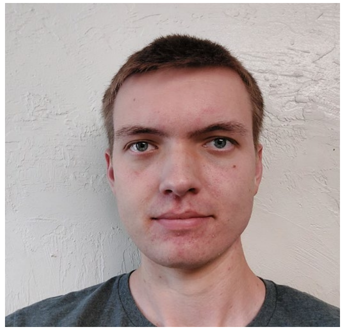
Fight and Flight:

HYDROPLANE

A Responsive Aerial Fire Fighting Aircraft

Team Members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Design Requirements

RFP Requirements

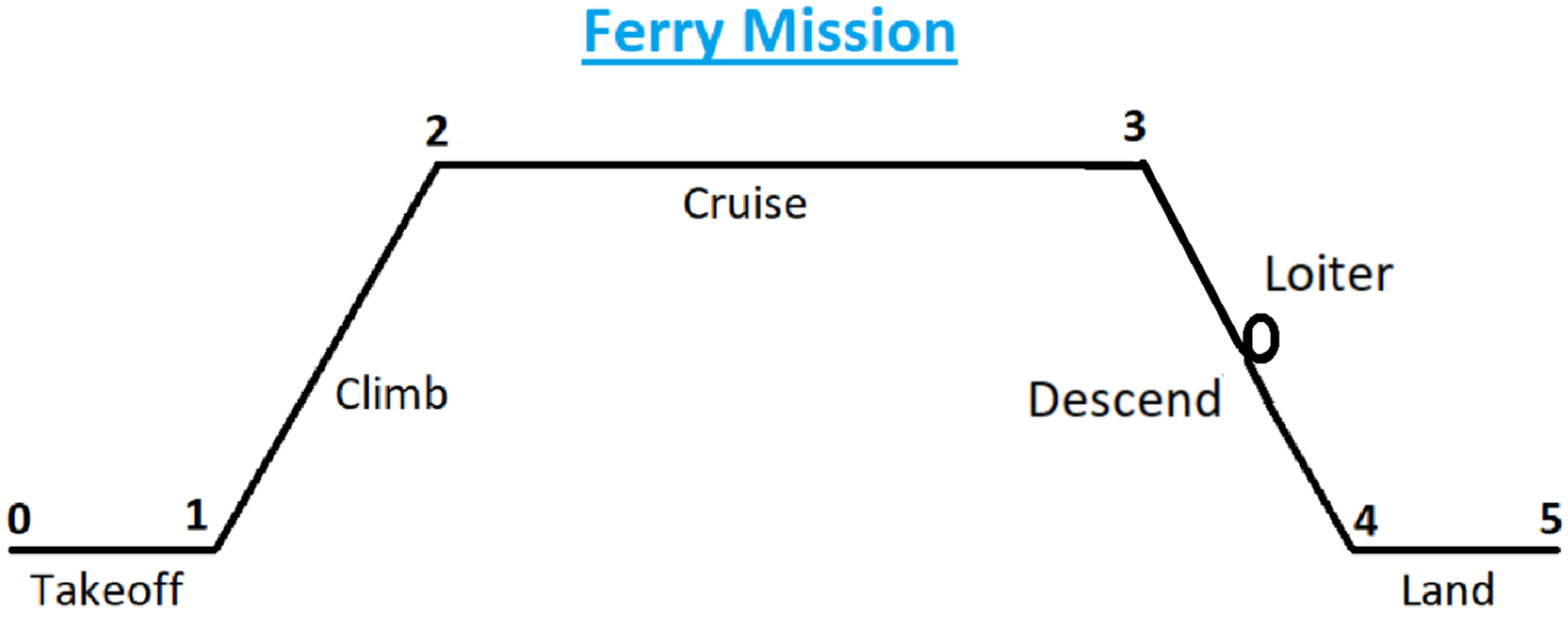
- Entry into Service (EIS)
  - [R] 2030
  - [R] Use existing engine(s) or one that is in development will be in service by 2028, or at least two years prior to the airplane EIS.
  - [R] Assumptions on at least specific fuel consumption/efficiency, thrust/power and weight must be documented.
- Fire Retardant Capacity
  - [R] 4,000 gal - [O] 8,000 gal
  - [R] Multi-drop capable; minimum 2,000 gal per drop
  - [R] Fire retardant reload >= 500 gal / min
  - [R] Retardant density of at least 9 lbs / gal
- Payload Drop
  - [R] Drop speed <= 150 kts - [O] Drop speed <= 125 kts
  - [R] Drop altitude <= 300 ft AGL
- Design Radius (Full Payload)
  - [R]200nmi - [O]400nmi
- Design Ferry Range (No Payload)
  - [R] 2,000 n mi - [O] 3,000 n mi
- Dash Speed (After Payload Drop)
  - [R] 300 kts - [O] 400 kts
- Field Requirements
  - [R] Balanced field length <= 8,000 ft @ 5,000 ft MSL elevation on a +35°F hot day
  - [O] Balanced field length <= 5,000 ft @ 5,000 ft MSL elevation on a +35°F hot day
- Certifications
  - [R] Capable of VFR and IFR flight with an autopilot
  - [R] Capable of flight in known icing conditions
  - [R] Meets applicable certification rules in FAA 14 CFR Part 25
    - All missions below assume reserves and equipment required to meet applicable FARs
  - [O] Provide systems and avionics architecture that will enable autonomous operations
    - Provide a market justification for choosing to either provide or omit this capability
    - Determine how the design would change with this capability

Implications of RFP

- We decided to go for the objectives/goals instead of the design requirements
    - This decision was made so if the objectives could not be reached it would still fit the design requirements
- A load factor of 5 was chosen
    - The importance of low altitude maneuverability during firefighting missions
- A/C reliability
    - Chosen in the case of smoke ingestion
- Ground Tracking Radar
    - Useful for ground tracking when in heavy smoke

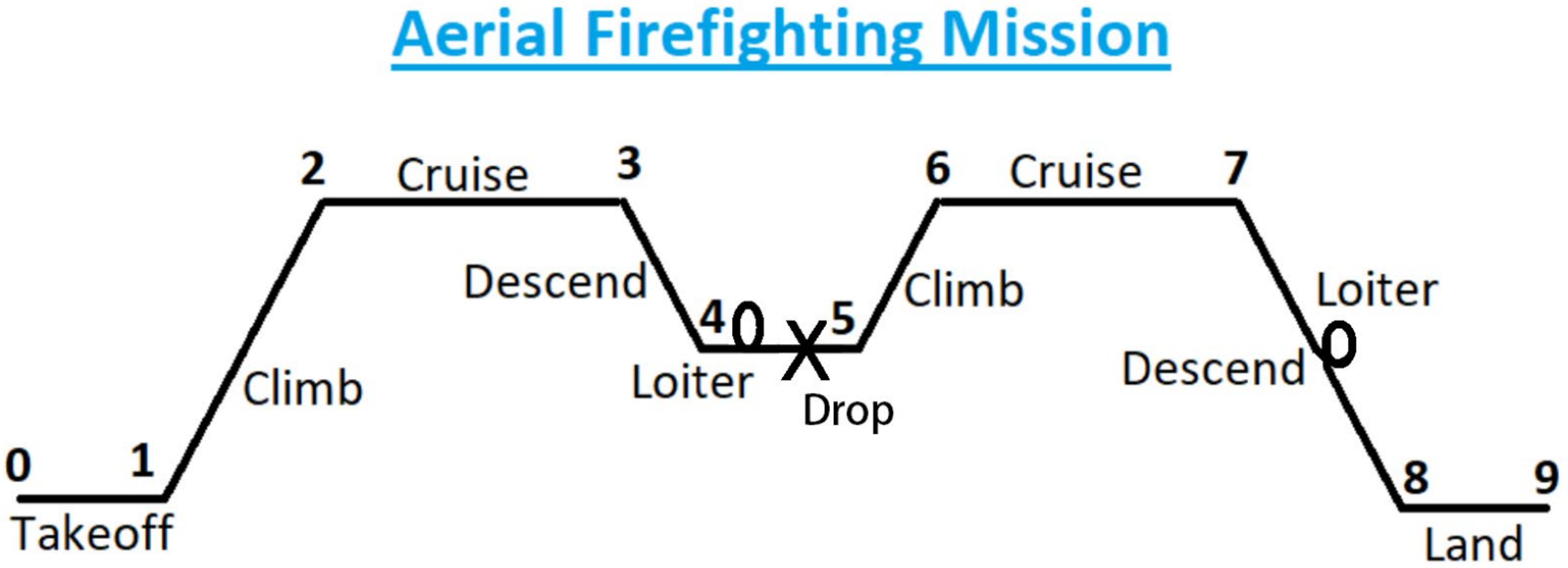
Sizing

Sizing: Ferry Mission (Graphic)



- A ferry mission was considered to relocate the aircraft closer to the fire.
- The mission profile with each profile segment labeled is displayed.

Sizing: Firefighting Mission (Graphic)



- An aerial firefighting mission was simplified for the fuel weight estimate because the method used does not allow for payload drops such as the fire-retardant.

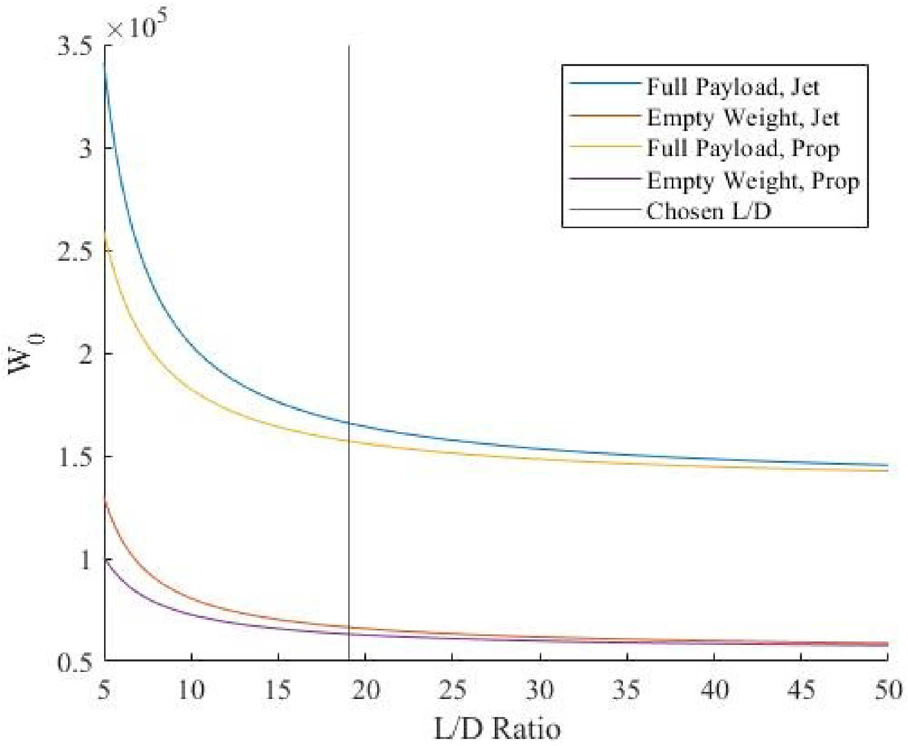
- This mission profile with each profile segment labeled is displayed.

Sizing: Weight Approximation

- An initial estimation of the aircraft's design takeoff gross weight, W_0, considered the weight of the crew, W_{crew}, the payload, $W_{payload}$, the fuel required for the mission, W_{fuel}, and the empty weight of the aircraft, W_e.
- Intermediate weights of the aircraft were summed, and iteration was required to determine the gross takeoff weight, W_0.
- An empty weight fraction, $\frac{W_e}{W_0}$, was estimated using a curve fit equation for its trend with versus W_0 for military/cargo bomber sized aircraft.
- The fractions of the aircraft's weight after each mission segment (due to fuel usage) over its weight before each segment, can be multiplied to obtain a ratio of the aircraft's weight at the end to the beginning of the mission. This was used to determine mission fuel fraction, $\frac{W_f}{W_0}$.

ESTIMATED AIRCRAFT WEIGHT

Category	Jet	Prop
T/O Weight, Drop (lb)	169548	159788
T/O Weight, Ferry (lb)	102812	85132
Empty Weight (lb)	67877	64236
Fuel Weight, Payload (lb)	29143	23018
Fuel Weight, Ferry (lb)	34333	20268

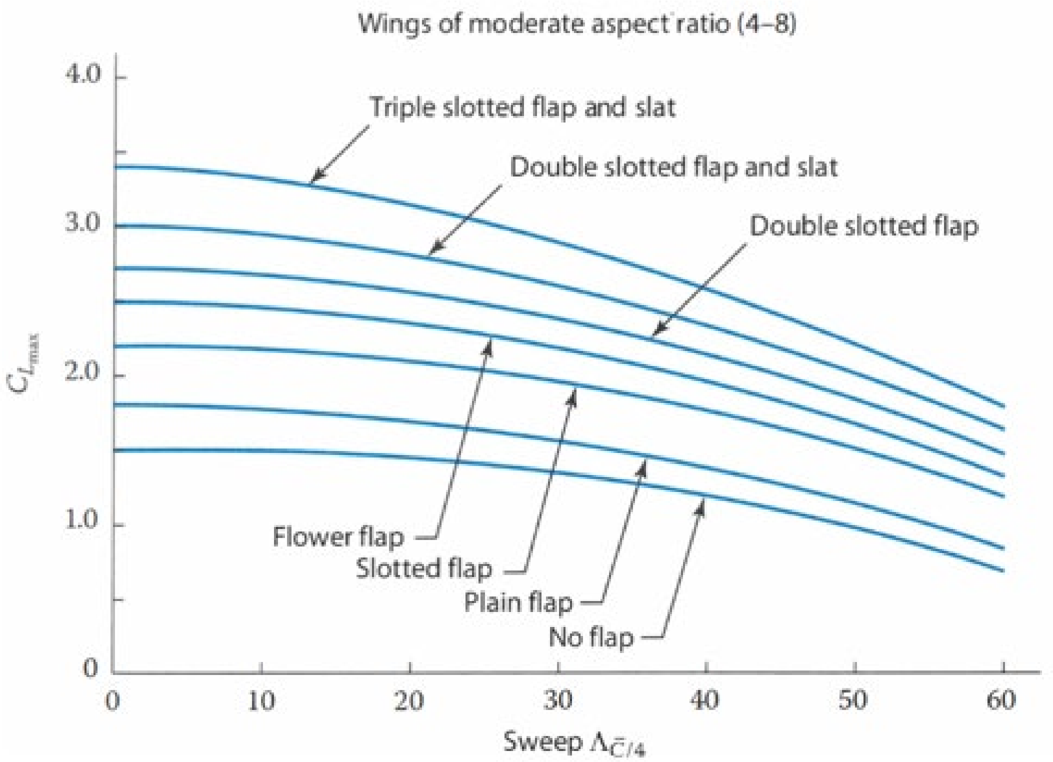


- $$W_0 = \frac{W_{crew} + W_{payload}}{\left(1 - \left(\frac{W_f}{W_0}\right) - \left(\frac{W_e}{W_0}\right)\right)}$$
- Aircraft weight values for jet and propeller configurations were estimated (see table).
- Takeoff weights with payload were found for different L/D ratios (see figure).

Wing Design

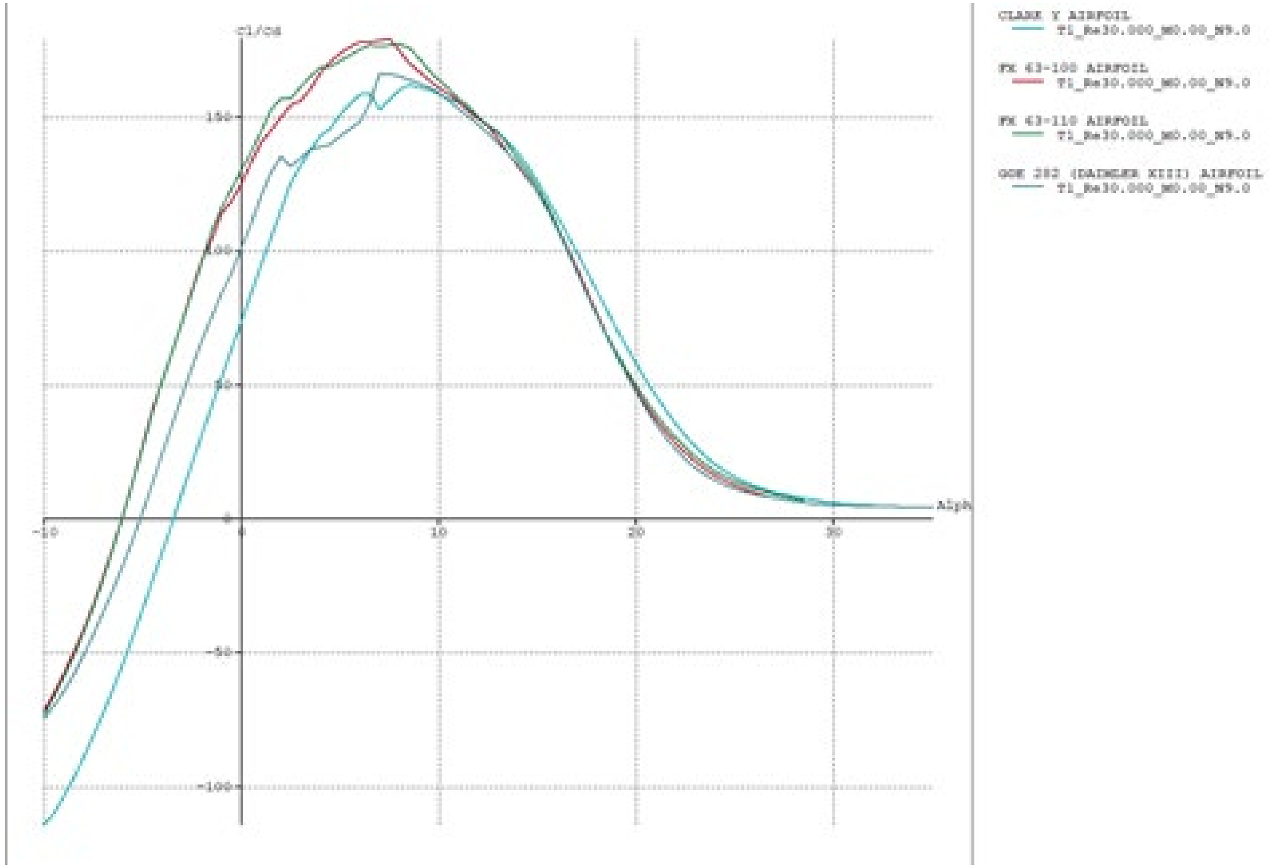
Wing Design: Wing Loading

- Wing design began with determination of the wing loading expected at stall
- Desired to have a 100 kt stall speed, and evaluated at sea level
- Flaps were desired on the aircraft, and slotted were chosen due to the simplicity over fowler, giving a coefficient of lift of 2.2
- $\frac{W}{S} = \frac{1}{2}\rho {V_{stall}}^2 C_{L_{max}} = 77.1\,\frac{lb}{ft^2}$



Wing Design: Airfoil Selection

- An FX 63-100 airfoil was chosen after an XFLR5 trade study involving multiple airfoils.
- Examined maximum Lift to Drag (L/D) ratio, the angle of attack where max L/D took place, the coefficient of drag at L/D, and the maximum coefficient of lift at stall.
- These values were analyzed in XFLR5 at a Reynolds number of 3 x10^7.



Wing Design: Wing Geometry

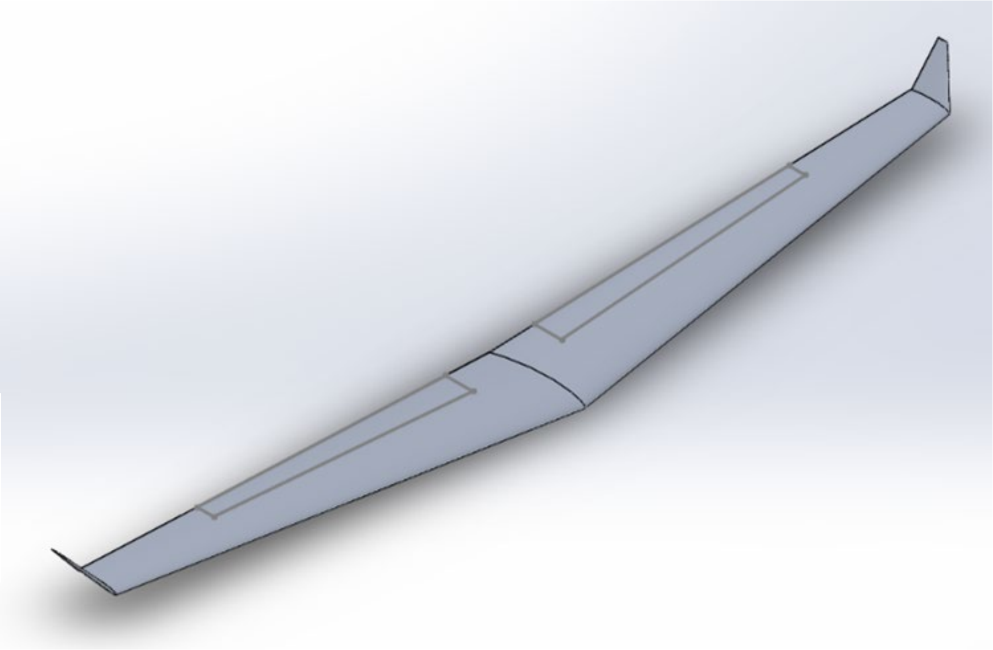
- The wing was developed after selection of the airfoil with a focus on optimizing L/D at cruise.
- Sweep, incidence angle, and dihedral were added for stability and to improve L/D in cruise.
- A mid wing layout is chosen for stability and to save on structure weight.

SUMMARY OF WING GEOMETRY	
Wingspan (with winglet)	159.41 ft
Reference Area	1861.74 ft^2
Sweep Angle	7.16°
Taper Ratio	0.405
Incidence Angle	0.0°
Wing Twist	-3.0°
Dihedral Angle	3.0°
Wing Vertical Location	Mid
Aspect Ratio (with winglet)	12.3 (14.4)
Root Chord	17.3 ft

Wing Design: Wing Geometry

- A winglet is present on the wing to reduce wingtip drag effects.
- The winglet was designed in XFLR5, varying span, taper, and winglet dihedral to affect wing L/D

SUMMARY OF WINGLET GEOMETRY	
Winglet Span	7.5 ft
Taper Ratio	0.24
Winglet Dihedral	50°



Wing Design: High Lift Devices

- Following creation of the wing, it is expected from XFLR5 analysis that the wing should have a max C_L of 2.0
- To meet landing requirements, the C_L needs to be 2.7 or higher. To meet this increase, slotted flaps were used with a ratio of flap area to wing area of 70%

SUMMARY OF FLAP GEOMETRY	
Flapped Area Ratio*	0.70
Hinge Line Sweep Angle	8.38°
Inboard Chord	4.87 ft
Outboard Chord	3.00 ft
Span**	45.3 ft
Spanwise Location***	0.107

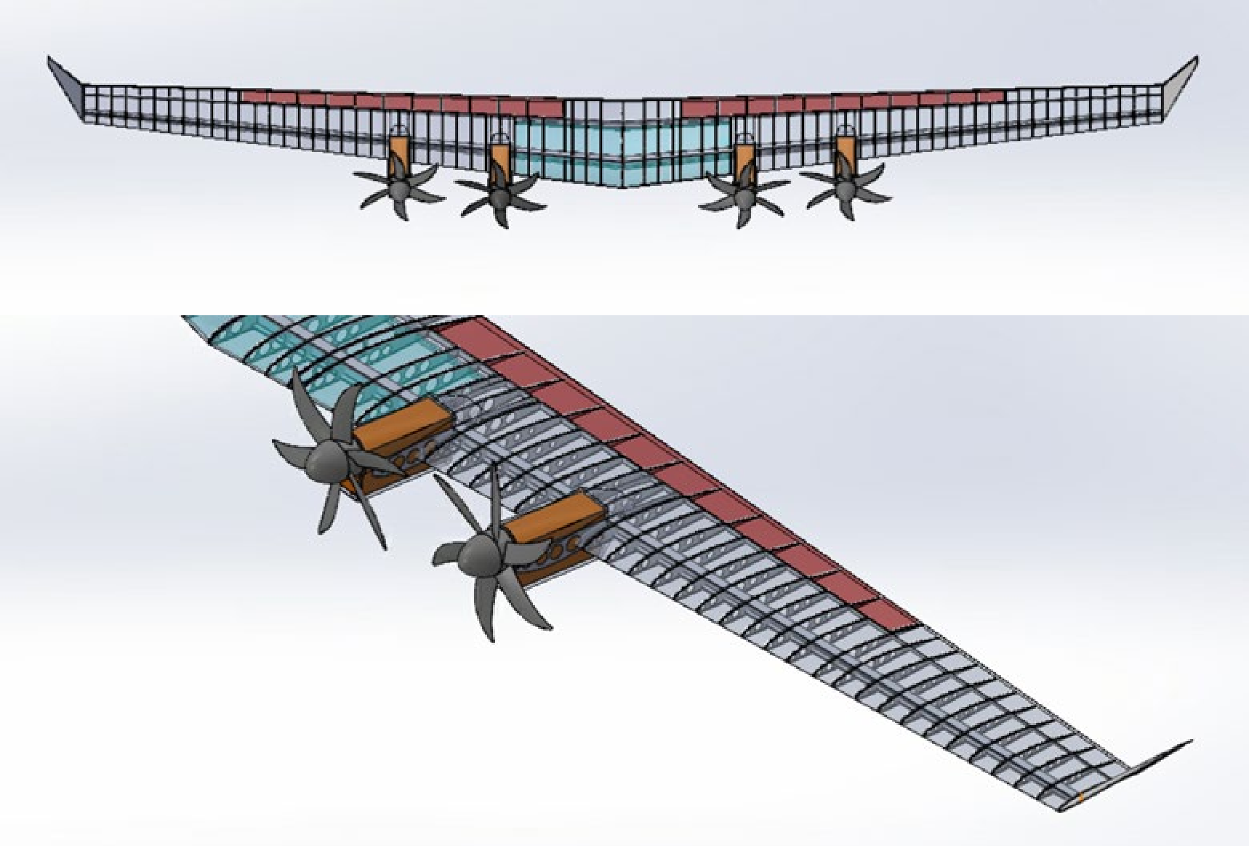
*Flapped Area Ratio defined as ${}^{S_{flapped}}/_{S_{ref}}$

**Span defined as the span of a single flap

**Spanwise location defined as the location of the inboard edge of the flap measured from the wing root as a fraction of the semispan

Wing Structural Analysis

- Material trade study was performed and determined that the ribs should be made from 2024-T4 Aluminum, while the wing spars should be composed of 7075-T6 Aluminum.
- A mechanics of Materials approach was used to size the spar as an I-beam, with analysis performed in MATLAB to vary spar heights, widths, and thickness to meet the minimum weight while having a 1.5 factor of safety.
- The wing was designed to handle a load factor of 5 as a focus for crew survivability.



Wing Structural Analysis

- The aft torsional spar is located immediately forward of the flaps and simply sized as a rectangular beam to say on computational time.
- Part of the torsional load is also carried by a carbon fiber skin.
- Wing ribs were modeled as being airfoil shaped I-beams, with flanges 2 in wide and flange and shear web thickness' of 1/8 in. Height varies with wing location.

SUMMARY OF PRIMARY SPAR GEOMETRY	
Spar Height (Root/Tip), inches	18 / 7.5
Spar Flange Width (Root/Tip), inches	12.1 / 12.1
Spar Flange Thickness (Root/Tip), inches	1.57 / 1.57
Spar Shear Web Thickness, inches	0.17
SUMMARY OF TORSIONAL SPAR GEOMETRY	
Spar Height (Root/Tip), inches	6.75 / 2.25
Spar Width, inches	0.5

Propulsion

Engine Selection

- Engine Type: Turboprop
- Power requirement from initial sizing: 20,000 Hp
- Design Considerations

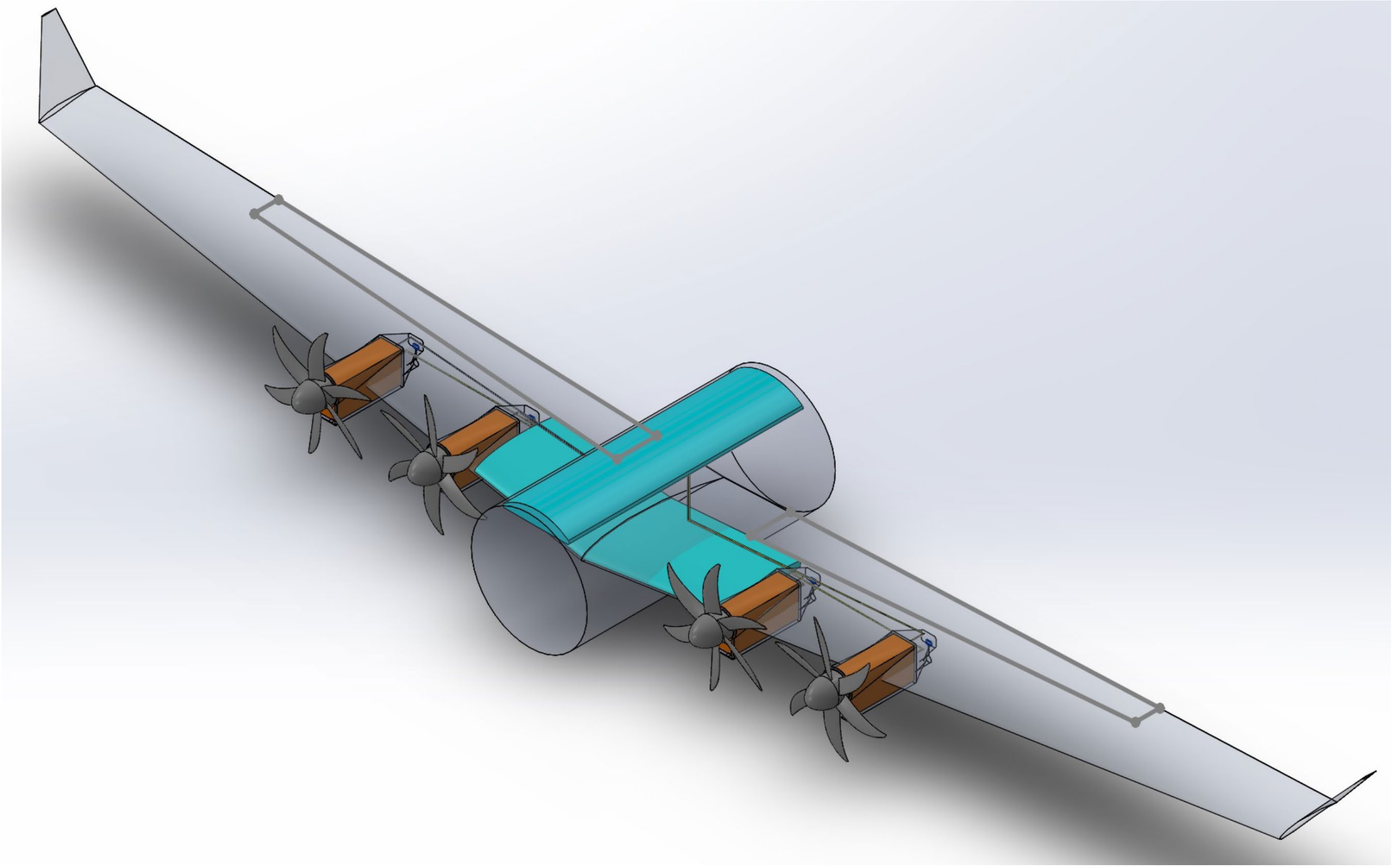
Selected Engine Configuration

- Four Pratt & Whitney 150 Turboprop Engines
- 6 blade Dowty R408 type propellor with a 13.5 ft diameter

Fuel System

- Discrete Fuel Tanks
- 610 cubic feet fuel capacity
  - Wing tank: 317 cubic feet
  - Fuselage tank: 293 cubic feet
- Jet A-1 fuel
- Fuel weight: 23,618 pounds

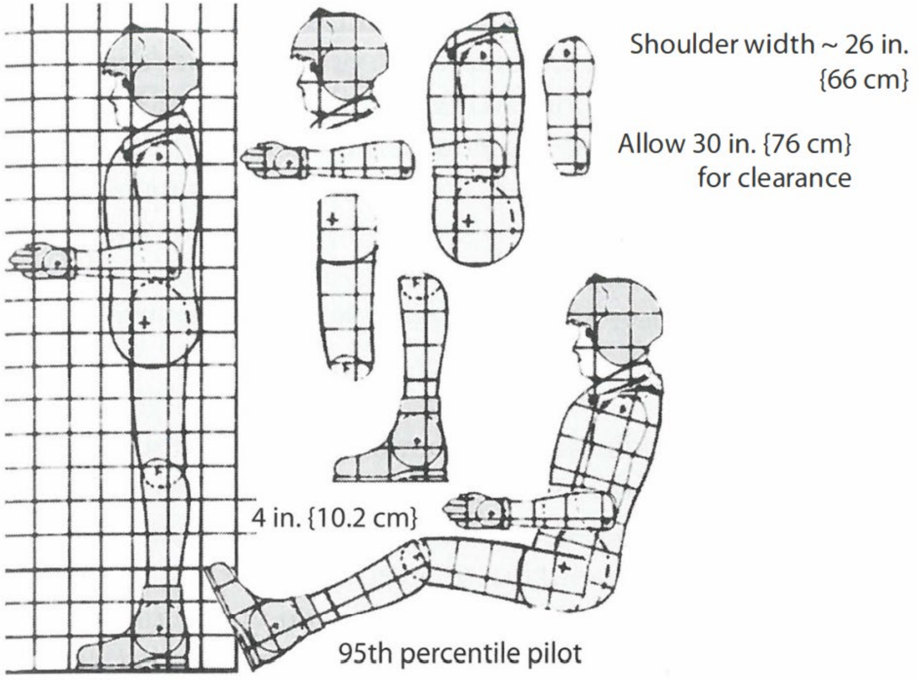
Fuel System



Crew Stations and Avionics

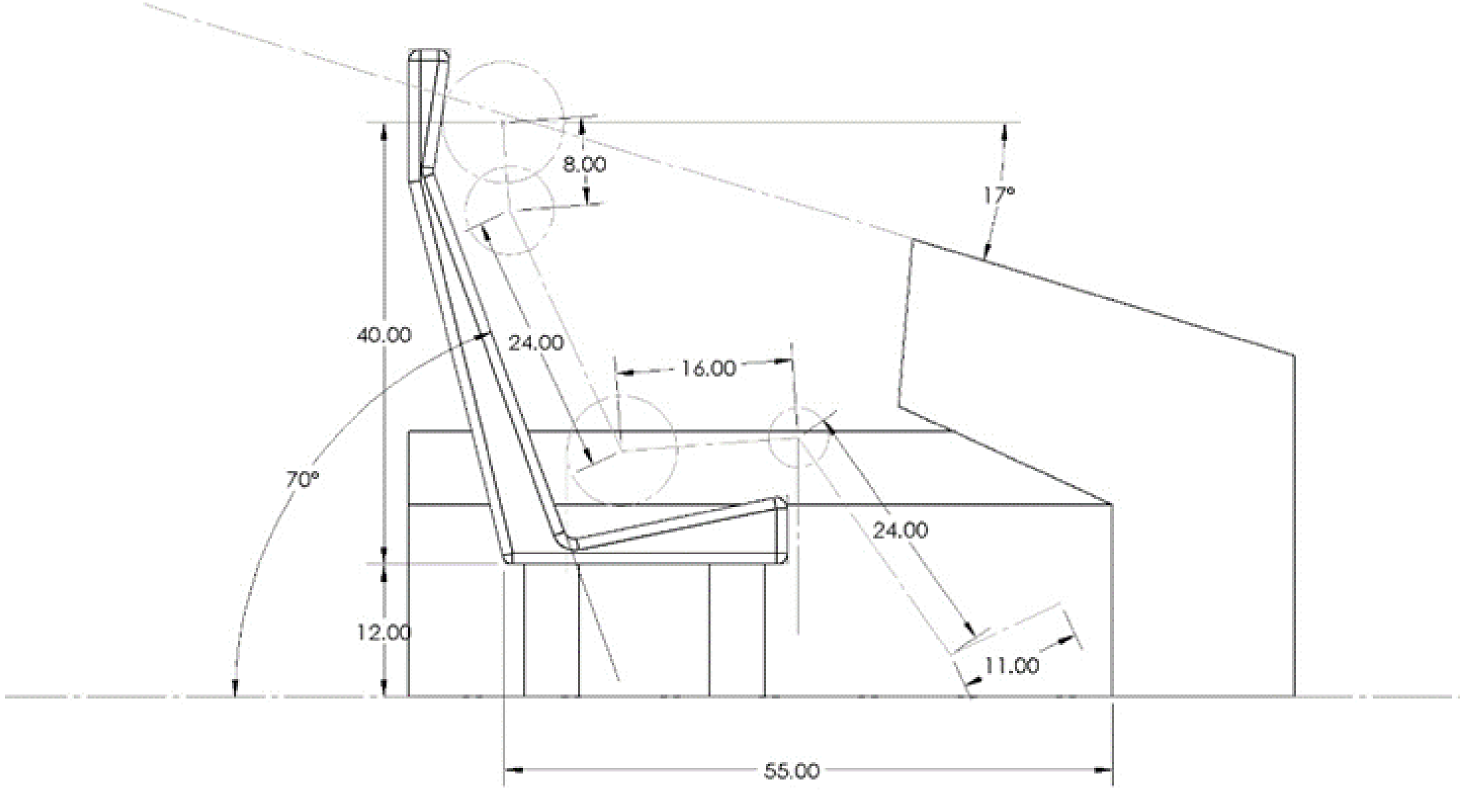
Crew Station Design Considerations

- Pilot and Co-Pilot Station
- Flight Engineer Station
- Lavatory
- Accommodate the 95th Percentile Pilot comfortably
- Adequate range of vision
- Plenty of room for avionics and equipment



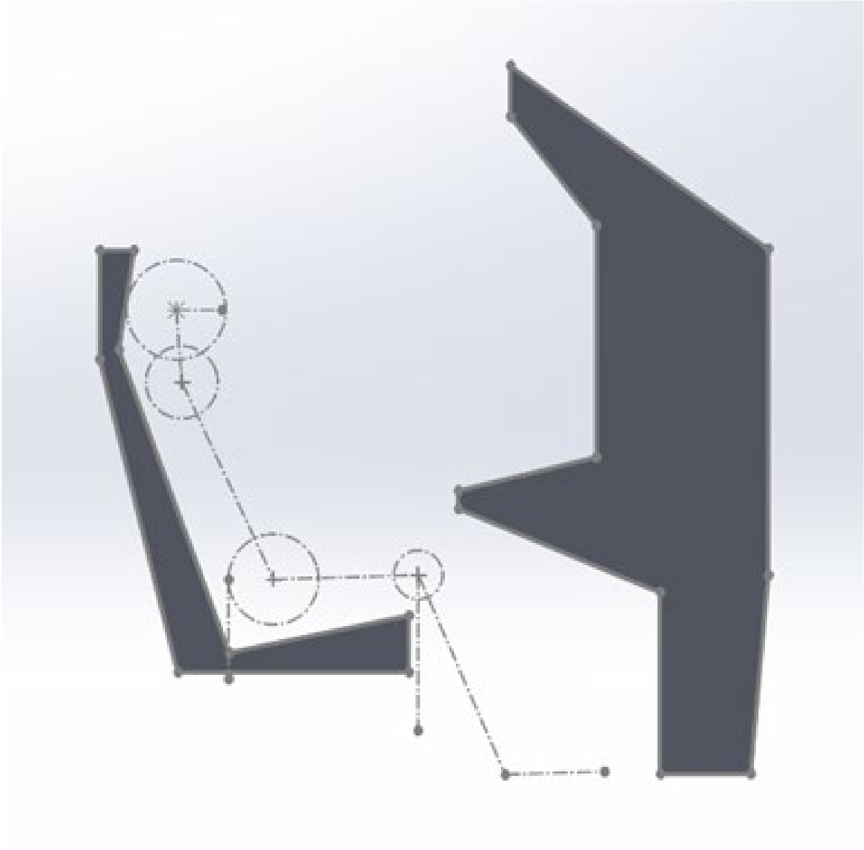
Pilot and Co-Pilot Station

- Seating for the pilot, co-pilot and avionics panel.



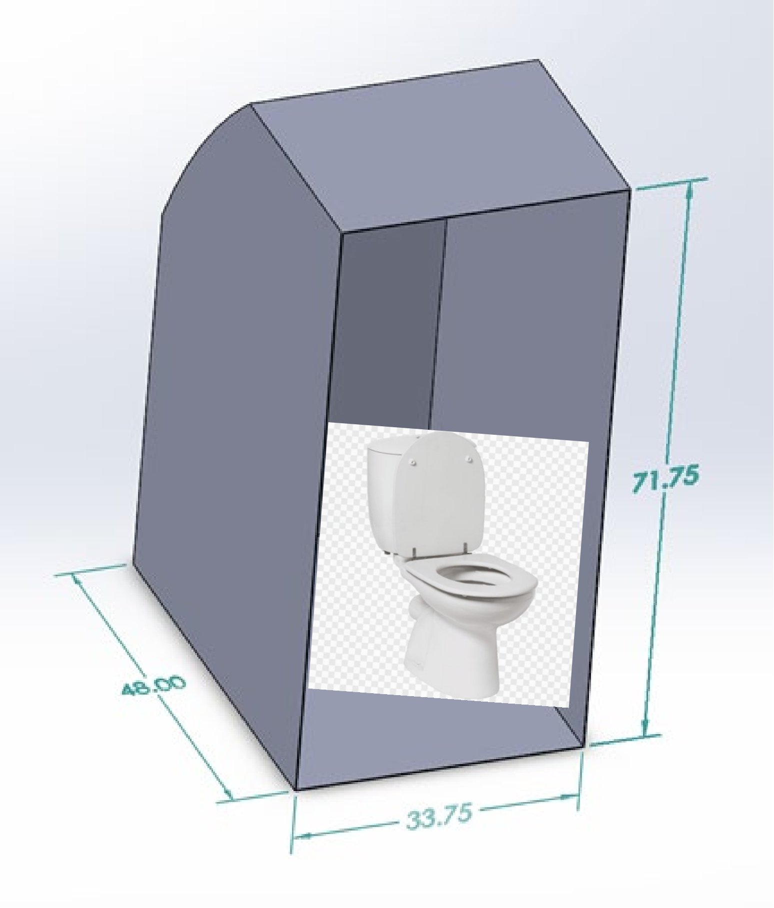
Flight Engineer Station

- Seating for flight engineer and instrument panel.

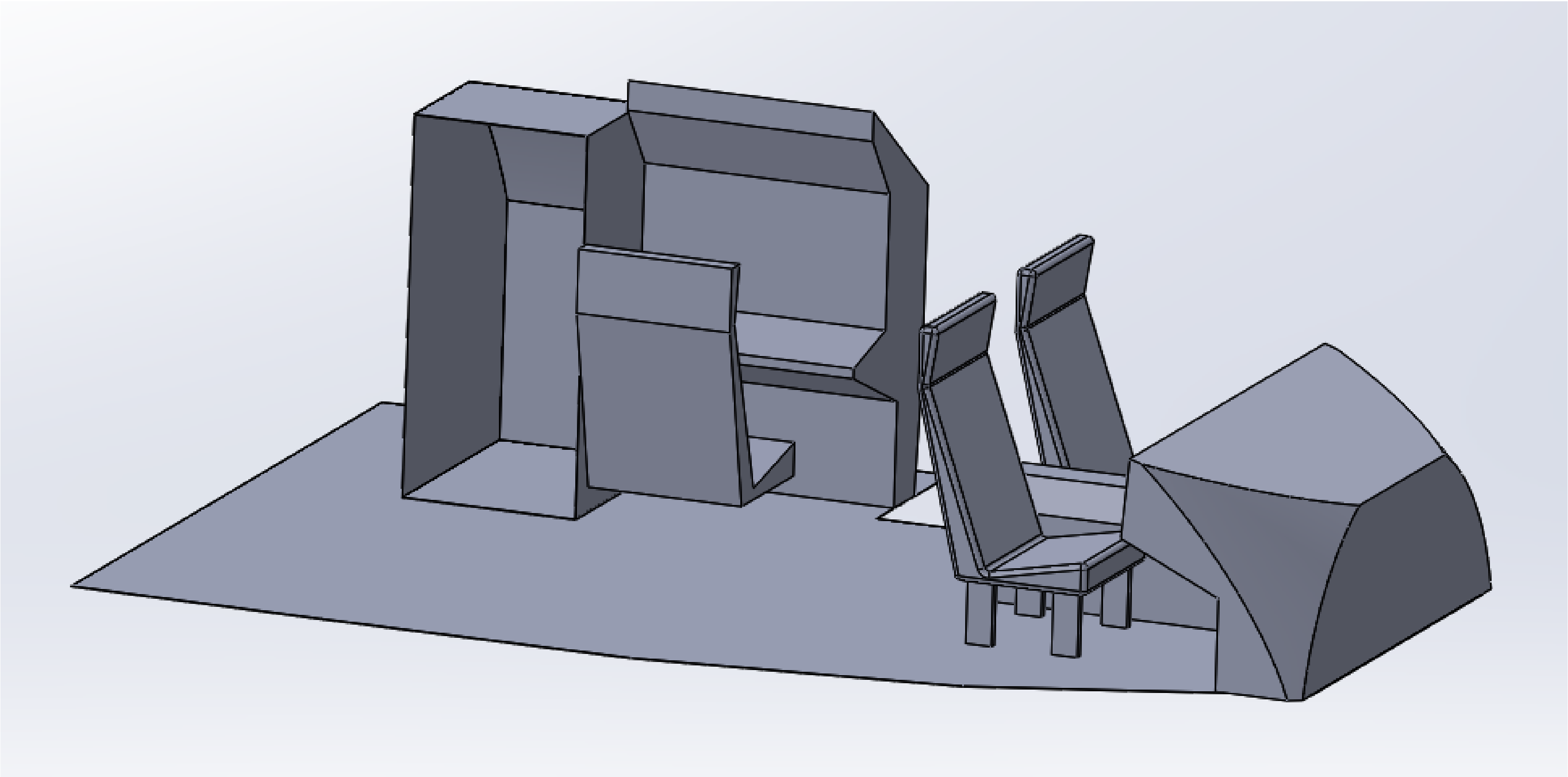


Lavatory

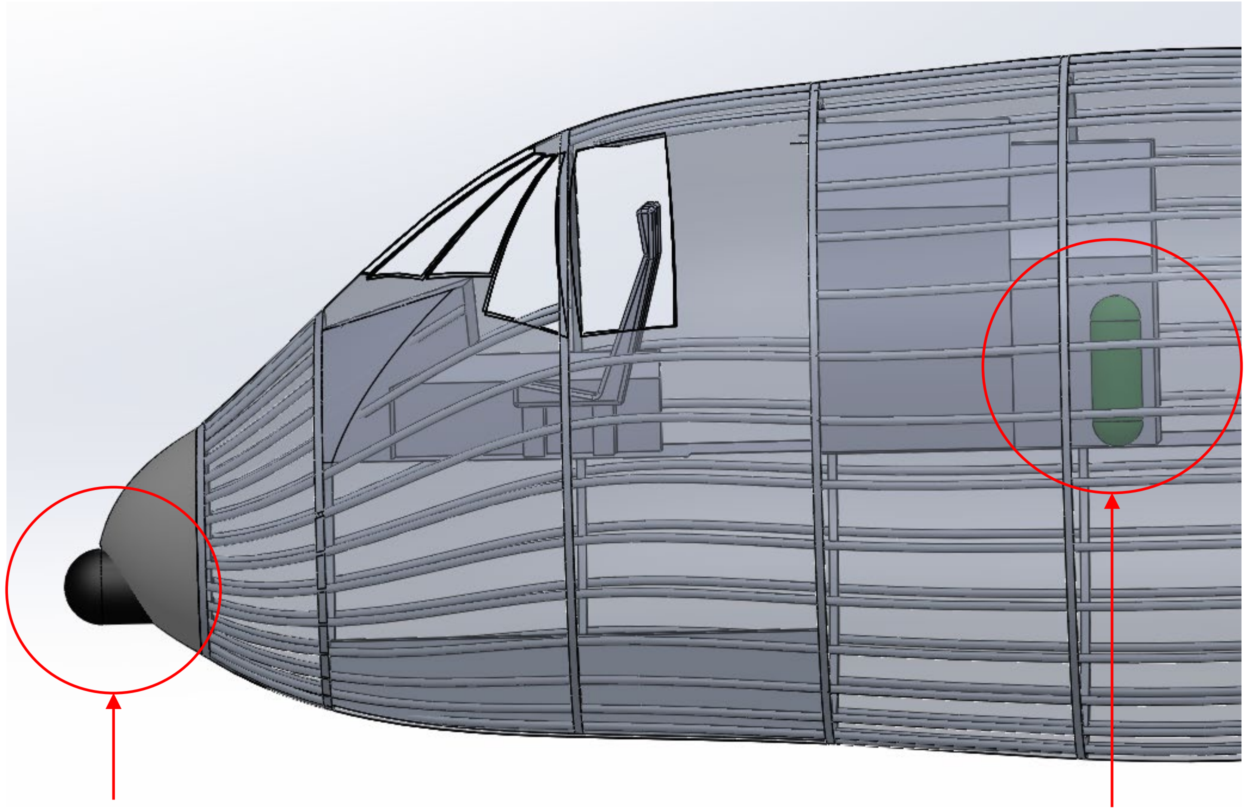
- Nature calls



Crew Station Layout



Avionics and Equipment



AN/APQ-187 Radar

Portable Oxygen Tank

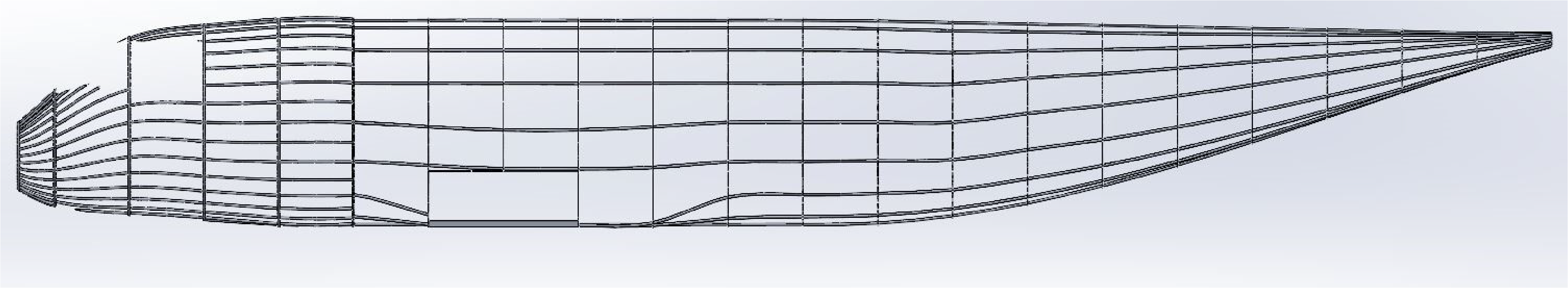
Honeywell 131-9A APU

Fuselage Design

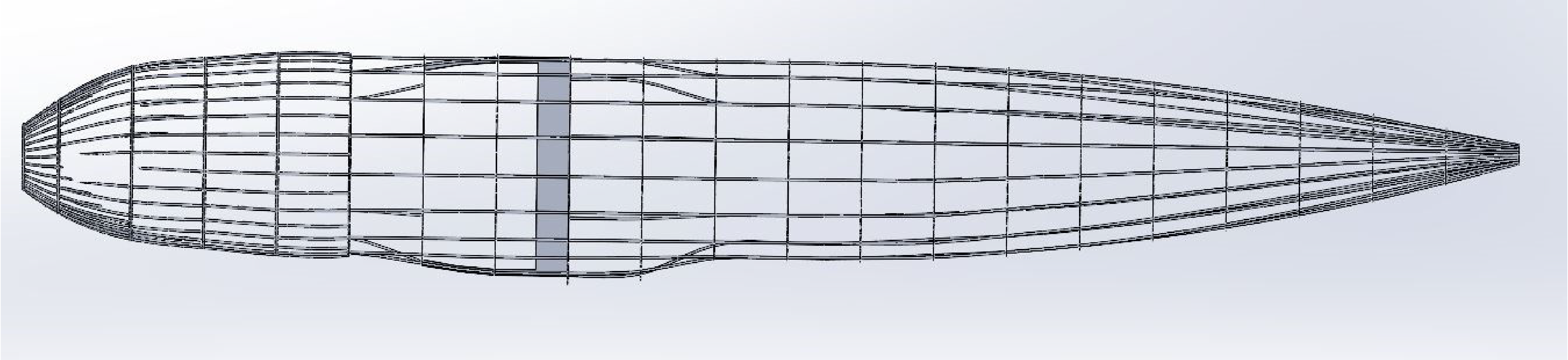
Fuselage Design

- Initial fuselage design based on existing similarly sized aircraft, RFP implications
  - 106 ft long, 14 ft wide
  - Width was influenced by the size of the tanks needed for the 8000 gal of fire retardant
  - Length was influenced by wanting a far back tail to help improve stability
- Design changed as items inside the fuselage became realized
  - Crew station and radar necessitated an updated nose
  - Main landing gear necessitated fairings on the side to house them

Fuselage Design



Side view of fuselage

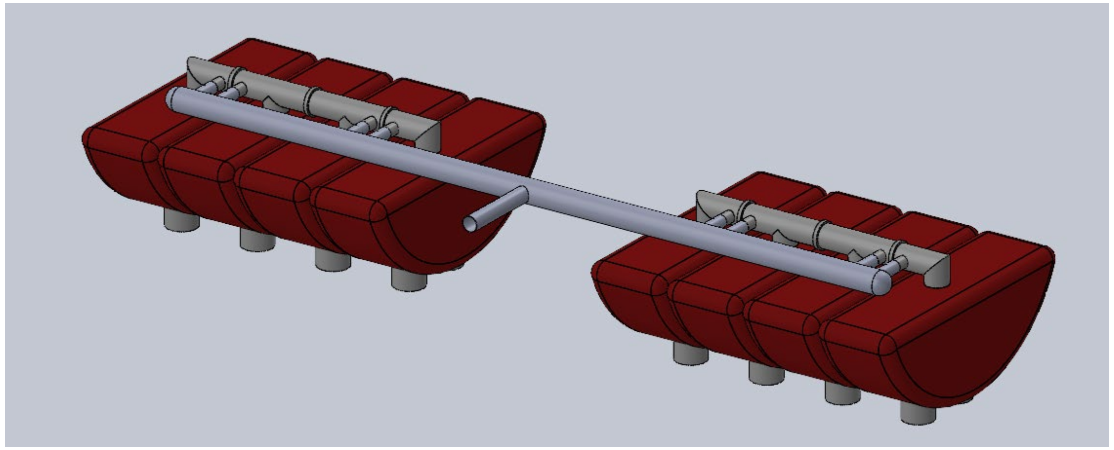


Top view of fuselage

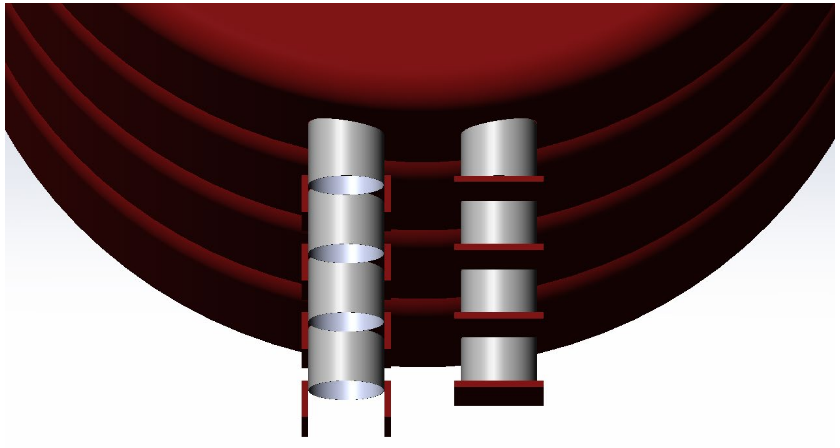
Fire Retardant Drop Mechanism

- Retardant is stored in 8 semicircular tanks of 1000 gallons each along the length of the fuselage
  - Separated into 2 sets of 4 tanks, each set mounted fore and aft of the main landing gear respectively
  - Tanks are connected by a single pipe system above the tanks, with a loading port on the side which fills all the tanks at once on the ground
- Retardant is dropped from doors at the bottom of each tank
  - Drop time is 1s for one tank, but each tank is independent so all tanks can drop in 1s simultaneously
  - During a standard 2000 gal drop, a pair of tanks, one from the forward set, one from the aft set, equidistant from the landing gear, are used to maintain aircraft cg

Fire Retardant Drop Mechanism



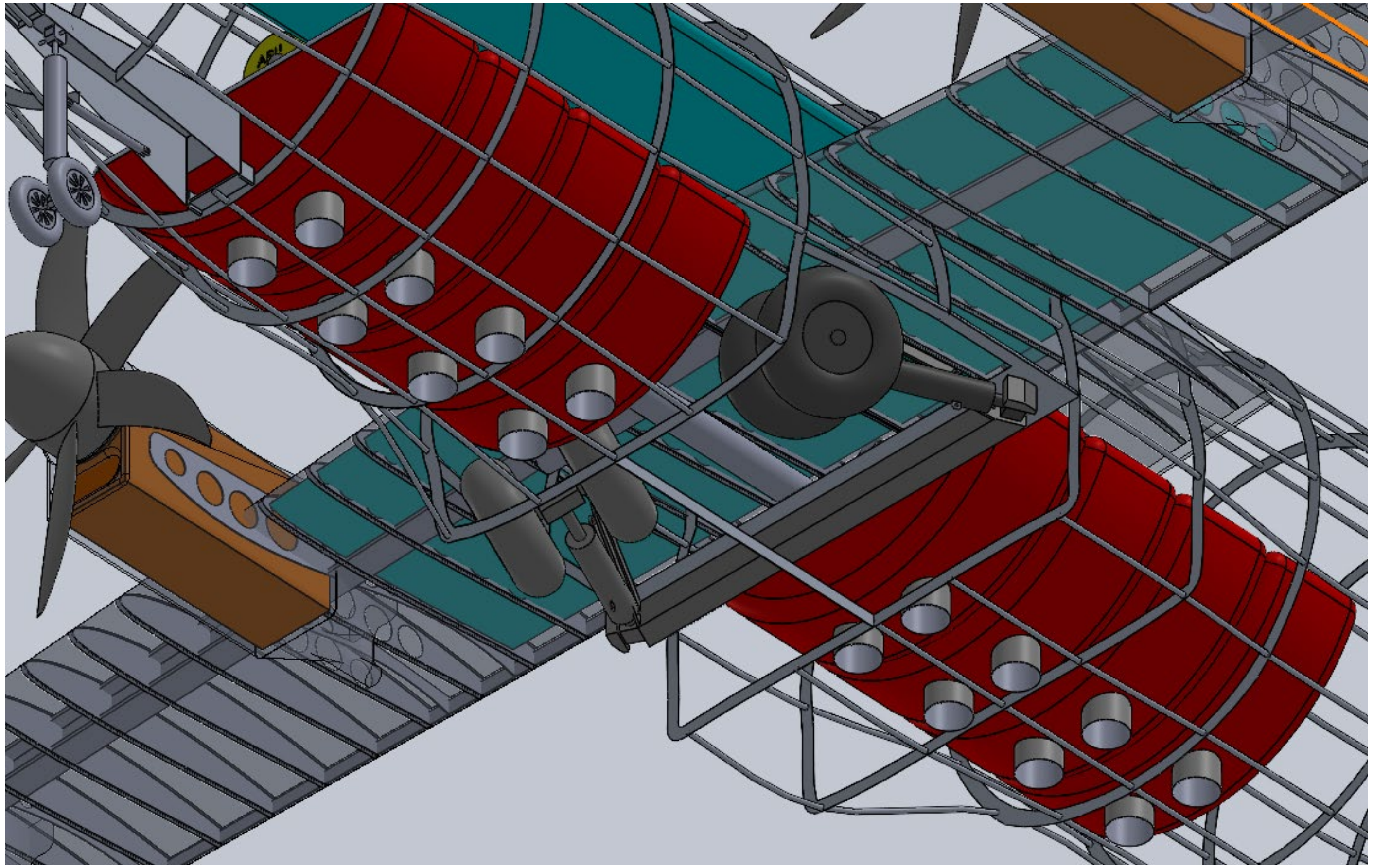
Isometric view of retardant tank system



View of drop hatches at the bottom of the retardant tanks, left doors are open, right doors are closed

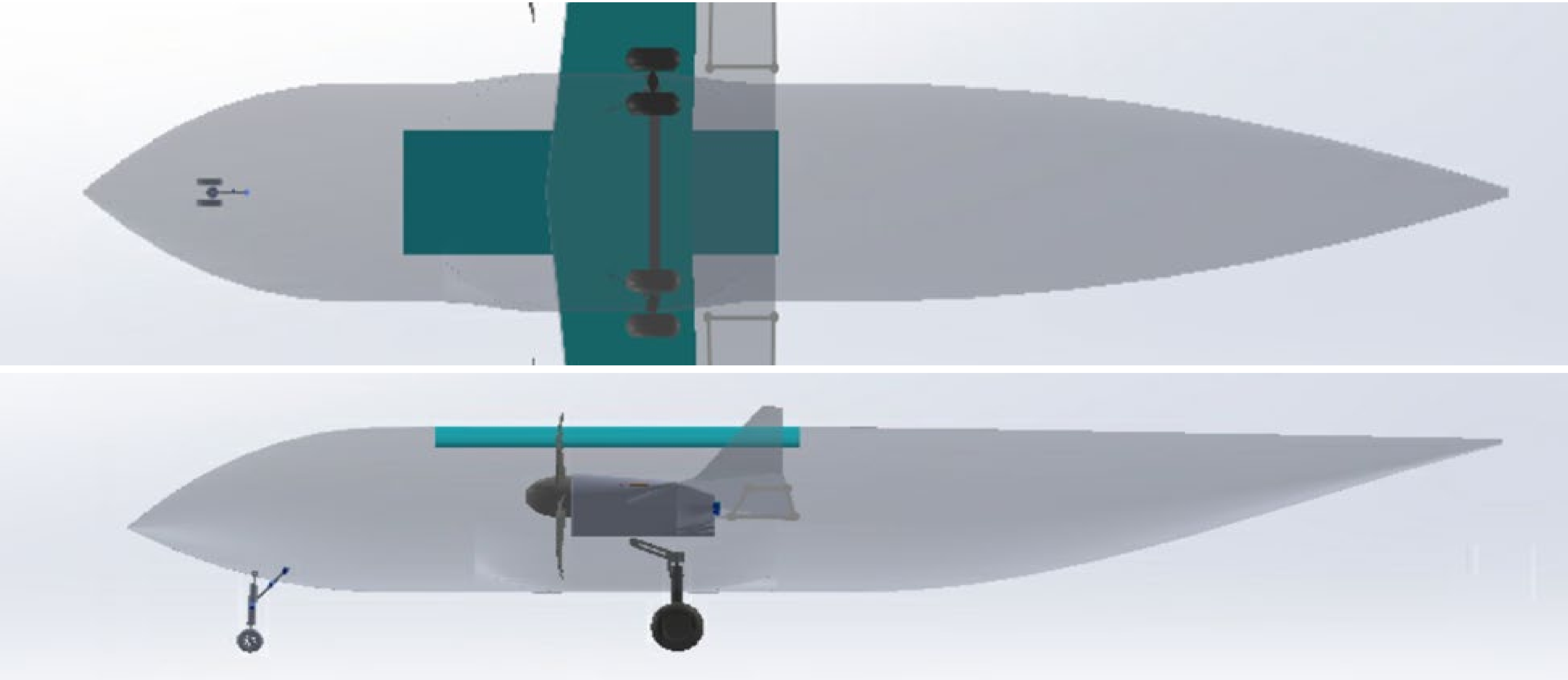
Fire Retardant Drop Mechanism

Orientation of retardant
tanks within fuselage

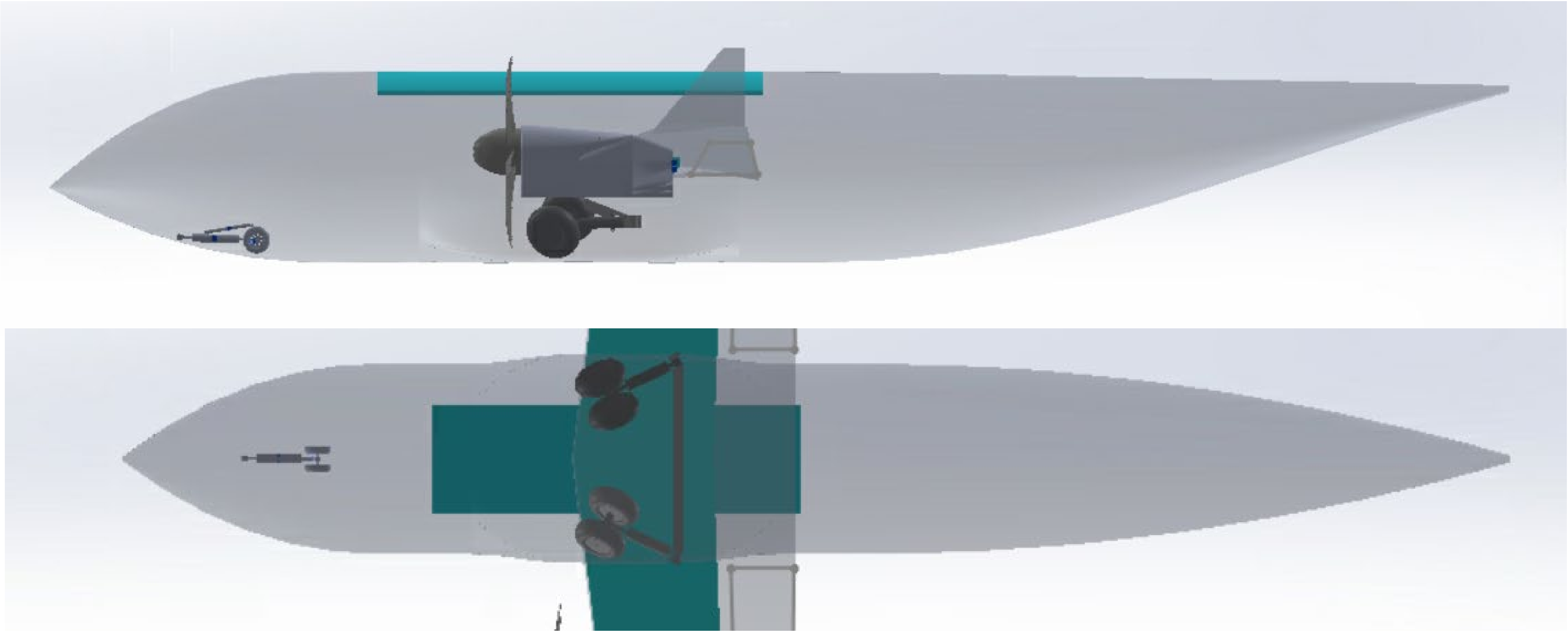


Landing Gear

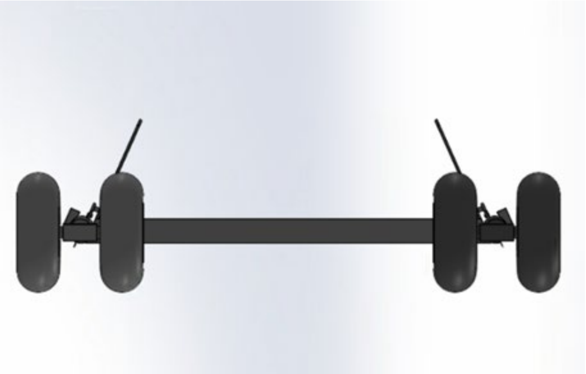
Landing Gear



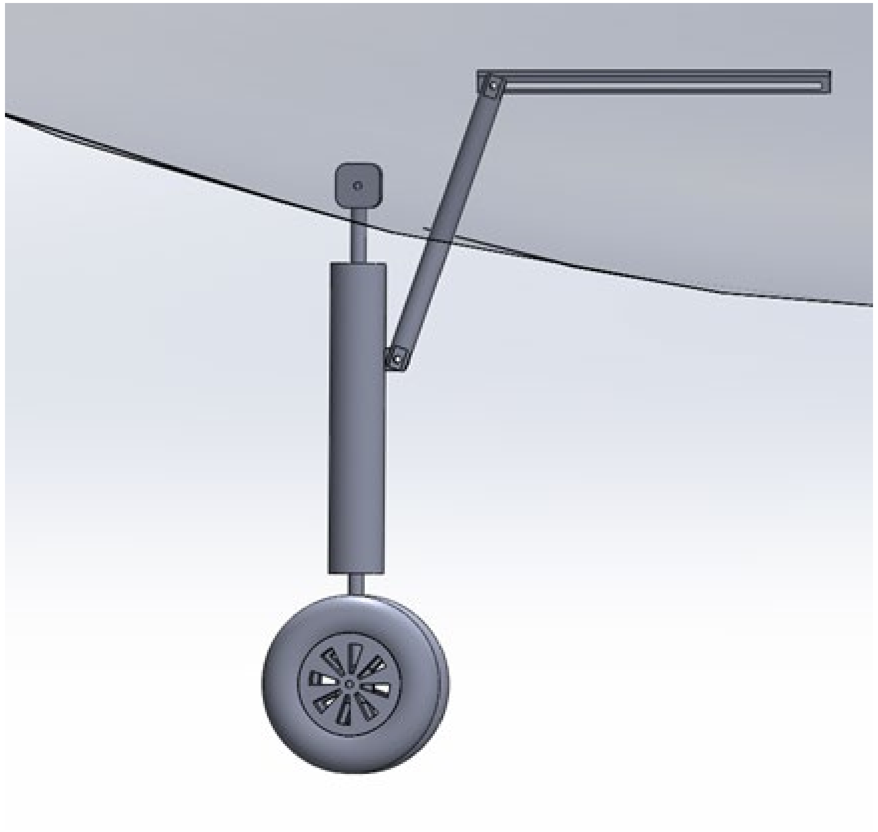
Retracted View in Fuselage

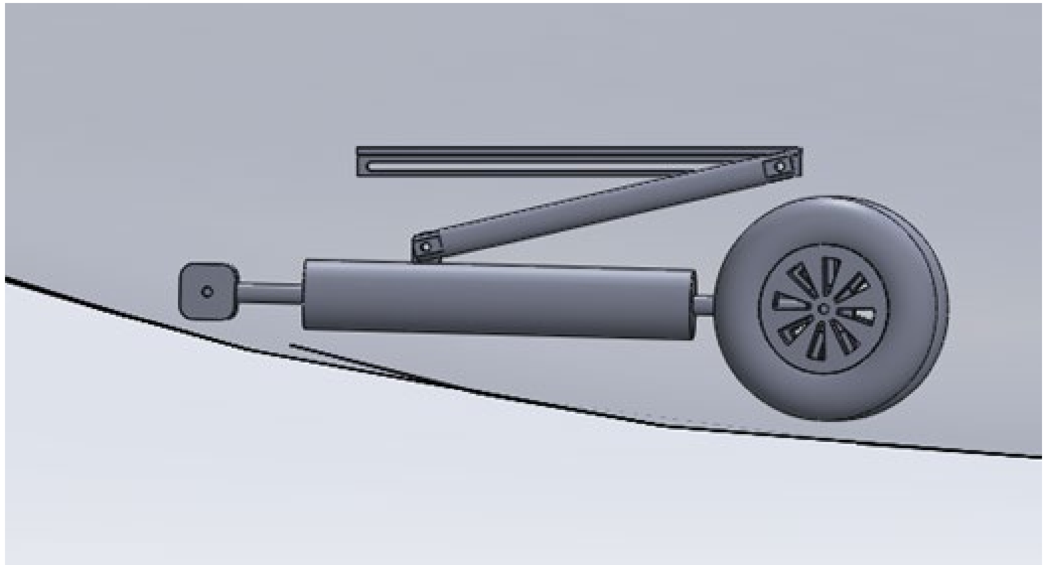


Main Gear

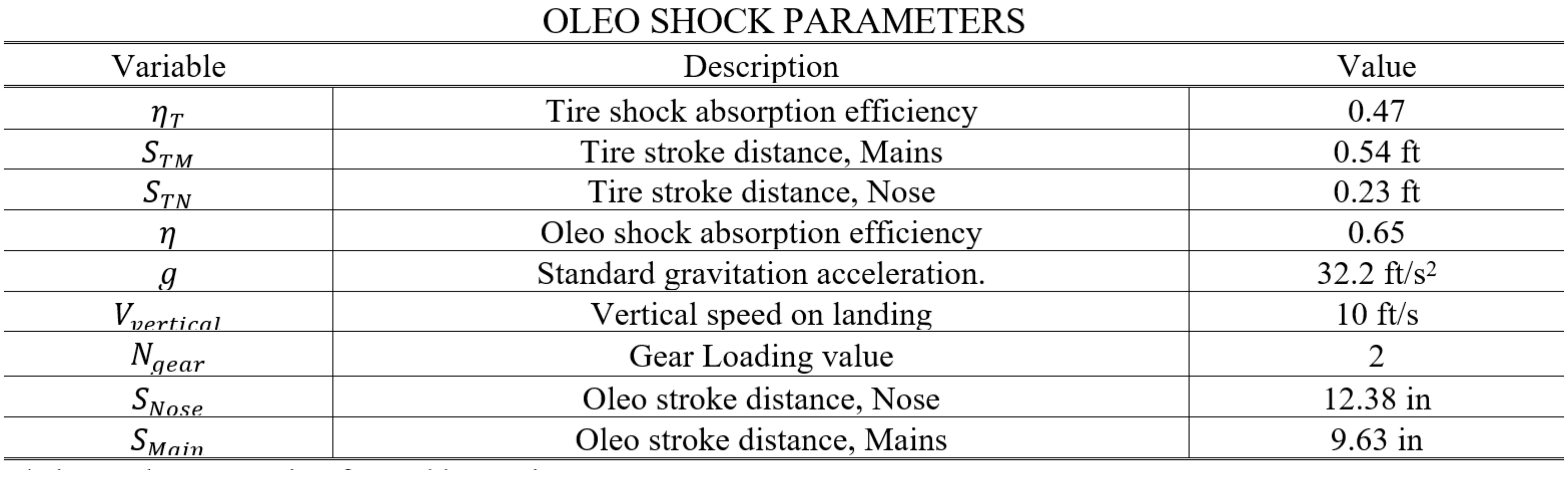


Nose Gear





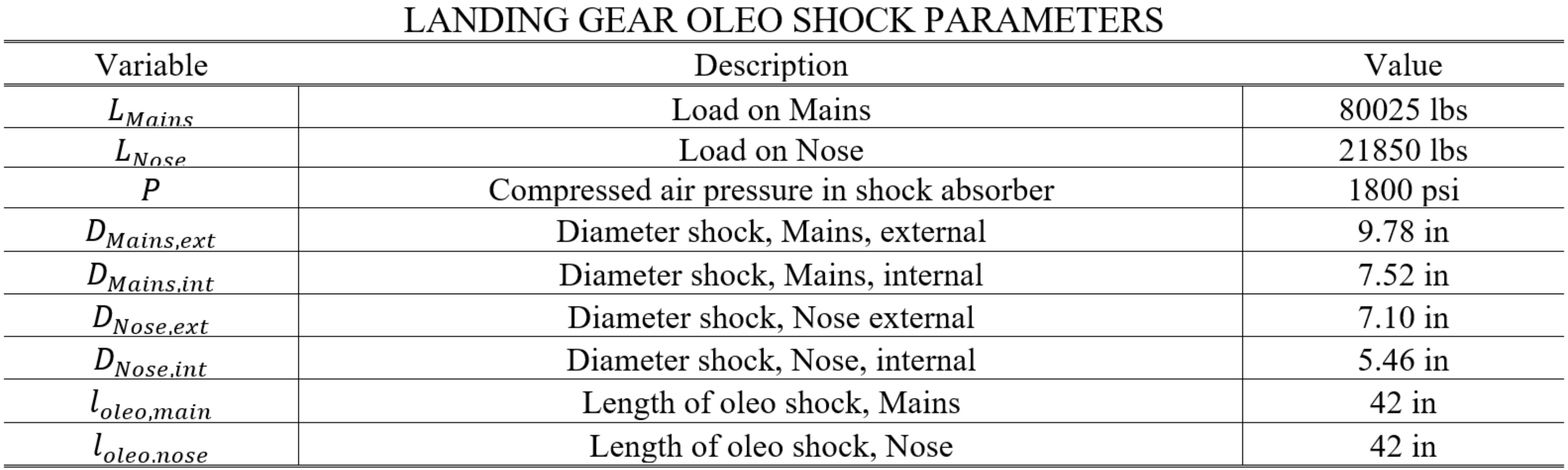
Oleo Shock Parameters



OLEO SHOCK PARAMETERS

Variable	Description	Value
η_T	Tire shock absorption efficiency	0.47
S_{TM}	Tire stroke distance, Mains	0.54 ft
S_{TN}	Tire stroke distance, Nose	0.23 ft
η	Oleo shock absorption efficiency	0.65
g	Standard gravitation acceleration.	32.2 ft/s^2
$V_{vertical}$	Vertical speed on landing	10 ft/s
N_{gear}	Gear Loading value	2
S_{Nose}	Oleo stroke distance, Nose	12.38 in
S_{Main}	Oleo stroke distance, Mains	9.63 in

Landing Gear Oleo Shock Parameters



LANDING GEAR OLEO SHOCK PARAMETERS

Variable	Description	Value
L_{Mains}	Load on Mains	80025 lbs
L_{Nose}	Load on Nose	21850 lbs
P	Compressed air pressure in shock absorber	1800 psi
$D_{Mains,ext}$	Diameter shock, Mains, external	9.78 in
$D_{Mains,int}$	Diameter shock, Mains, internal	7.52 in
$D_{Nose,ext}$	Diameter shock, Nose external	7.10 in
$D_{Nose,int}$	Diameter shock, Nose, internal	5.46 in
$l_{oleo,main}$	Length of oleo shock, Mains	42 in
$l_{oleo,nose}$	Length of oleo shock, Nose	42 in

Wheel Sizing

$$Max\ Static\ Load = W\frac{N_a}{B}$$

$$(Max\ Static\ Load)_{nose} = W\frac{M_f}{B}$$

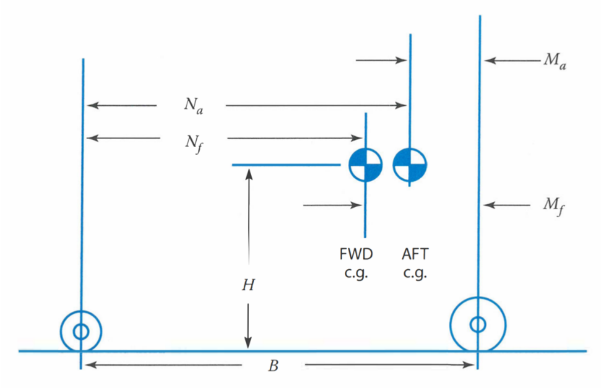
$$(Min.Static\ Load)_{nose} = W\frac{M_a}{B}$$

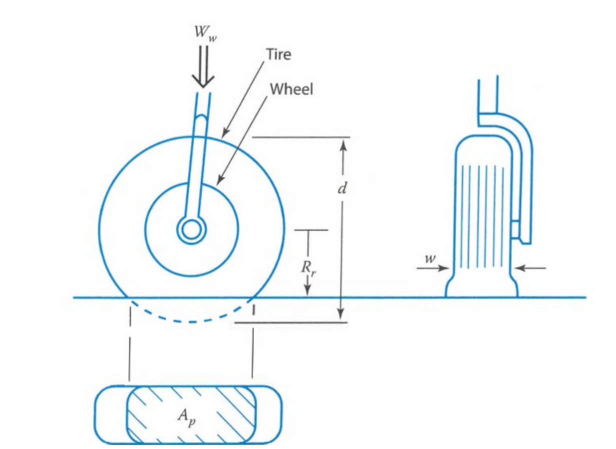
$$(Dynamic\ Braking\ Load)_{nose} = \frac{10HW}{gB}$$

$$R_r = r - \frac{d}{3}\,[4]$$

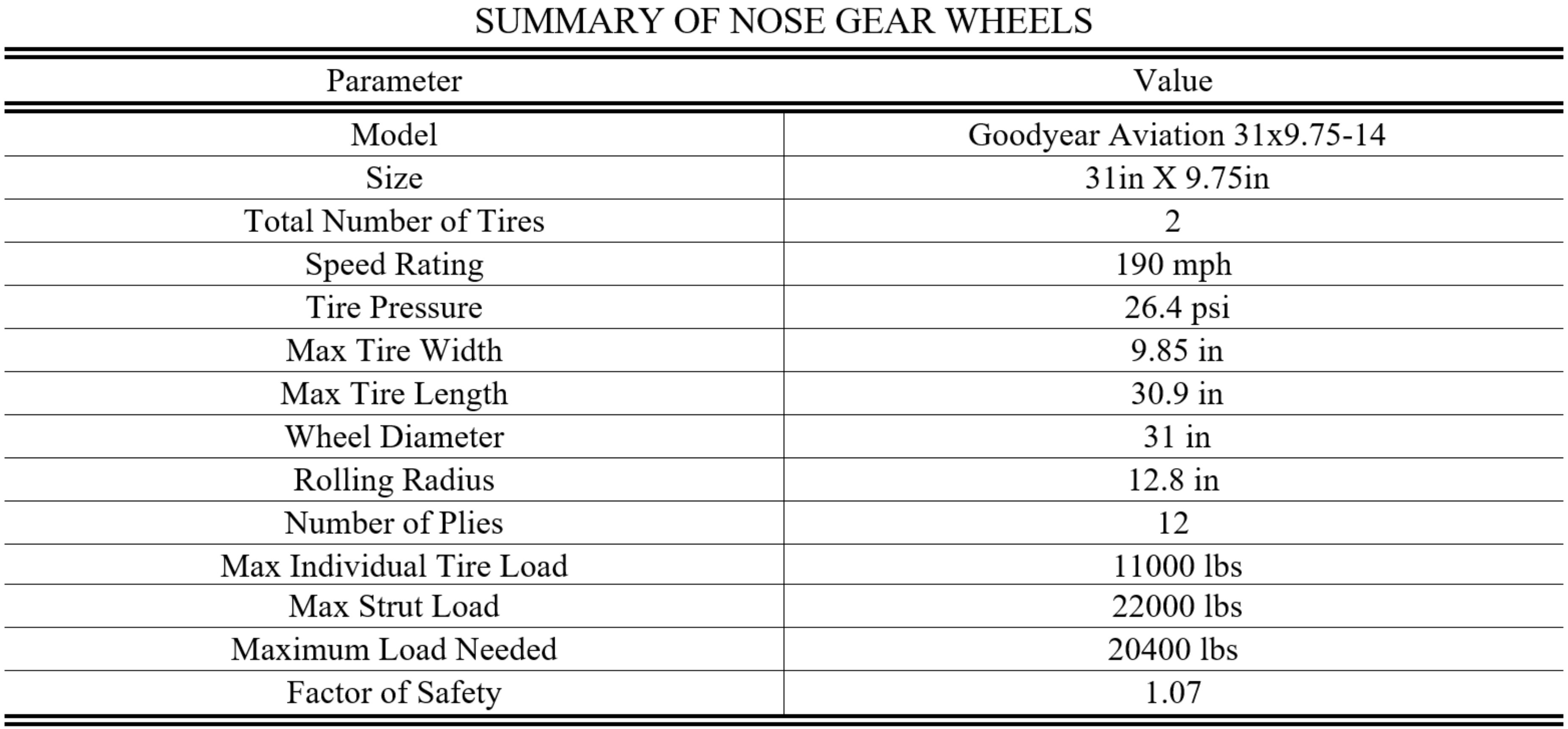
$$W_w = PA_p$$

$$A_p = 2.3\sqrt{wd} \times (\frac{d}{2} - R_r)$$





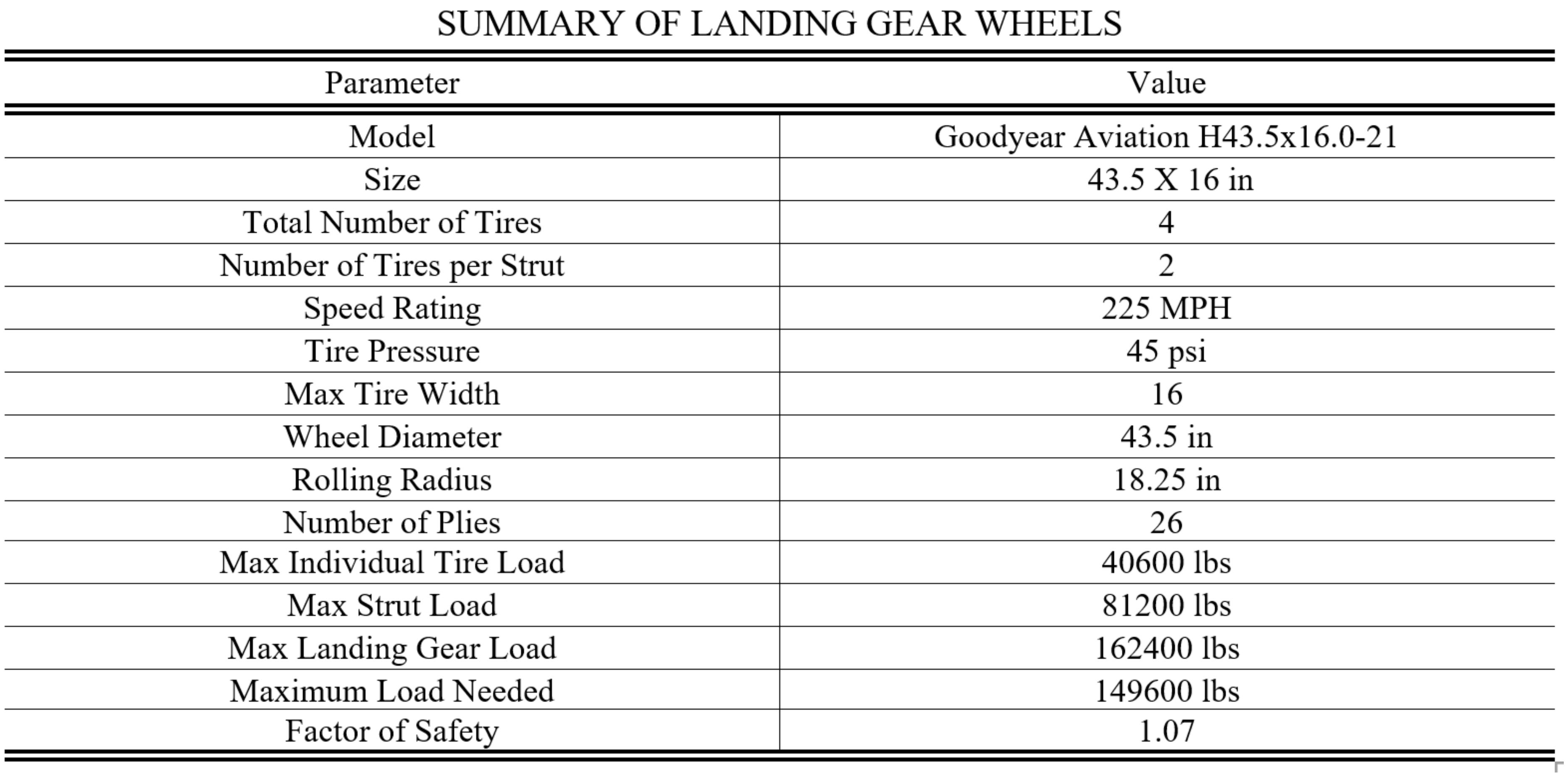
Nose Gear Wheel Sizing



SUMMARY OF NOSE GEAR WHEELS

Parameter	Value
Model	Goodyear Aviation 31x9.75-14
Size	31in X 9.75in
Total Number of Tires	2
Speed Rating	190 mph
Tire Pressure	26.4 psi
Max Tire Width	9.85 in
Max Tire Length	30.9 in
Wheel Diameter	31 in
Rolling Radius	12.8 in
Number of Plies	12
Max Individual Tire Load	11000 lbs
Max Strut Load	22000 lbs
Maximum Load Needed	20400 lbs
Factor of Safety	1.07

Landing Gear Wheel Sizing



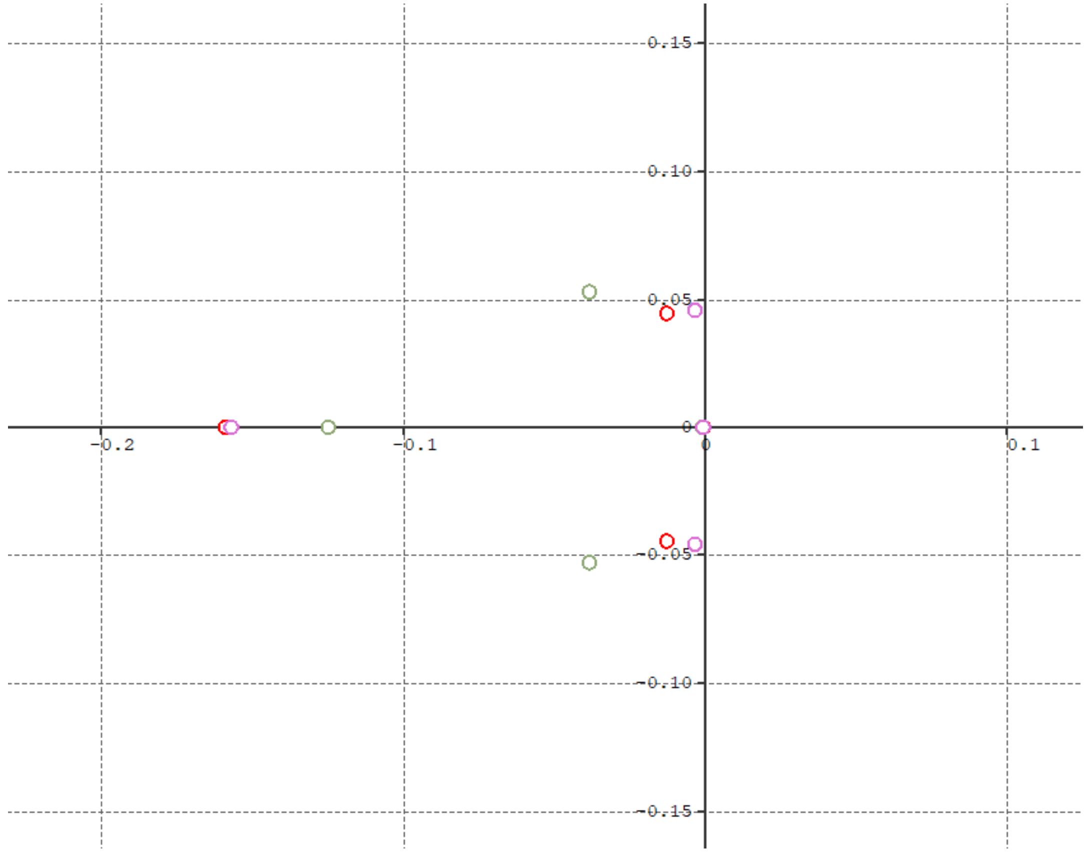
SUMMARY OF LANDING GEAR WHEELS

Parameter	Value
Model	Goodyear Aviation H43.5x16.0-21
Size	43.5 X 16 in
Total Number of Tires	4
Number of Tires per Strut	2
Speed Rating	225 MPH
Tire Pressure	45 psi
Max Tire Width	16
Wheel Diameter	43.5 in
Rolling Radius	18.25 in
Number of Plies	26
Max Individual Tire Load	40600 lbs
Max Strut Load	81200 lbs
Max Landing Gear Load	162400 lbs
Maximum Load Needed	149600 lbs
Factor of Safety	1.07

Tail and Control Surfaces

Tail Design

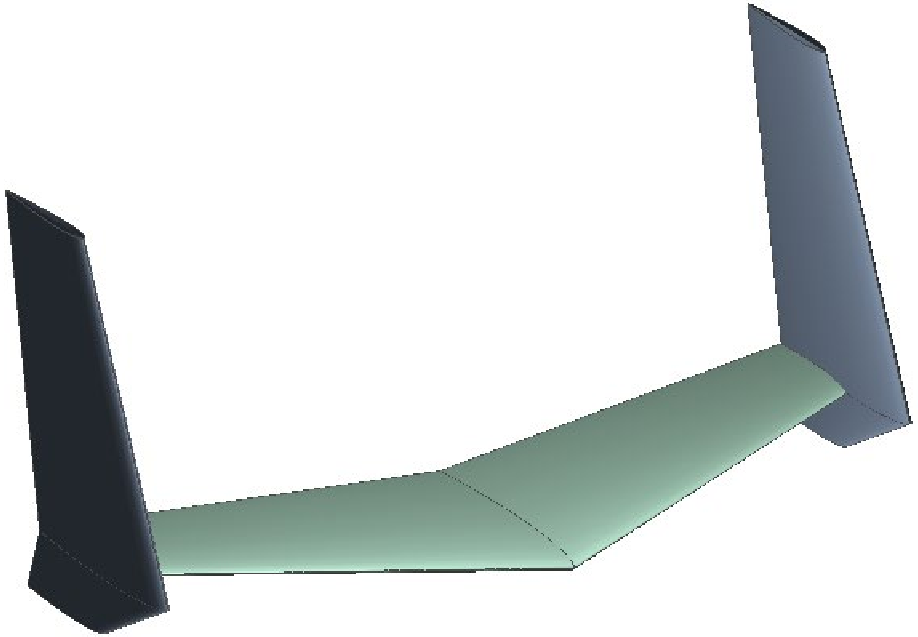
- Tail Configurations Considered:
  - Conventional
  - V-Tail
  - H-Tail
- Tail Volume Coefficient Method
  - $S_{VT} = \frac{C_{VT} b_w S_w}{L_{VT}}$
  - $S_{HT} = \frac{C_{HT} \bar{C_w} S_w}{L_{HT}}$
- For horizontal surfaces, a C_{HT} value of 1 was used and for the vertical surfaces a C_{VT} value of 0.09 was used as suggested for a jet transport



Root locus plot for lateral stability of the three tail configurations. Green is H-tail, red is conventional tail, and pink is V-tail. The H-tail displays the best Dutch roll stability, while the spiral convergence is similar. Roll convergence is slightly better for the conventional and V-tail configurations but is acceptable for all.

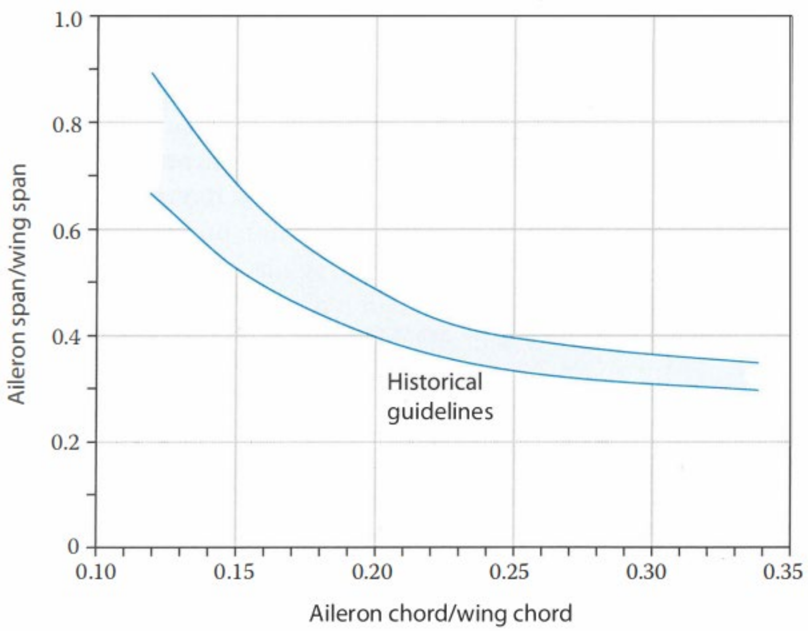
SELECTED TAIL GEOMETRY

Parameter	Dimension
Horizontal Tail Span	18.04 ft
Horizontal Tail Root Chord	12.03 ft
Horizontal Tail Tip Chord	6.01 ft
Horizontal Tail Sweep of Leading Edge	19.8°
Horizontal Tail Dihedral	4°
Vertical Tail Span	18.46 ft
Vertical Tail Root Chord	11.54 ft
Vertical Tail Tip Chord	6.92 ft
Vertical Tail Sweep of Leading Edge	7.4° for top section (0° from tip to tip)



Aileron Sizing

- Initial sizing of the ailerons was based on historical guidelines from existing aircraft. Given the existing span of the flaps, the maximum allowable ratio of aileron span to wingspan is 0.289. Based on the guidelines, a corresponding ratio of aileron chord to wing chord of 0.335 was selected.



SUMMARY OF AILERON GEOMETRY	
Parameter	Value
Span Fraction	0.289
Chord Fraction	0.335
Span (Of 1 Aileron)	21.675 ft
Inboard Chord	3.35 ft
Outboard Chord	2.345 ft
Distance To Inboard Edge	53.325 ft
Distance Fraction*	0.711

***Distance Fraction is Distance to Inboard Edge expressed as a fraction of the wing semispan**

Elevator Sizing

- The ratio of the elevator chord to the horizontal stabilizer chord is selected to be 0.25. This gives a root chord of the elevator of 3.006 ft and a tip chord of 1.503 ft. The span fraction of the elevator with respect to the horizontal stabilizer is selected to be 1 in order to take advantage of the endplate effect of the H-tail configuration. The hinge line of the elevator is placed at 10% of the elevator chord to provide an overhung aerodynamic balance.

Aircraft	Elevator C_e/C	Rudder C_r/C
Fighter/attack	0.30*	0.30
Jet transport	0.25†	0.32
Jet trainer	0.35	0.35
Biz jet	0.32†	0.30
GA single	0.45	0.40
GA twin	0.36	0.46
Sailplane	0.43	0.40

SUMMARY OF ELEVATOR GEOMETRY	
Parameter	Value
Span Fraction	1
Chord Fraction	0.25
Span	18.038 ft
Root Chord	3.006 ft
Tip Chord	1.503 ft

Rudder Sizing

- Initial sizing of the rudder was performed using the same process as the elevator with a chord ratio of 0.32. This resulted in the following geometry.

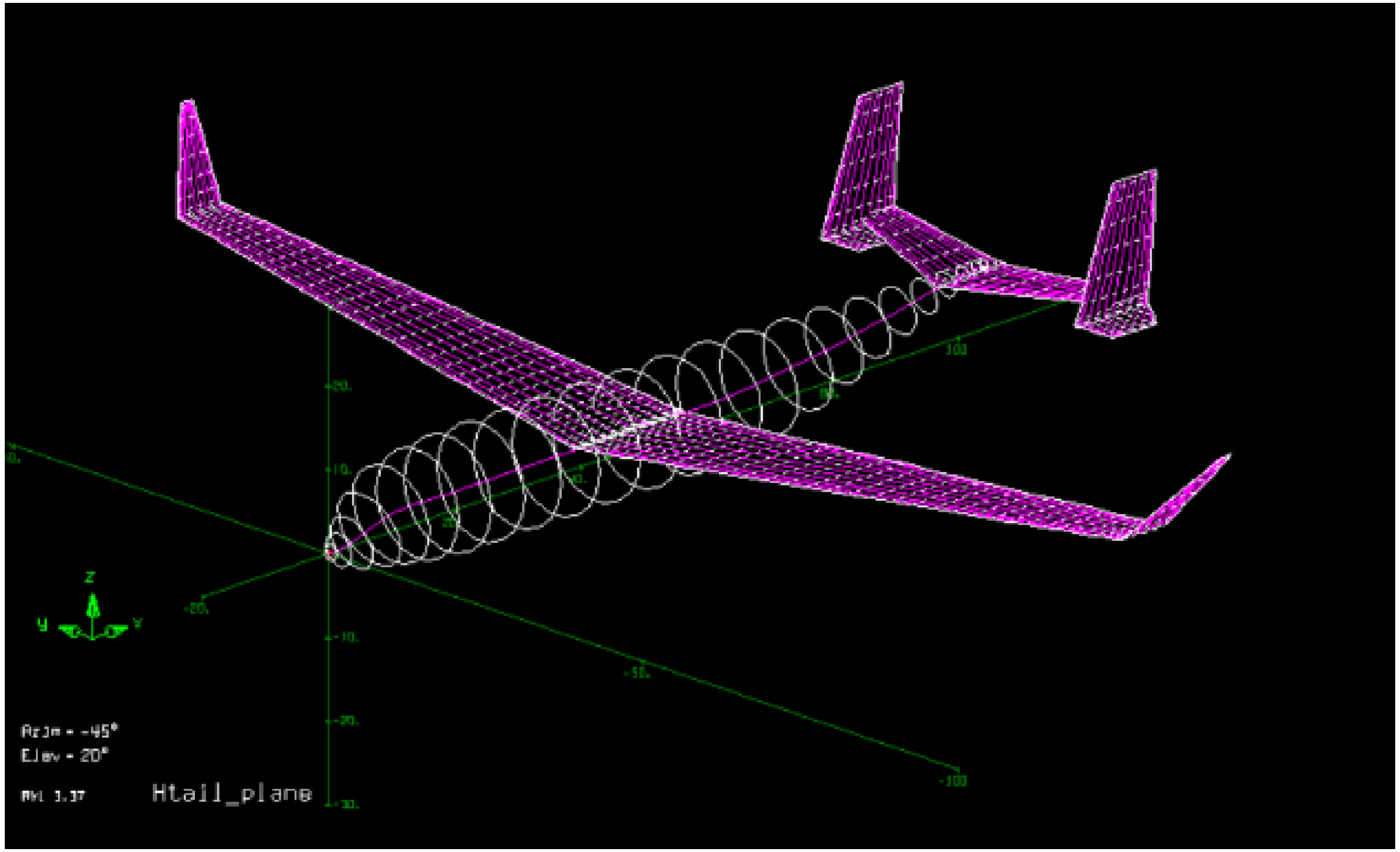
SUMMARY OF RUDDER GEOMETRY

Parameter	Value
Span Fraction	0.675
Chord Fraction	0.32
Span	12.458 ft
Inboard Chord	3.500 ft
Outboard Chord	2.310 ft
Distance To Inboard Edge	2.000 ft

- However, following stability analyses in AVL, the vertical stabilizers were designed to be all-moving in order to trim to zero sideslip in an engine-out scenario

Static Stability Analysis

- Static stability was evaluated using XFLR5 and AVL
  - XFLR5 generates a solution based on the wing and tail based on a viscous VLM solution but cannot account for the fuselage
  - AVL generates a VLM based solution for the wings, tail, and fuselage, but the solution is inviscid with constant zero lift drag coefficient added so does not evaluate stall effectively
- The airplane is statically stable longitudinally, laterally, and directionally
  - Longitudinal stability derivative is in the range -0.28 (empty with gear down) to -2.3 (full fuel and fire-retardant with gear up)
  - Lateral stability derivative is in the range -0.19 (empty with gear up) to -0.27 (empty with gear down)
  - Directional stability derivative is in the range 0.06 (empty with gear down) to 0.08 (full fuel and fire-retardant load with gear up)
- The airplane is longitudinally stable past the stall angle of attack

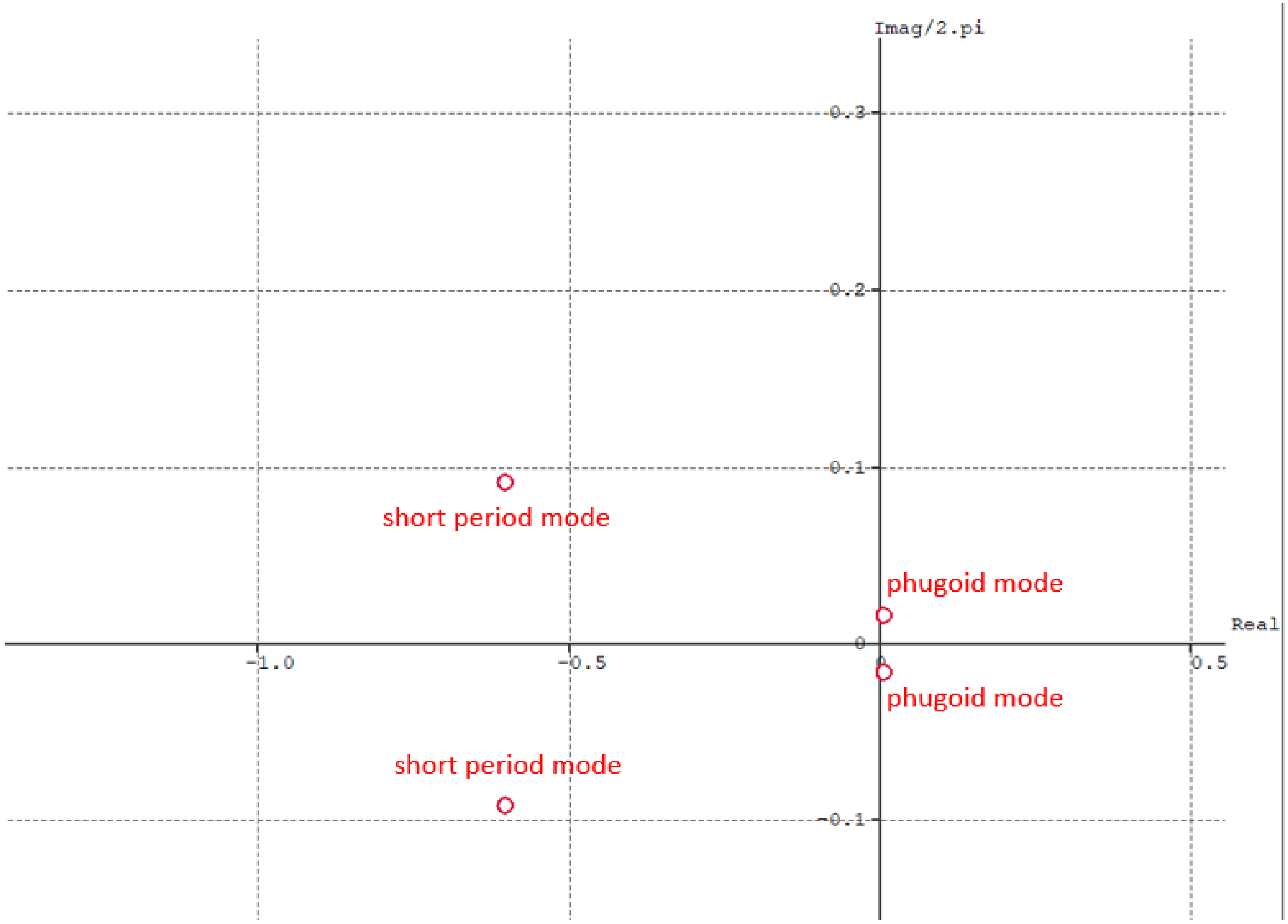


Vortex Spacing for AVL Model

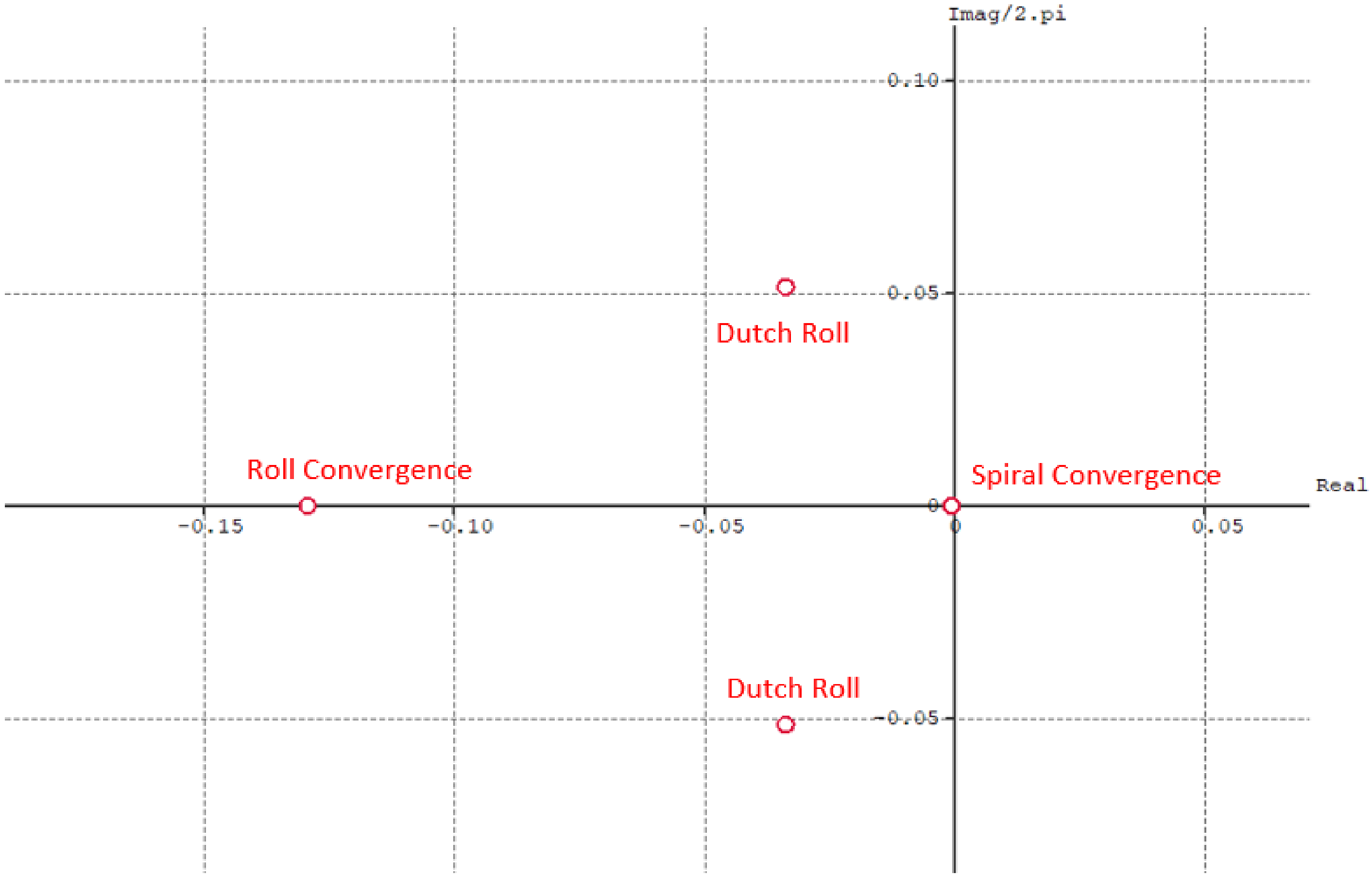
Dynamic Stability Analysis

- Dynamic stability was evaluated using XFLR5 and AVL as discussed for static stability
  - A zero angle of attack drag coefficient was approximated for the fuselage based on cross-sectional area, surface area, and fineness ratio. This value and the fuselage reference area were entered into XFLR5 as constants and used to find a zero lift drag coefficient which was then entered into AVL as well.
  - AVL and XFLR5 results agreed well at small angles of attack and sideslip. XFLR5 results were used for large angles of attack because of better evaluation of flow separation and stall and are presented here.
- The airplane is dynamically stable in Dutch roll, spirally, in roll, and in the short period mode
- The phugoid mode is slowly divergent at lower angles of attack due to the high L/D ratio

Longitudinal Stability Root Plot



Lateral Stability Root Plot



Trim Conditions

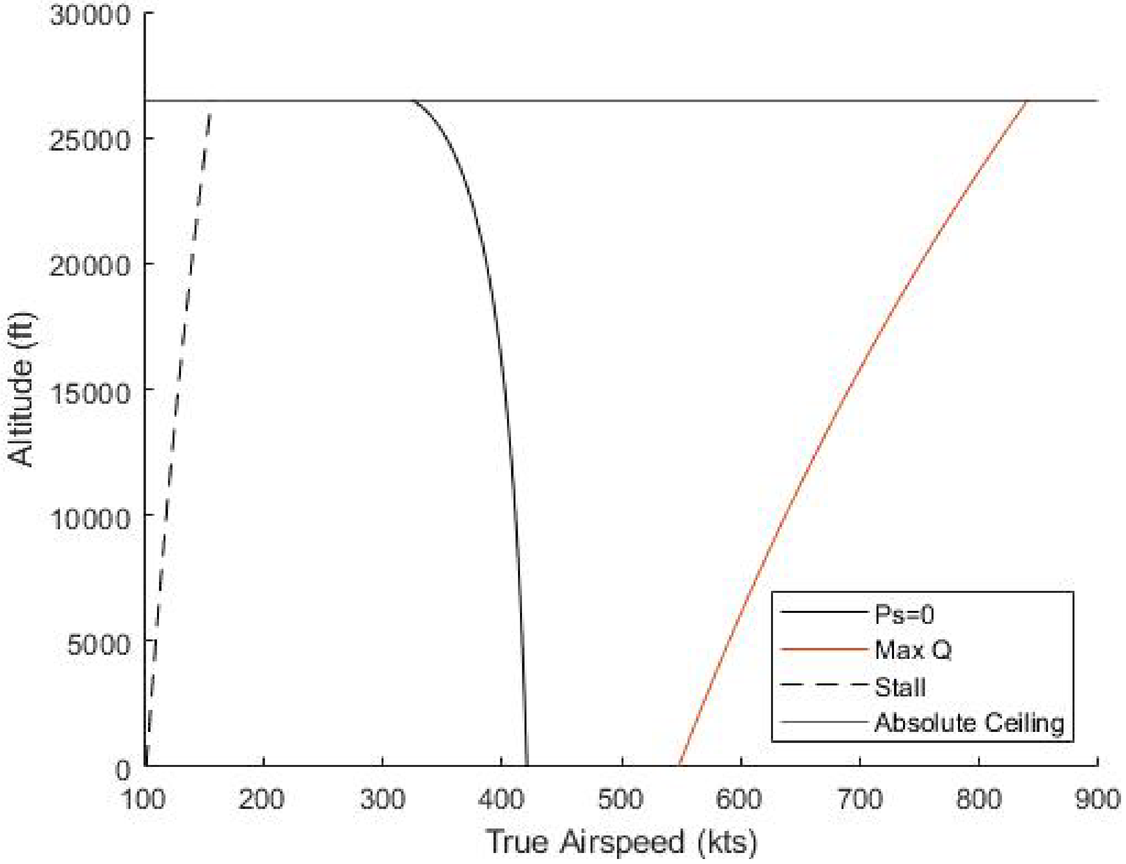
- Trim was evaluated using AVL because XFLR5 is inconvenient to use for testing wide ranges of control surface deflection.
  - All angles of attack were well below stall so AVL predictions should be valid
  - Caution needed to be used with calculated trim values as AVL allows infinite deflection with a linear increase in control force
- Trim is possible to up to 10° angle of attack in the most statically stable pitch configuration
  - Takeoff occurs at 130 kts and 8.4° angle of attack and is already well below required field length
- Trim is possible to 16° angle of attack in the least statically stable pitch configuration
  - Stall does not occur until about 20° angle of attack
- The best L/D ratio is achieved when the airplane is at approximately zero angle of attack
  - Cruise for the firefighting mission is at 311 kts
  - Cruise for the ferry mission is at 205 kts
  - Both values can be exceeded and airplane can still easily meet range requirements

Engine Out and Cross Wind Operations

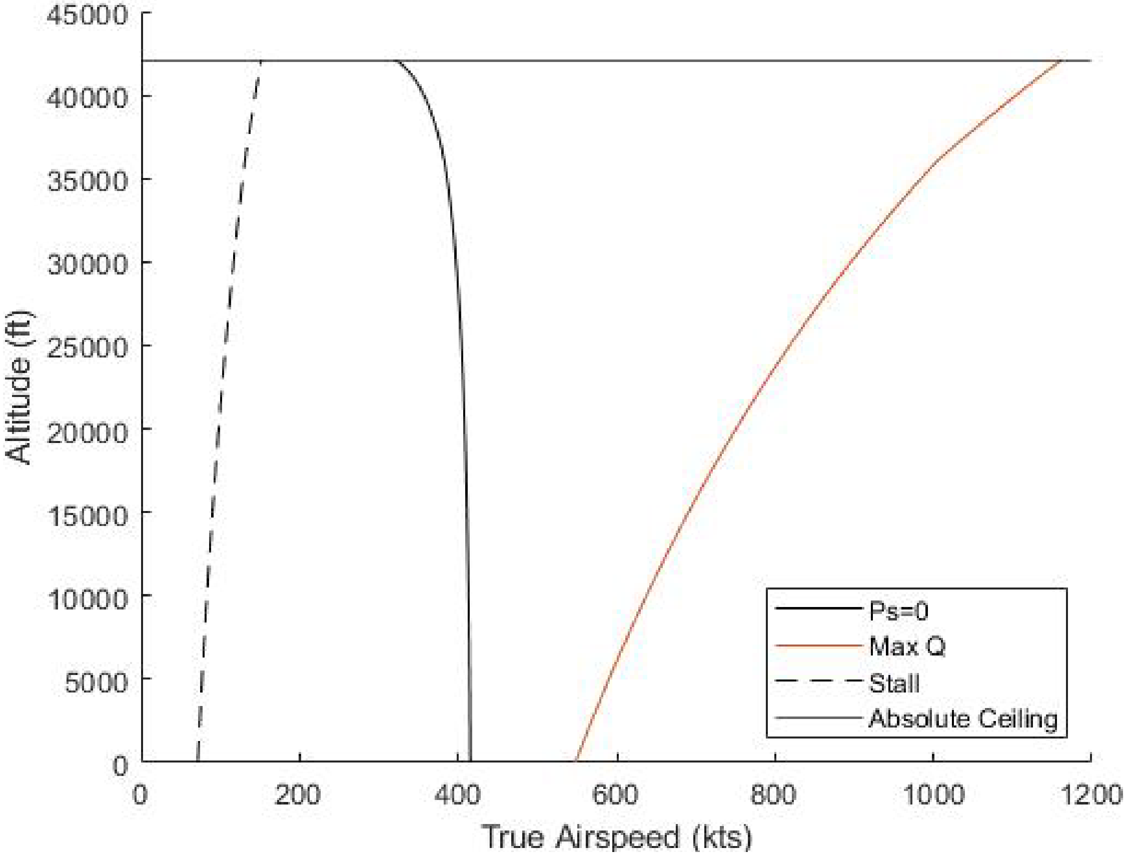
- Airplane can fly with any two engines out
  - One engine out without other damage to airframe allows continuation of mission
  - Second engine out necessitates immediate diversion to nearest airport for landing
  - Airplane can fly and trim with only one engine but has very limited excess power for maneuvering and cannot trim at zero sideslip increasing pilot workload
  - With one outboard engine out, the airplane trims at 8° rudder deflection while with two 13° deflection are required
  - With a third engine out, the airplane can trim with 17° rudder deflection (stall at 19°) and at a sideslip angle of 4°
  - To remain spirally stable while also being able to trim for an engine out scenario, the use of all moving vertical stabilizers is necessary
- With a 20 kt crosswind and 100 kt landing speed, the airplane is expected to land at a sideslip angle of 11°
  - The excellent control authority generated by the twin all-moving vertical stabilizers makes this easy to achieve with 6° rudder deflection

Performance and Cost

Performance Analysis

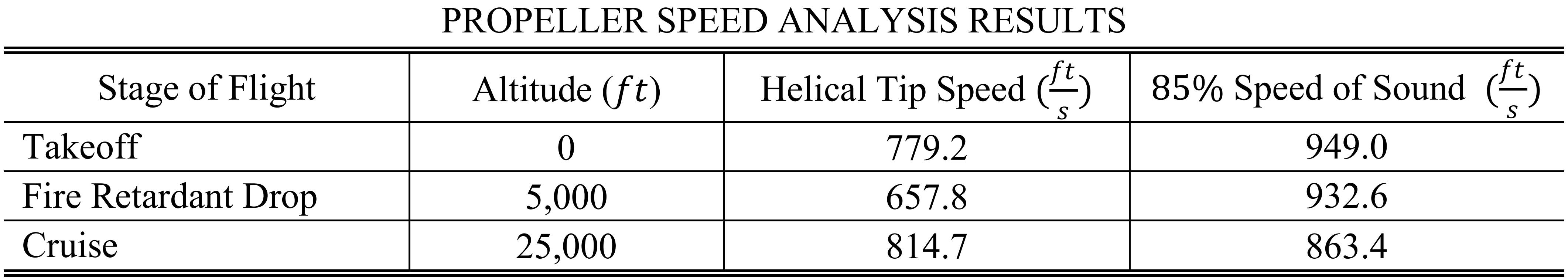


Firefighting Mission



Ferry Mission

Performance Analysis



PROPELLER SPEED ANALYSIS RESULTS

Stage of Flight	Altitude (ft)	Helical Tip Speed ($\frac{ft}{s}$)	85% Speed of Sound ($\frac{ft}{s}$)
Takeoff	0	779.2	949.0
Fire Retardant Drop	5,000	657.8	932.6
Cruise	25,000	814.7	863.4

Performance Analysis

FIREFIGHTING MISSION RANGE CALCULATIONS

Flight Section	Weight Fraction	Weight W_i (lbs)	ΔW_{stage}	ΔW_{total}
TOW	1	151617	0	0
Takeoff	0.97	147068	4548	4548
Climb	0.985	144862	2206	6754
Cruise (1126 nm)	0.9578	138753	6109	12864
Loiter (1 hr.)	0.984	136533	2220	15084
Payload Drop	N/A	64532	N/A	N/A
Cruise 2 (1126 nm)	0.9140	58986	5547	20630
Landing	0.995	58691	295	20925

$$R = \frac{V}{C}\frac{L}{D}\ln\left(\frac{1}{W_i/W_{i-1}}\right)$$

Ferry range—4856 nmi
Firefighting range—1126 nmi
1.1 Factor of Safety

Performance Analysis

- $\boldsymbol{BFL = \frac{0.863}{1+2.3G}\left(\frac{W/S}{\rho g C_{L_{climb}}} + h_{obstacle}\right)\left(\frac{1}{T_{av}/W-u} + 2.7\right) + \left(\frac{655}{\sqrt{\rho/\rho_{SL}}}\right)}$
  - $T_{av} = 7.75\ bhp\ \left[\frac{(\rho/\rho_{SL})N_e D_p^2}{bhp}\right]^{\frac{1}{3}}$
  - $G = \gamma_{climb} - \gamma_{min}$
  - $\gamma_{climb} = arcsine\left[\frac{T-D}{W}\right]$
  - $u = 0.01C_{L_{max}} + 0.02$

- **BFL = 1949.4 ft**

Cost Estimation

INPUTS TO DAPCA MODEL COST ESTIMATE

Parameter	Value
Empty weight, W_e	45493 lb
Max velocity, V	420 kts
Production run, Q	25
Prototypes, FTA	2
Number of engines, N_{eng}	4
Avionics cost, $C_{avionics}$	$300,000
Hours fudge factor	1-1.2
Engineering wrap rate, R_E	115
Tooling wrap rate, R_T	118
Quality control wrap rate, R_Q	108
Manufacturing wrap rate, R_M	98

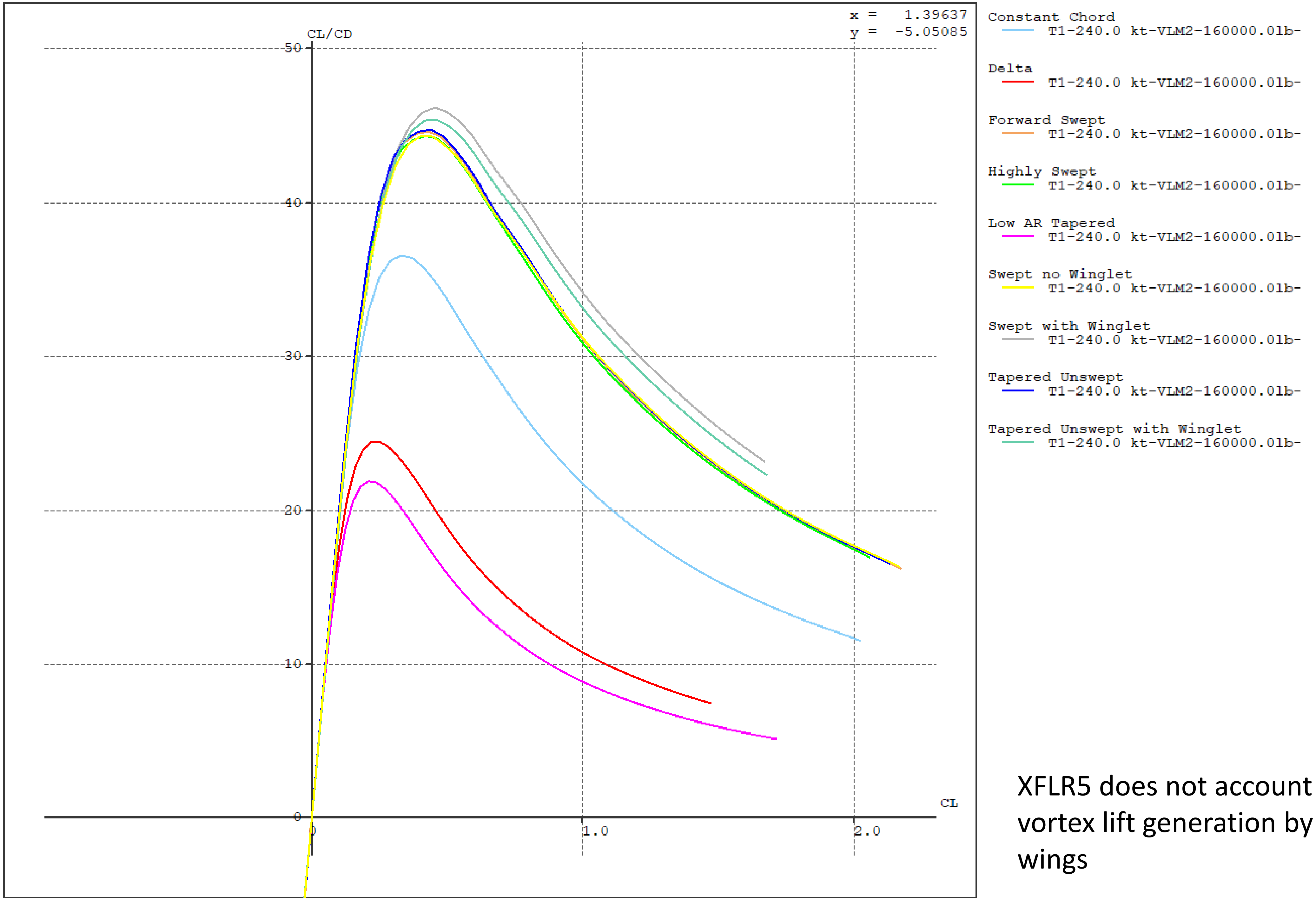
Cost Estimation

- $C_{program} = H_E R_E + H_T R_T + H_M R_M + H_Q R_Q + C_D + C_F + C_M + C_{eng} N_{eng} + C_{avionics}$

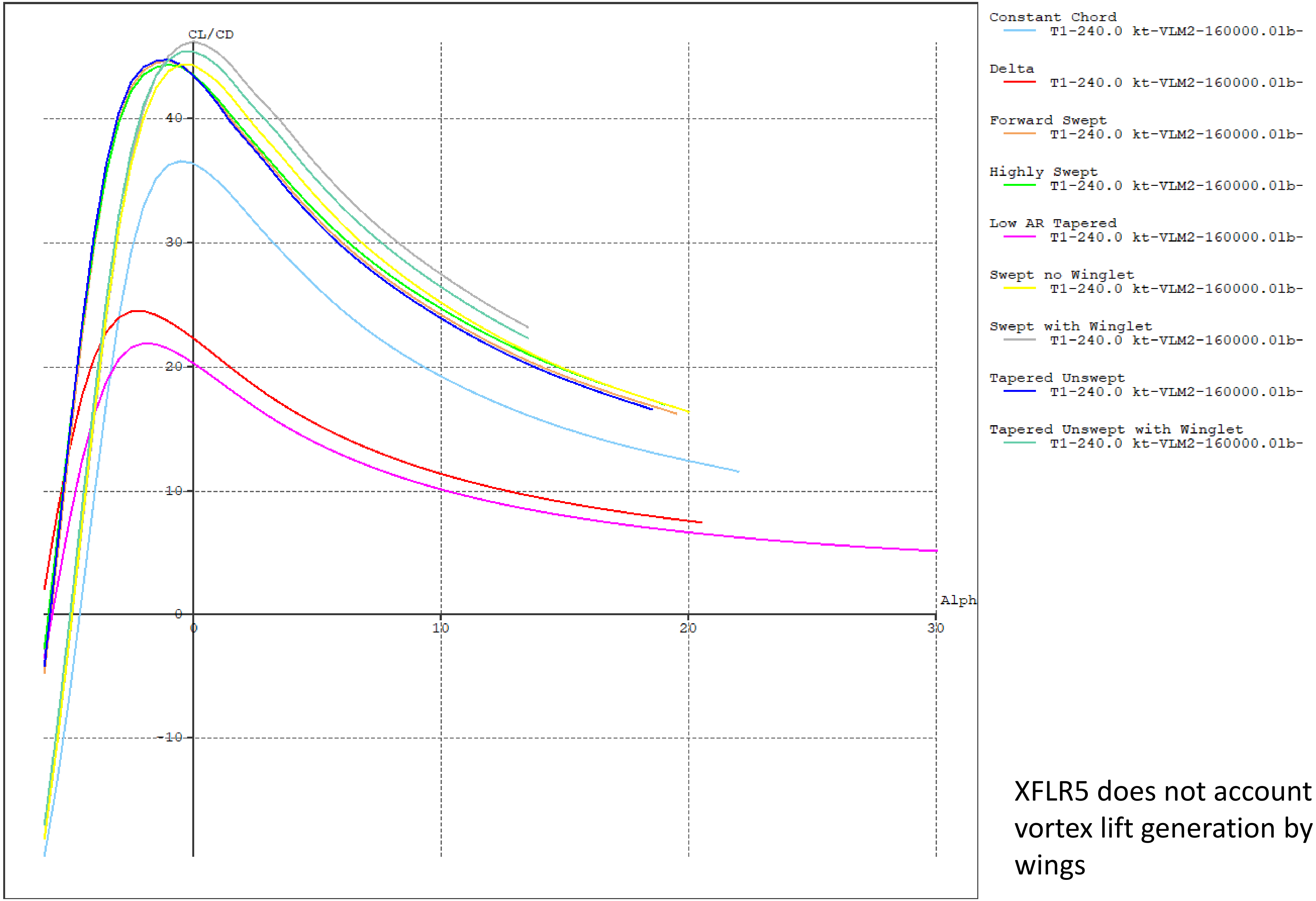
DAPCA MODEL COST ESTIMATE

Parameter	Cost with Factor of 1 (million \$)	Cost with Factor of 1.2 (million \$)
Engineering	870.18	1044.21
Tooling	459.17	551.00
Manufacturing	567.42	680.90
Quality control	65.35	78.41
Development	201.93	201.93
Flight test	27.04	27.04
Manufacturing materials	2400.78	2400.78
Engines	5.20	5.20
Program cost (2012)	**4597.06**	**5035.27**
Program cost (2022)	**5746.32**	**6294.09**
Unit cost (2022)	**229.85**	**251.76**
Unit cost Q=500 (2022)	**83.19**	**86.67**

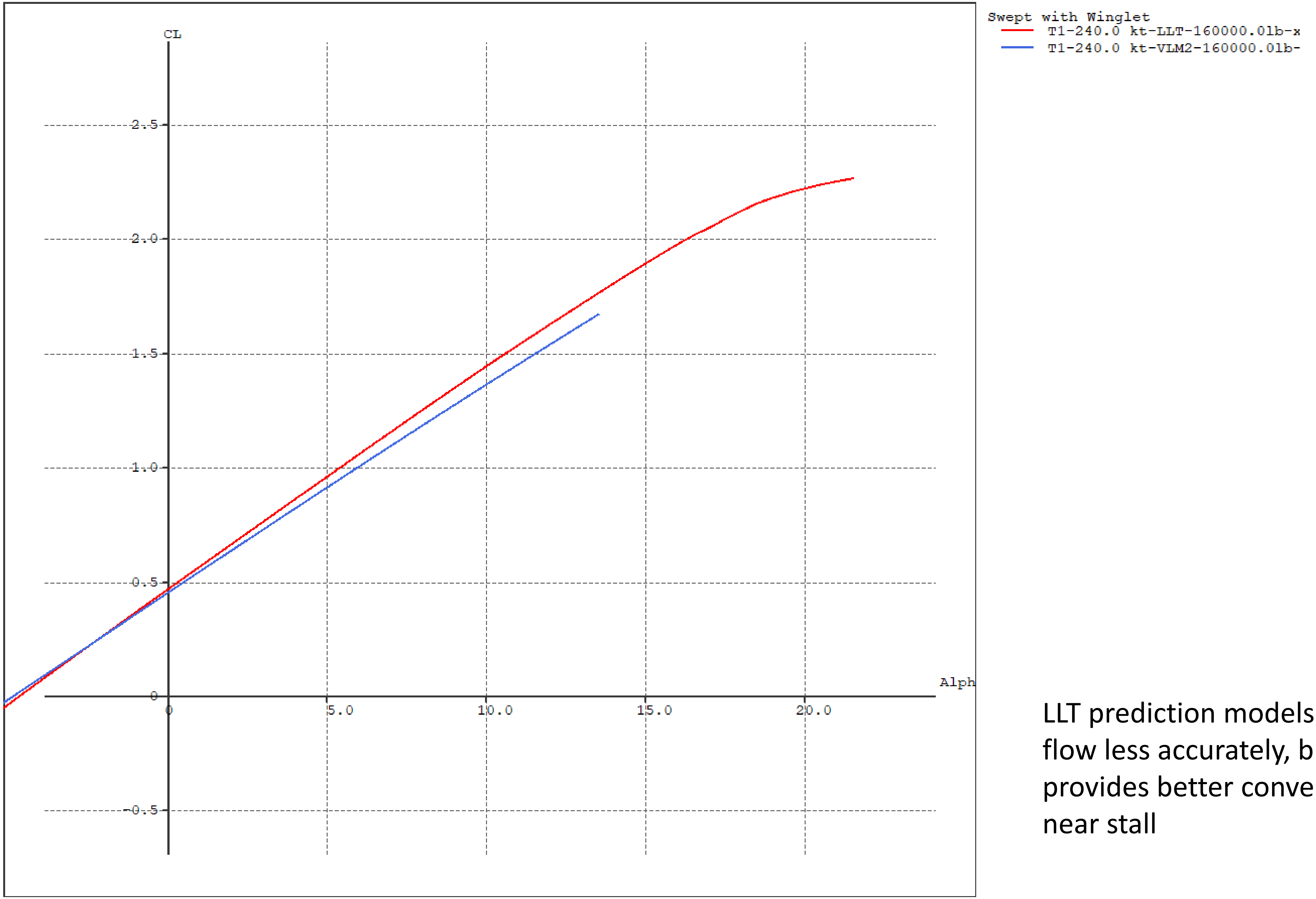
Additional Slides



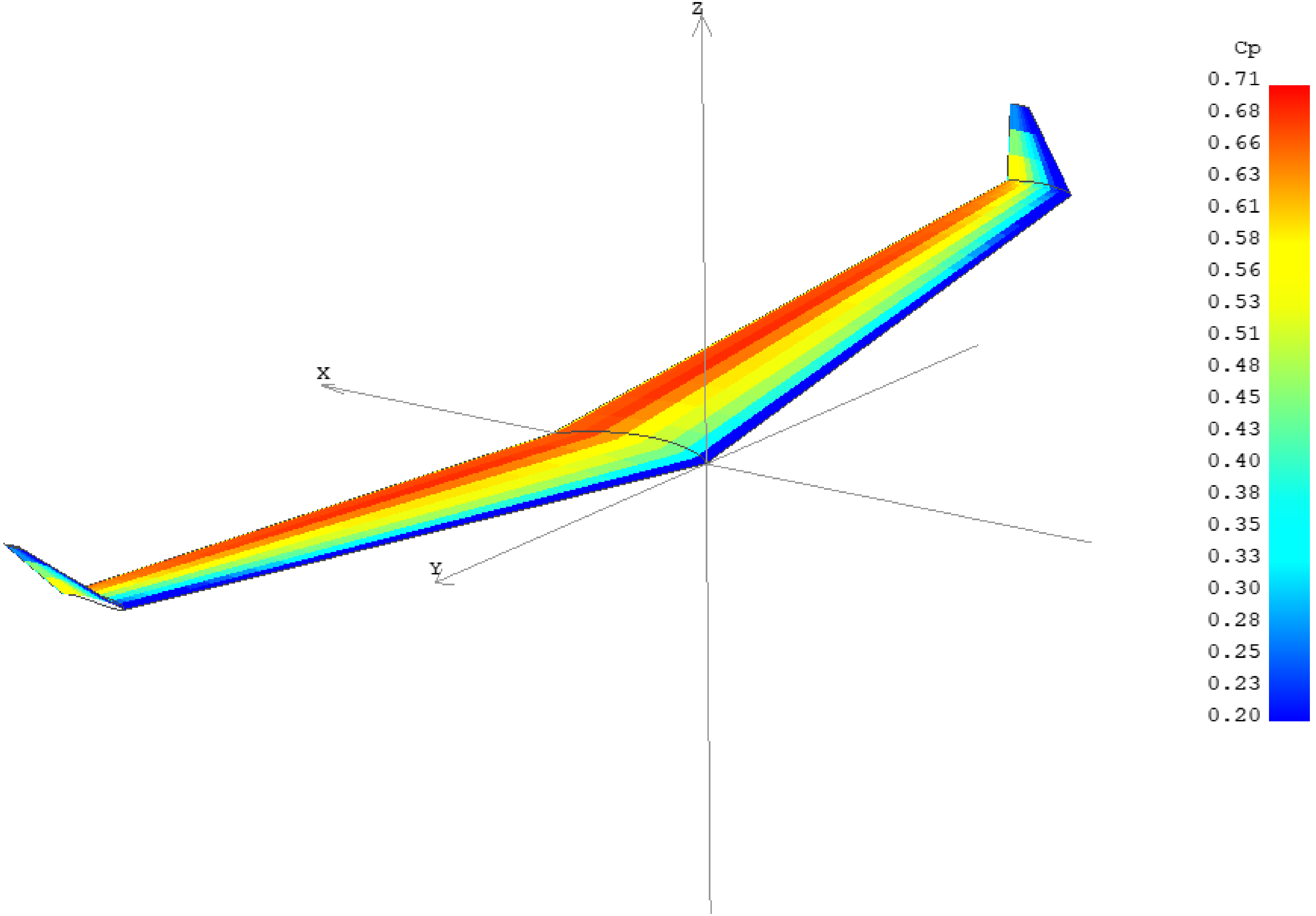
XFLR5 does not account for vortex lift generation by delta wings



XFLR5 does not account for vortex lift generation by delta wings



LLT prediction models spanwise flow less accurately, but provides better convergence near stall


Z
X
Y
Cp
0.71
0.68
0.66
0.63
0.61
0.58
0.56
0.53
0.51
0.48
0.45
0.43
0.40
0.38
0.35
0.33
0.30
0.28
0.25
0.23
0.20