 18.1.



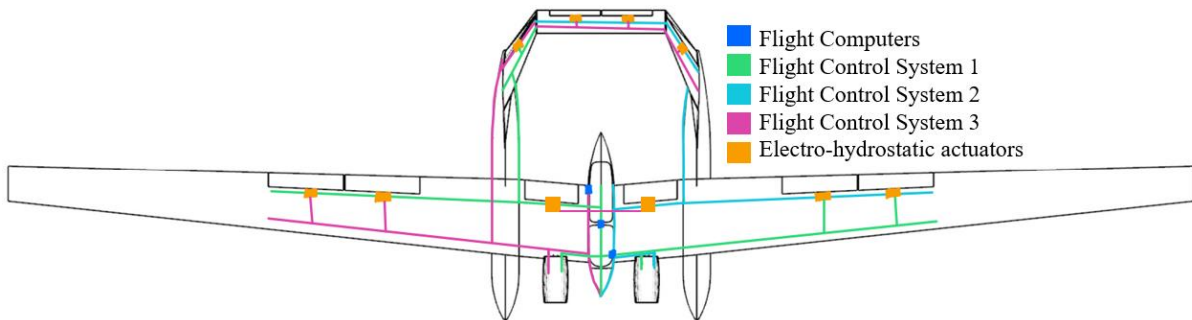


**FIGURE 18.1: FUEL/SULFURIC ACID TANK SYSTEM**

To supplement the tanks, a sump pump has been added to each. This allows for the tank to be emptied in case of an emergency. The sulfuric acid tanks will be fitted with a custom pump that can handle the corrosive nature of sulfuric acid. Each fuel tank will have a scavenging pump to empty the tank of any water that may enter. Finally, the lines will be outfitted with pumps to transport the fuel and sulfuric acid to the necessary location. The fuel lines will lead to the engine and the APU system to power the ECHO aircraft.

**18.2 Flight Control System**

For the flight control system, there will be three systems for triple redundancy. If a system fails, there will be two backup systems to continue controlling the aircraft, as shown in Figure 18.2. The pink, green, and light blue lines represent each of the control systems that are present. The systems will run forward of the front spar and aft of the back spar. The system in front of the forward spar will be armored to protect from any forces during flight. Placing the control systems forward and aft of the main bay will provide easier access for maintenance.



**FIGURE 18.2: FLIGHT CONTROL SYSTEM**

For the actuators, electro-hydrostatic actuators have been selected. Each control surface will have one actuator with two flight control systems that can control each actuator to create double redundancy. The flight



computers will be spaced from one another to create redundancies as well. Each flight computer controls one flight control system.

### 18.3 Electrical System

The electrical system will be comprised of 4 generators and four batteries. Each battery will control a set of control surfaces and the engine (ailerons, rudders, elevators, and engine). The electric system will also have redundant systems in case of an outage or a battery failure. As well as this, the electric system will power the APU. Finally, the ECHO aircraft will be outfitted with landing lights in case of a nighttime landing. The full electrical diagram is shown in Figure 18.3.

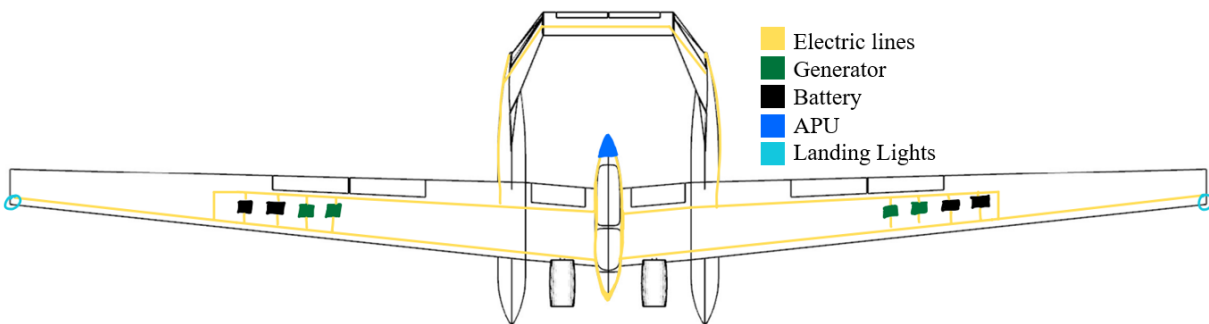


FIGURE 18.3: ELECTRICAL SYSTEMS

### 18.4 Hydraulic Systems

The hydraulic system will be used to power the engines and the landing gear. The hydraulic fluid will be stored in a reservoir in the nose of the fuselage, and there will be two redundant systems. As well as this, a ram air turbine will be housed in the nose of the right tailboom in case of a power outage. The full hydraulics diagram is shown in Figure 18.4.

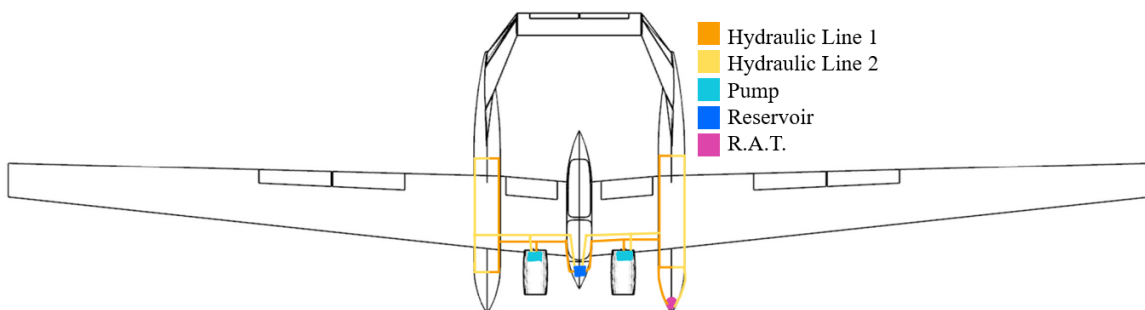


FIGURE 18.4: HYDRAULIC SYSTEM



### 18.5 De-Icing System

To prevent and mitigate any icing that may occur, a de-icing and an anti-icing system will be installed. Due to the high altitudes the ECHO aircraft will be cruising at, icing conditions are to be expected. For the de-icing system, air will be flown through the leading edge of the wing and empennage to remove any icing that occurs. The anti-icing system will also flow air through the leading edge of the aircraft to prevent the wing, empennage, tips of the wings, and the front of the engine nacelles from forming ice. Ice increases the drag of the aircraft and can cause more turbulent flow, so it is important to plan for icing conditions. Figure 18.5 details the de-icing system, as well as the configurations for both the de-icing and anti-icing systems [31].

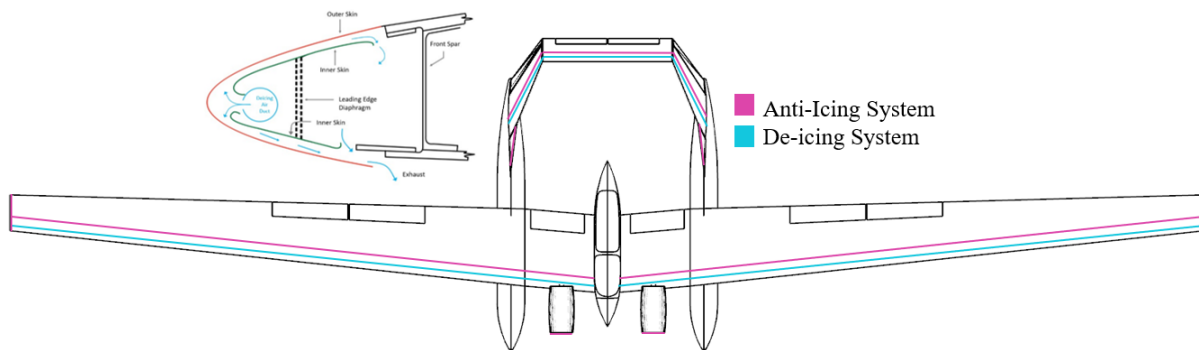


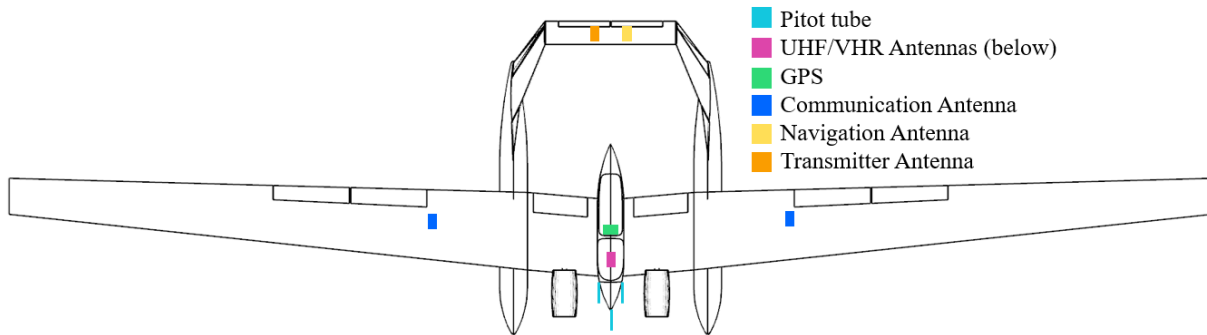
FIGURE 18.5: DE-ICING AND ANTI-ICING SYSTEMS

### 18.6 Antenna System

For the antenna system, the standard systems will be utilized. The aircraft will have three pitot tubes for redundancy. The pitot tubes will supply the pilot with necessary flight data, including altitude and airspeed. The pitot tubes will also have de-icing and anti-icing measures implemented. The aircraft will have a UFR/VFR antenna below the fuselage. The aircraft will also have communication antennas, navigation antenna, GPS, and



transmitter antennas. This will help the aircraft successfully complete the required mission. The locations of each of the systems are shown in Figure 18.6 [32].



**FIGURE 18.6: ANTENNA SYSTEM**

**18.7 Escape/Emergency System**

For the escape system, the aircraft will be fitted with ejection seats in case of an emergency. However, the ejection seats will be blocked from deploying at high altitudes. The aircraft will also have an emergency raft under the fuselage in case of a water landing.

**18.8 Cockpit Pressurization System**

The main fuselage will be pressurized using a positive displacement system. However, in case of a pressurization system failure, each crew member will wear a pressurized suit. This will prevent a catastrophic failure in case the pressurization fails.

**19 Structures**

The structures of each component of the ECHO aircraft are shown in this section.

**19.1 Materials**

The materials selected for the aircraft are shown in Table 19.1.

**TABLE 19.1: MATERIAL SELECTION FOR THE ECHO AICRAFT**

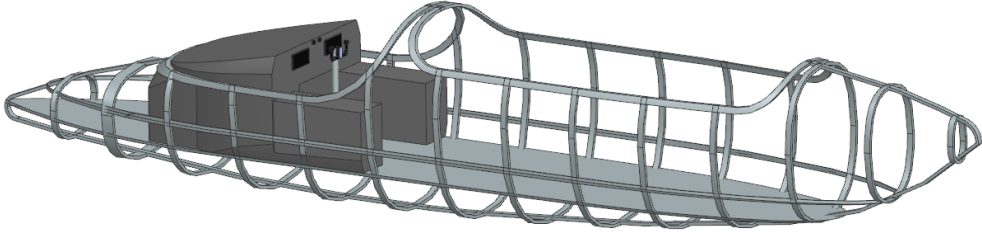
Material Selection	
<b>Skins</b>	Carbon Fiber
<b>Ribs</b>	Aluminum
<b>Spars</b>	Aluminum
<b>Fuselage/Tailboom Frames</b>	Aluminum
<b>Landing Gear Structure</b>	Titanium



Engine Structures	Titanium
-------------------	----------

**19.2 Fuselage Structure**

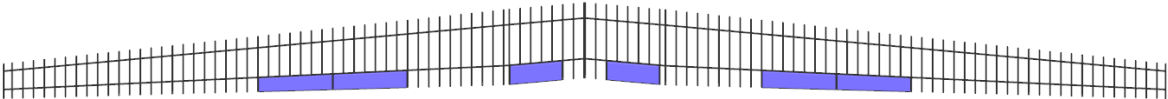
The fuselage substructure is shown in Figure 19.1. For the substructure, the longerons are spaced 24 in apart, and there is a vertical frame and a horizontal frame. The floor of the cabin is also shown, along with the control panel. The sections of the fuselage are cut out for the window for visibility and the top door for the crew to enter/exit the aircraft.



**FIGURE 19.1: FUSELAGE SUBSTRUCTURES**

**19.3 Wing Structure**

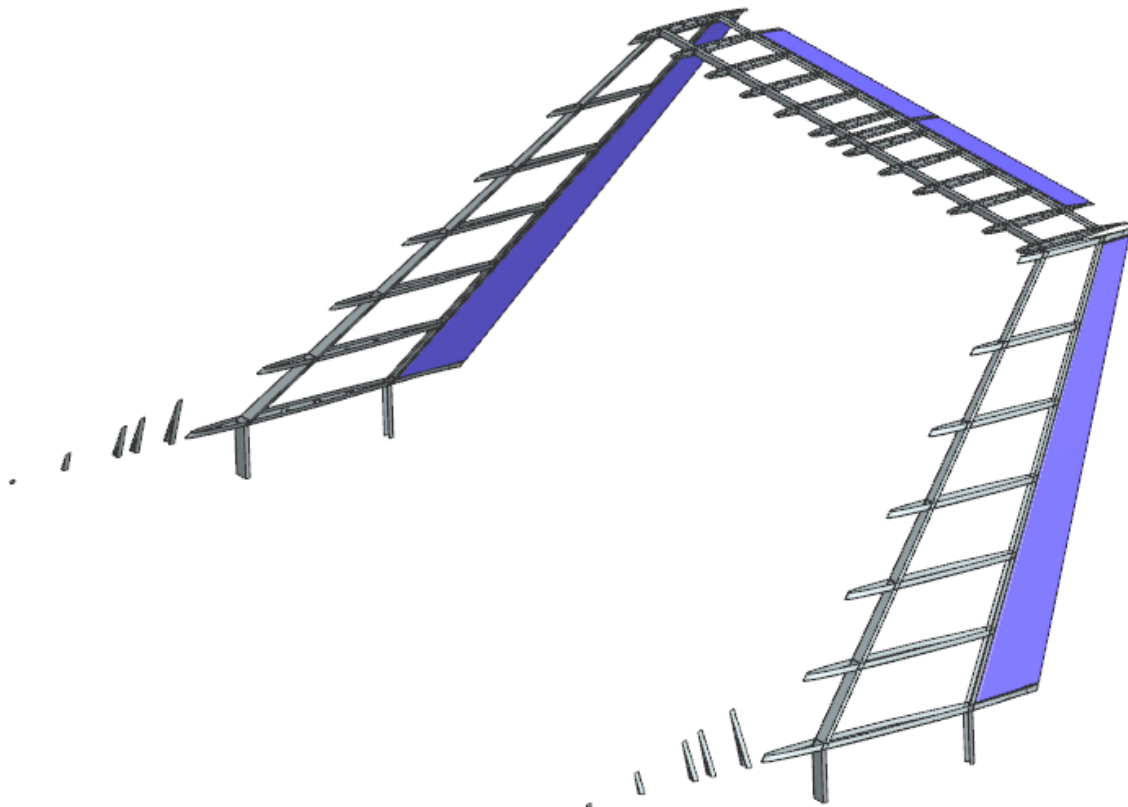
The wing substructure is shown in Figure 19.2. The ribs are spaced 24 in apart, and the spars are placed at 20% and 75% of the chord. The ribs are cut out with lightning holes to decrease weight and material cost, as well as to allow for any wiring to pass through. The ribs and spar continue to the tip of the wings to provide structural support.



**FIGURE 19.2: WING SUBSTRUCTURES**

**19.4 Empennage Structure**

The empennage substructure is shown in Figure 19.3. The ribs are spaced 24 in apart for the vertical and horizontal tail. Like the wing, the ribs have lightning holes for decreased weight and for wiring. The spin strakes also have a substructure, which will incorporate with the longerons on the tailbooms. The empennage has two spars, in the 20% and 75% chord location for both the vertical and horizontal tail. As well as this, the spars from the vertical tail continue into the tailboom for more structural support.

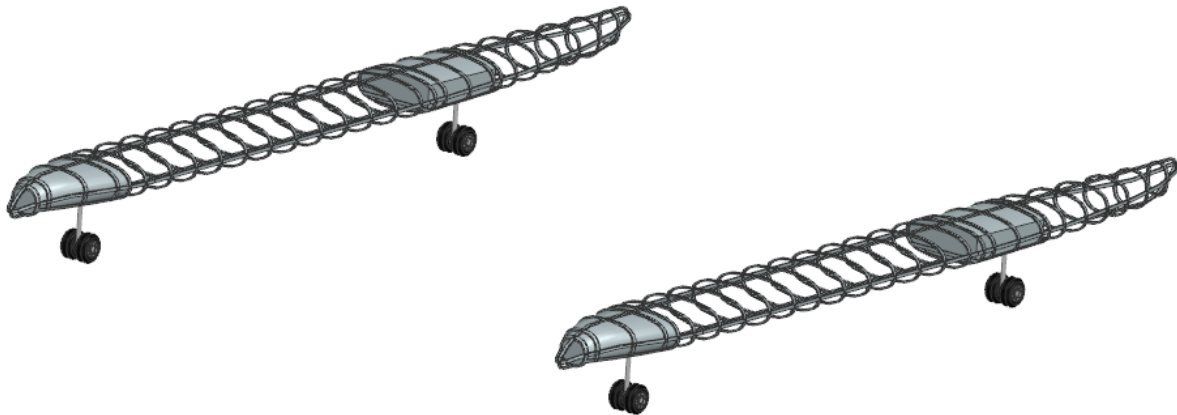


**FIGURE 19.3: EMPENNAGE SUBSTRUCTURE**

### **19.5 Tailboom Structure**

The substructure of the tailboom is shown in Figure 19.4. The longeron spacing is 24 in, and there is a horizontal and vertical frame. For the landing gear, the containment of the landing gear accounts for a minimum 2 inches of space for the landing gear to expand and contract. As well as this, any systems associated with the landing gear will be stored in the containment section. The sulfuric acid tanks will go in between the forward and aft landing gears, and the acid will dispense out the back of the tailboom.

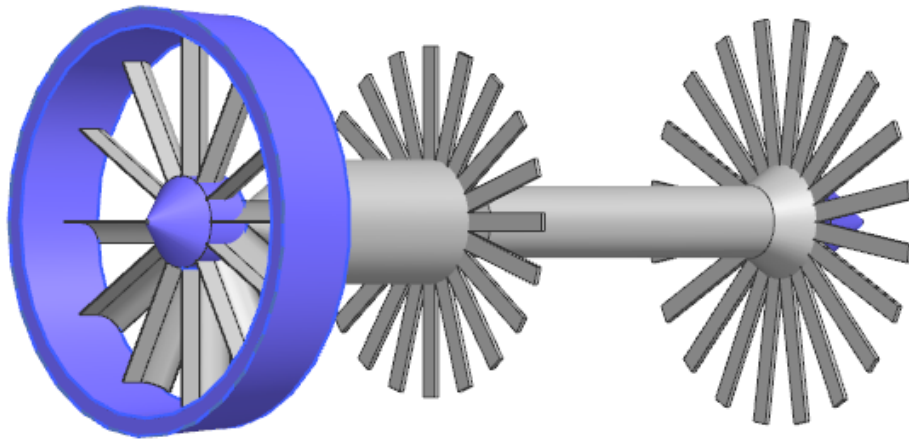




**FIGURE 19.4: TAILBOOM/LANDING GEAR SUBSTRUCTURE**

### 19.6 Engine Structure

The substructure of the engine is shown in Figure 19.5. The main blades shown are the end of the compressor section, the first fan, and the end of the turbine section. More blades will be incorporated to compress air and produce thrust. The model of the engine is based off the F118-100 engines, as these engines will be used for the ECHO aircraft.



**FIGURE 19.5: ENGINE SUBSTRUCTURE**

### 19.7 ECHO Aircraft Structure

The final substructure of the aircraft is shown in Figure 19.6 and Figure 19.7. The structure of the spin strakes incorporates with the tailbooms, and the spars and ribs go underneath the floor of the fuselage.



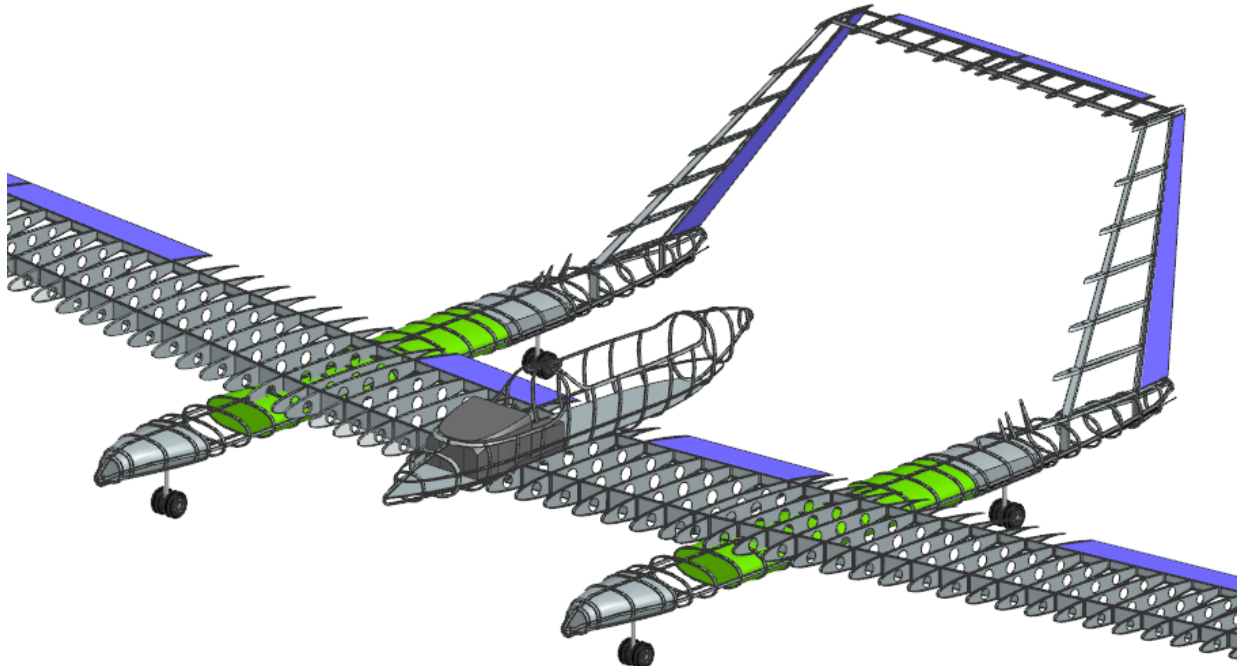


FIGURE 19.6: ECHO AIRCRAFT SUBSTRUCTURE

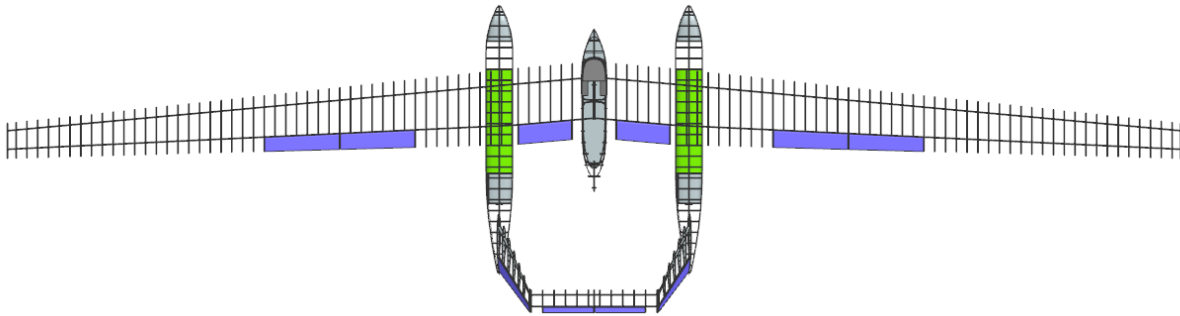
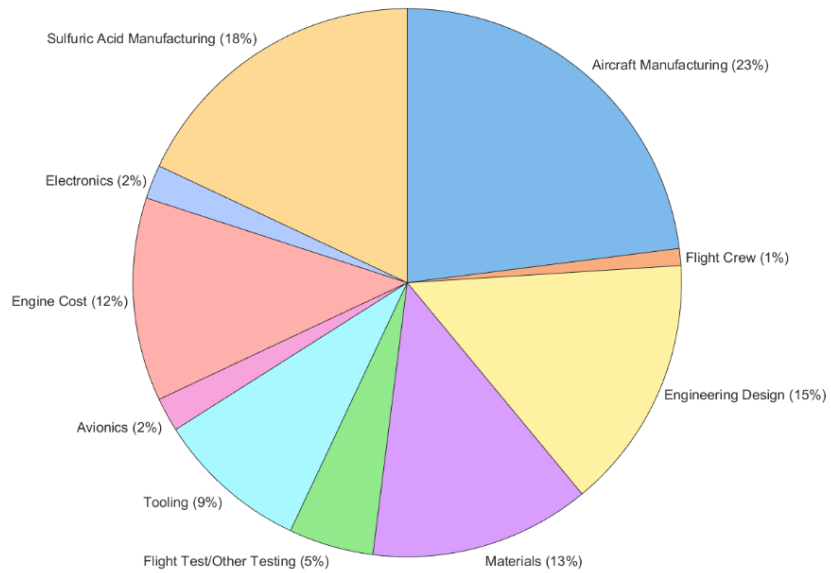


FIGURE 19.7: ECHO AIRCRAFT SUBSTRUCTURE TOP VIEW

20 **Cost Analysis**

To estimate the cost of the ECHO aircraft, the estimated percentage of cost of design, manufacturing, as well as other factors was considered. The cost breakdown of the aircraft is shown in Figure 20.1. The estimated cost of an ECHO aircraft is estimated to be 83.6 million dollars.

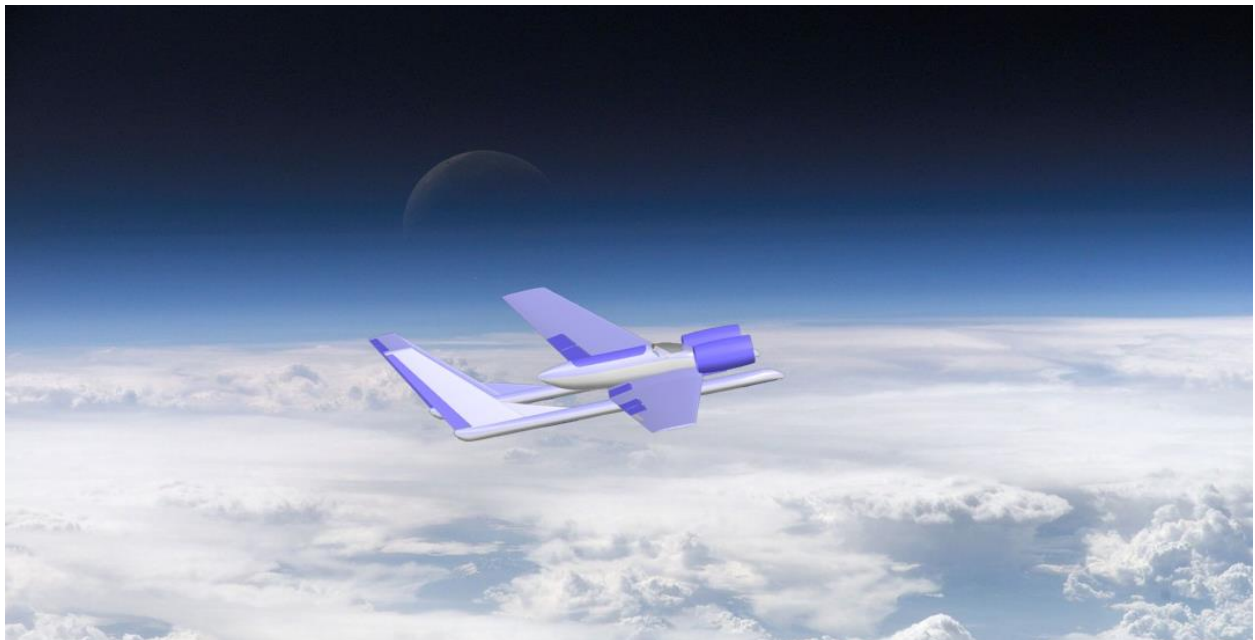




**FIGURE 20.1: COST BREAKDOWN OF THE ECHO AIRCRAFT**

**21 Situational Renderings**

Situational rendering of the ECHO aircraft are shown in Figure 21.1 and Figure 21.2.



**FIGURE 21.1: ECHO AIRCRAFT CRUISING AT ALTITUDE**





**FIGURE 21.2: ECHO AIRCRAFT BEGINNING TO LAND**

**22 Conclusion and Recommendations**

The ECHO aircraft was designed to safely dispense 30,000lb of sulfuric acid into the stratosphere at 65,000 ft and ferry 3,000 nmi. The report details the methods used to identify the required geometry and details the methods used to determine the weight, balance, and stability and control of the aircraft. The report then detailed the structural layout of the aircraft and estimated the projected cost of the ECHO aircraft.

The author recommends that the aircraft perform dispensing operations over non-populated areas, like an ocean or other body of water. Not only does it reduce possible loss of life in case of a catastrophic instance, but it avoids local politics similar to those in Mexico and Tennessee, who have planned or begin enacting laws to ban or restrict geoengineering [33] [34].

As well as this, the author recommends that in upcoming iterations, the aircraft become fully autonomous. Due to the dangerous properties associated with sulfuric acid, the mission becomes high risk. By removing the crew, the mission would become much safer.



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