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Ultra Efficient Commercial Transport Challenge- NASA Design Challenge- X-JAB-ECT

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Ultra Efficient Commercial Transport Challenge

NASA Design Challenge

X-JAB-ECT

Kennesaw State University

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By: Ramin Abdul, Jacob Beiting, and Evan Johnston

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Executive Summary

Today's aircraft require new innovation to be able to produce the same amount of lift, but with the design decrease the amount of drag produced. The X-JAC ECT has the ability and is an innovative airframe to reduce today's fuel costs. The baseline comparison for the X-JAB is the Boeing 747-400 aircraft, the payload, range, speed, and altitude are the same for the X-JAB and the 747. Through use of supercritical airfoils, the X-JAB was designed as a blended wing body aircraft to produce more lift while evenly balancing the weight of the aircraft and the payload. Through parametric analysis and flow simulations, the X-JAB is able to achieve a 31.6% reduction in fuel costs compared to the Boeing 747-400.

Team Members

Ramin Abdul - Structural and Layout Engineer, Design Engineer

Jacob Beiting - Project Manager, Design Engineer

Evan Johnston - Propulsion and Energy Engineer, Design Engineer

Introduction

The overall goal of this project is a challenge presented by NASA; the challenge is to design an ultra efficient commercial transport for 2045 with the potential to surpass 30%-60% reduction of energy. The basis for comparison of the X-JAB is a 2005 best-in-class aircraft, we have chosen the Boeing 747-400 as the basis for our aircraft. The overall task of this challenge is to achieve a dramatic reduction in energy consumption through innovative airframe and propulsion systems, new approaches to integration of the airframe and propulsion systems, and new operational paradigms.

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near-term 2015-2025	Mid-term 2025-2035	Far-term Beyond 2035
Noise (cumulative below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NO_x Emissions (below CAEP 6)	70 - 75%	80%	>80%
Cruise NO_x Emissions (relative to 2005 best in class)	65 - 70%	80%	>80%
Aircraft Fuel/Energy Consumption (relative to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

Figure 1: NASA's Strategic Implementation Plan

Figure 1 shows NASA's targeted improvements in subsonic transportation system metrics for the next few decades.

System Overview

The baseline aircraft is the Boeing 747-400:

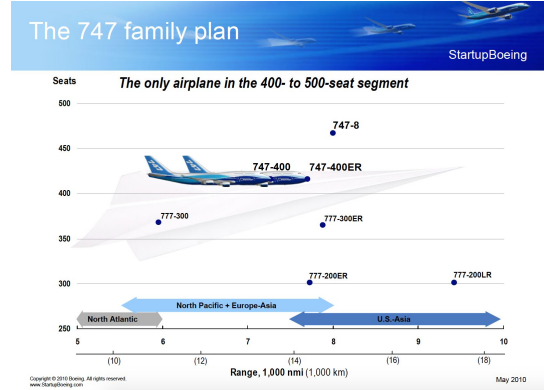Figure 2: Dimensions of 747-400

Figure 3: Range of 747-400

Design Requirements

Specific mission requirements are dictated by the Boeing 747-400. The newly designed aircraft concept must have the same or better mission performance capabilities as the baseline comparison.
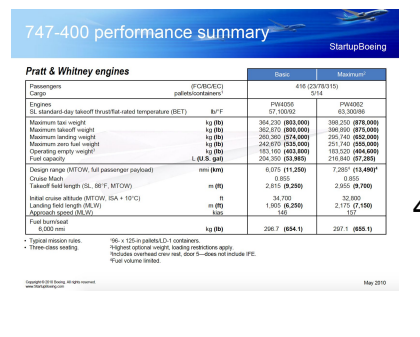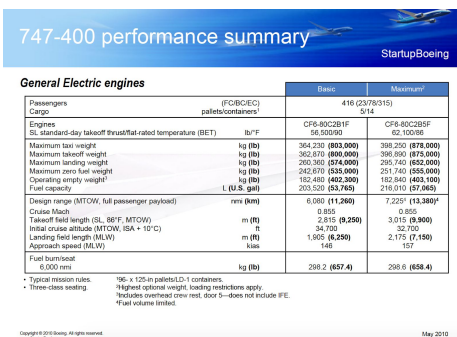
Figure 4: GE Performance

Figure 5: P&W Performance

4

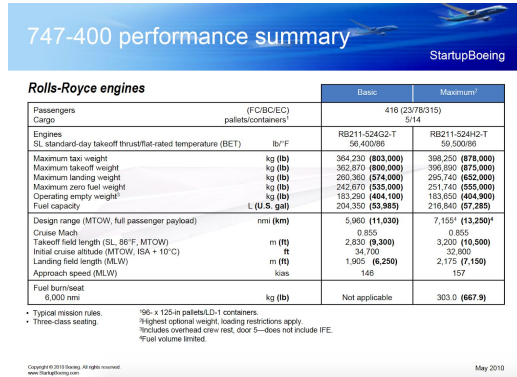Figure 6: Rolls-Royce Performance

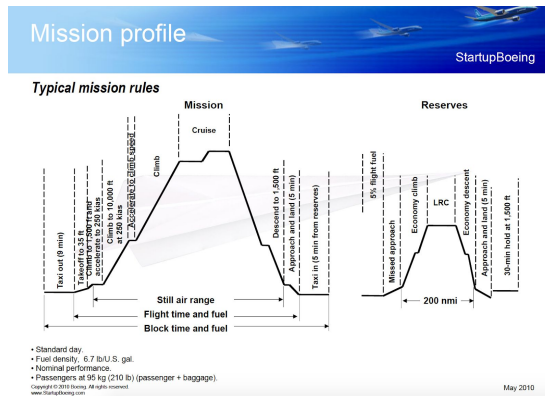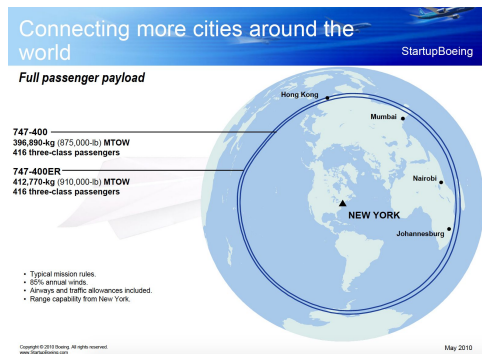Figure 7: Mission Profile 747-400

Figure 8: Full passenger payload

Other design requirements include the needs of possible passengers, passenger acceptance, development cost and risk, and FAA certification. Special considerations need to be if part of the design features are incompatible with current FAA regulations or passenger expectations. Ideally designs would like to be within today's ground infrastructure, but designs that require changes to infrastructure are allowed but the final report must address the practicality and implementation challenges of any of the required changes needed. Changes made to flight operations to improve the efficiency need to be addressed for cost and scheduling impacts to the air transportation system.

Mission Requirements:
The specific mission requirements will be dictated by the existing baseline aircraft selected by the teams. The advanced, ultra-efficient aircraft concept must have the same or better mission performance capabilities as the baseline comparison aircraft. This includes matching the range performance at the same payload weight while flying at the same cruise speed. Takeoff and landing performance should also be the same or better than the selected baseline aircraft.

Figure 9: NASA Challenge Mission Requirements

Design Concepts and Trade Study

The challenge itself calls for an innovative airframe, the group has decided that we will design a blended wing aircraft for commercial transportation. Since this is a design challenge for the year 2045, information for a blended wing aircraft is limited in terms of commercial aircrafts. Boeing has two experimental blend prototypes the X-45 and the X-48. The X-45 is an unmanned combat air vehicle and the X-48 is an unmanned aerial vehicle both in partnership with NASA. Fortunately we also have the Lockheed F-117 Nighthawk to study as well.

Figure 10: Boeing X-45

Figure 11: Boeing/NASA X-48

Figure 12: Lockheed F-117 Nighthawk

Due to the fact that there is not any commercial blended wing aircraft all designs and research will have to be considered experimental.

Analysis and Verification Process/Minimum Success Criteria:

For analysis and verification of the chosen design, SOLIDWORKS Computational Fluid Dynamics will be used. Due to the experimental design, many iterations are expected till the final design requirement of a 30-60% reduction in energy is achieved. Once a 30-60% reduction is met, we would like to 3D print the prototype design and test it in the school's wind tunnel in the Fluid Mechanics Laboratory. The minimum success point is the 30- 60% reduction in energy, ideally the goal is to get the aircraft to achieve and energy reduction in the range of 60%-80%.

<u>**Available and Required Resources**</u>

Resources needed for this project is the software SOLIDWORKS and its Computational Fluid Dynamics simulation, which is available for free for students, staff, and faculty. Hardware required will be the use of a 3D printer and the wind tunnel in the Fluid Mechanics Laboratory.

Budget

SOLIDWORKS as stated earlier is free for students of the school and 3D printers are available for students. A cost on materials has not been calculated as of yet, as we are finding more information on using the 3D printers and the cost of the material. A program called Aero Foil was found for inverse airfoil modeling, cost $20 (student copy, when product is available)

Conceptual Design

The design choice as stated earlier is a blended wing model, something akin to the Boeing X-48. The reason for a blended wing design, is that when the profile of the plane is viewed from the side, the fuselage is an airfoil.
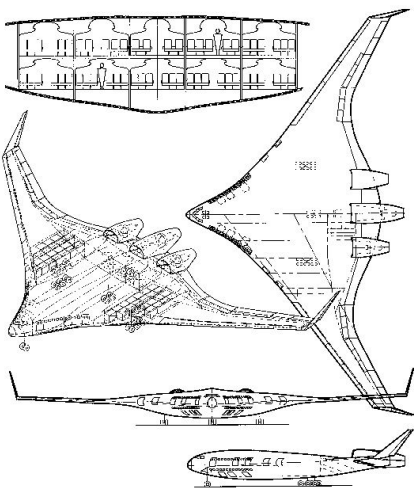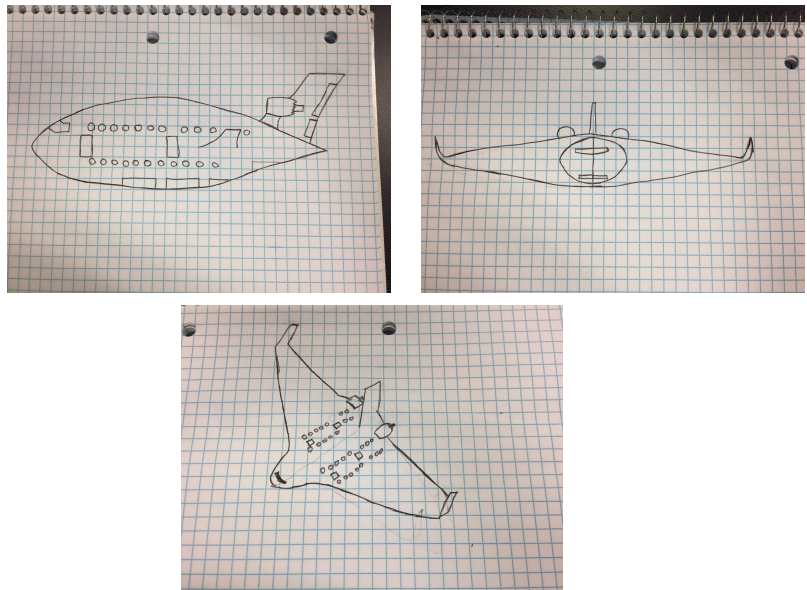

Figure 13: Drawing of Boeing X-48

Figure 14-16: Free-hand Design Drawings

As noted above, looking at the figures, an airfoil shape can be observed from the side profile. For designing the initial airfoil, a program called Aero Foil was found. The software program can be obtained from www.AeroFoilEngineering.com. A student edition was obtained for $20, and with this software we will be able to create the airfoil and submit it into SOLIDWORKS for further implementation of the overall design of the aircraft. Through a website called grabcad.com, we were able to obtain a CAD drawing for a blended wing design and a Boeing 747-400.
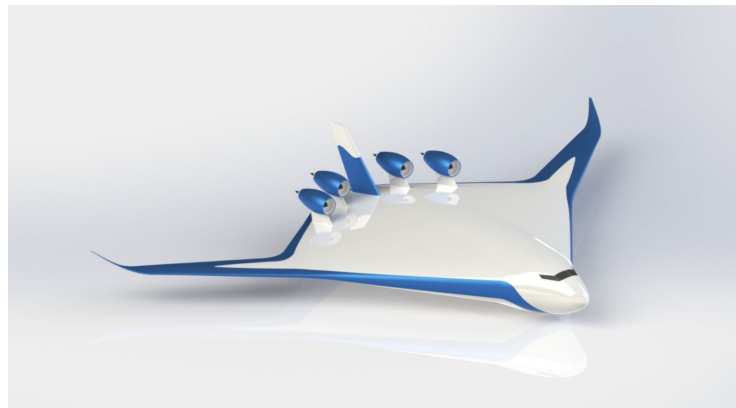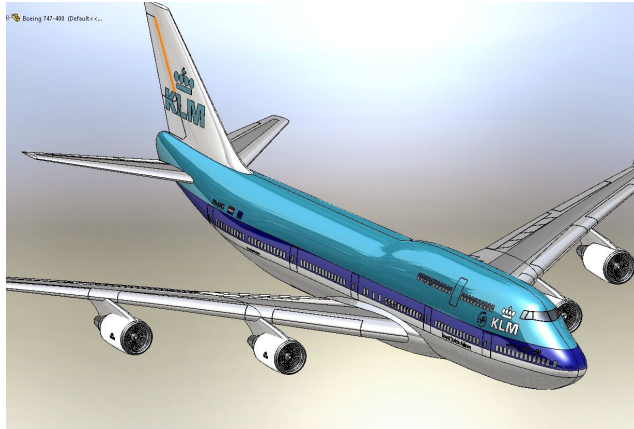

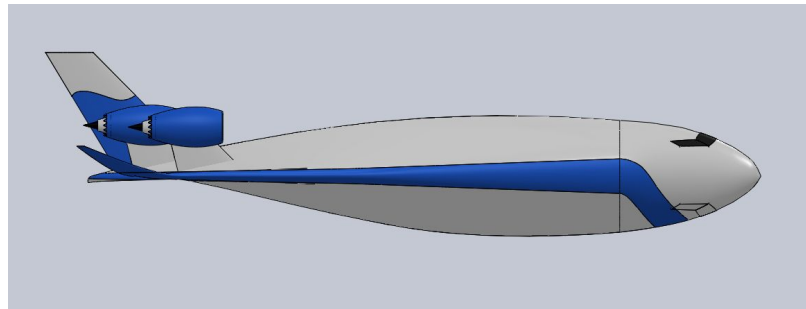Figure 17: Blended CAD Drawing

Figure 18: Boeing 747-400 CAD Drawing
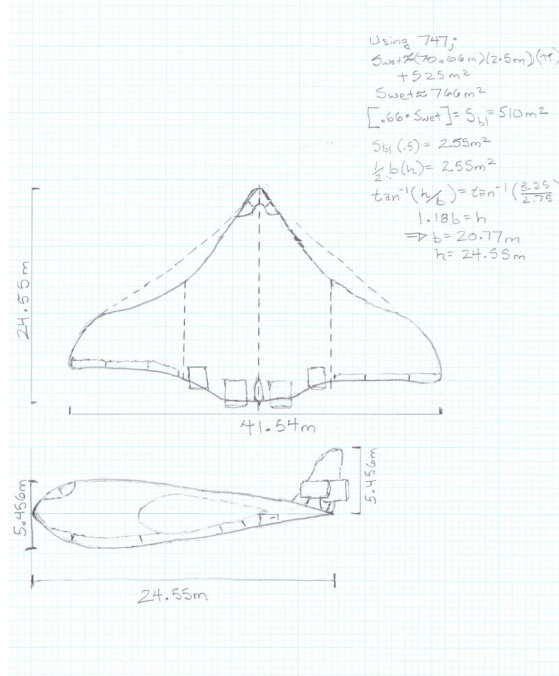

Figure 19: Side Profile Blended Wing Design

Figure 20: Sizing Sketch of BWB

Airfoil Selection

NACA 63015
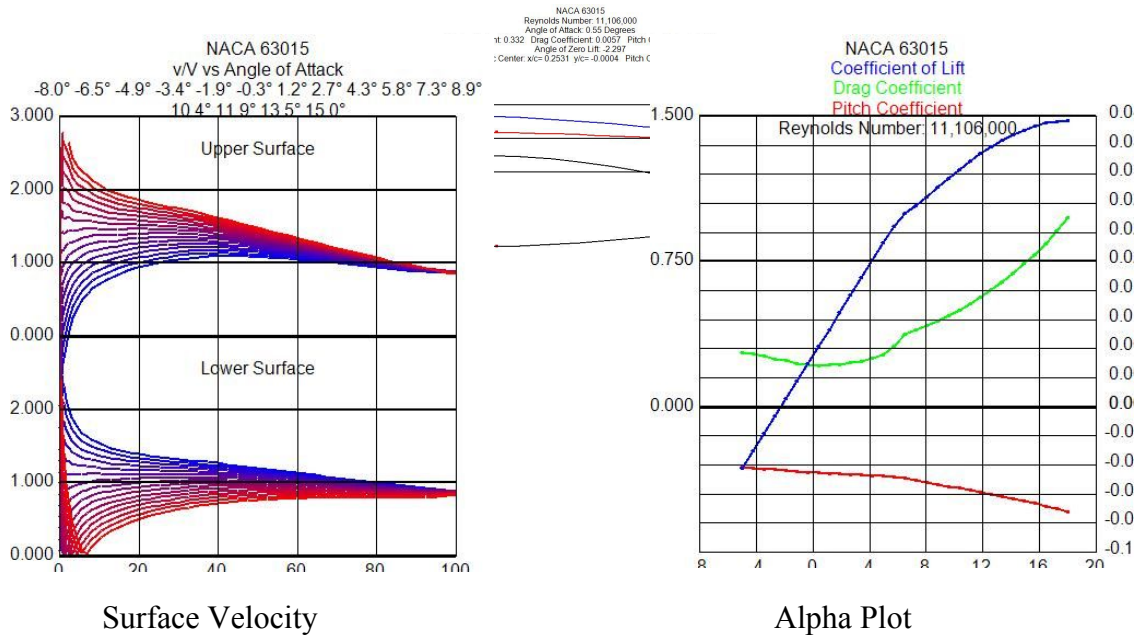
Surface Velocity   Alpha Plot

NACA 63015
Reynolds Number: 11,106,000
Angle of Attack: 0.55 Degrees
Lift Coefficient: 0.332   Drag Coefficient: 0.0057   Pitch Coefficient: -0.045
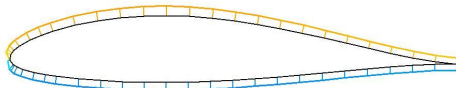Angle of Zero Lift: -2.297
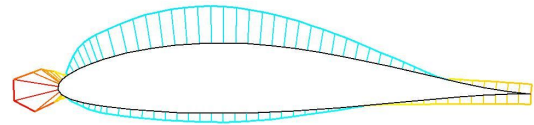Aerodynamic Center: x/c= 0.2531 y/c= -0.0004   Pitch Coefficient: -0.044

NACA 63015
Reynolds Number: 11,106,000
Angle of Attack: 0.55 Degrees
Lift Coefficient: 0.332   Drag Coefficient: 0.0057   Pitch Coefficient: -0.045
Angle of Zero Lift: -2.297
Aerodynamic Center: x/c= 0.2531 y/c= -0.0004   Pitch Coefficient: -0.044

Gamma Plot   Pressure Coefficient vs Surface

Figures 21-25: Aerofoil results of NACA 63015

NACA 63015
Reynolds Number: 11,106,000
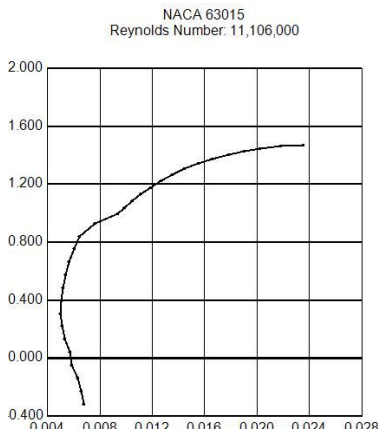
Drag Polar

The initial airfoils presented above were giving data that showed that the flow over the

top of the airfoil at the given parameters of 34,400 ft with a velocity of 255.9 m/s was going

supersonic, and therefore was breaking the speed of sound create supersonic drag and could

damage the airplane as well as increase the drag and lower the efficiency and increase fuel

consumed. Going back through further trade studies that had been done, considering that only a

NASA SC(2)-0518 AIRFOIL (sc20518-il)

scale model has been made of a blended wing aircraft, the studies shown that thicker

supercritical airfoils were needed for the overall design of the fuselage and the wings. One study

from the Society of Women Engineers from Embry-Riddle Aeronautical showed that for the

fuselage an airfoil with a maximum thickness at 18% chord would be needed for the fuselage and

for the wing an airfoil with a maximum thickness at 10% chord.

Figure 26: NASA SC(2)-0518 Airfoil
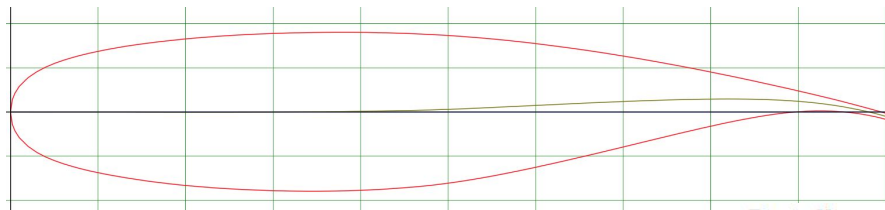
Details

(sc20518-il) NASA SC(2)-0518 AIRFOIL
NASA SC(2)-0518 airfoil (NASA TP-2969)
Max thickness 18% at 35% chord.
Max camber 1.9% at 82% chord

NASA SC(2)-0610 AIRFOIL (sc20610-il)

Details

(sc20610-il) NASA SC(2)-0610 AIRFOIL
NASA SC(2)-0610 airfoil (NASA TP-2969)
Max thickness 10% at 38% chord.
Max camber 1.8% at 82% chord

Figure 27: NASA SC(2)-0610 Airfoil

From searching www.airfoiltools.com the two airfoils above were found for the design,

the SC(2)-0518, airfoil for fuselage, has a max thickness of 18% at 35% of the chord and the

SC(2)-0610, airfoil for wing, has a max thickness of 10% at 38% chord.

Preliminary Design

The initial design was done through hand drawing and calculations the verify sizing, from

the initial design it was determined that the total wingspan of the blended wing body would

41.54 meters and the length of the aircraft would be 24.55 meters. The first iteration of the

aircraft fuselage was not a pretty one, with this being the first aircraft designed for the team, the

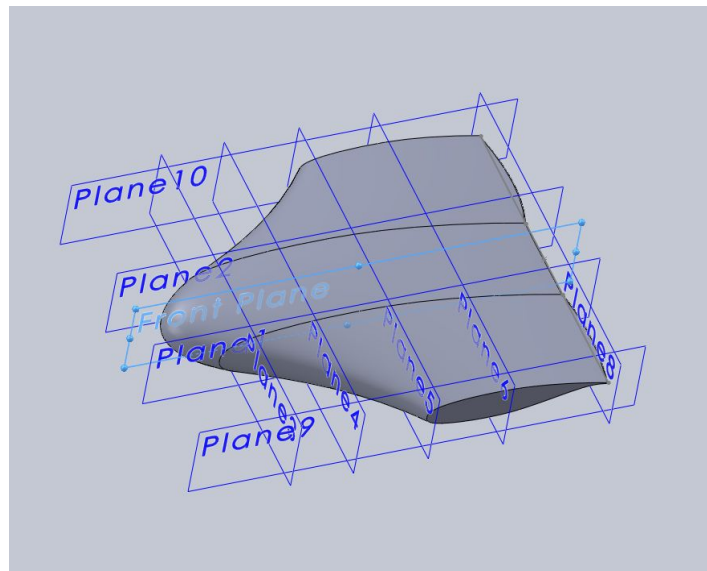results speak for itself.

Figure 28: 1st Iteration

The back of the fuselage is almost flat and takes up to much surface area and allows for turbulent

flow to be created at the end of the fuselage. Going back to the trade studies, it was noticed that

the back of the fuselage design was rounded and therefore the 2nd iteration of the aircraft

fuselage would be rounded and allowing for more natural flow off the back of the aircraft.
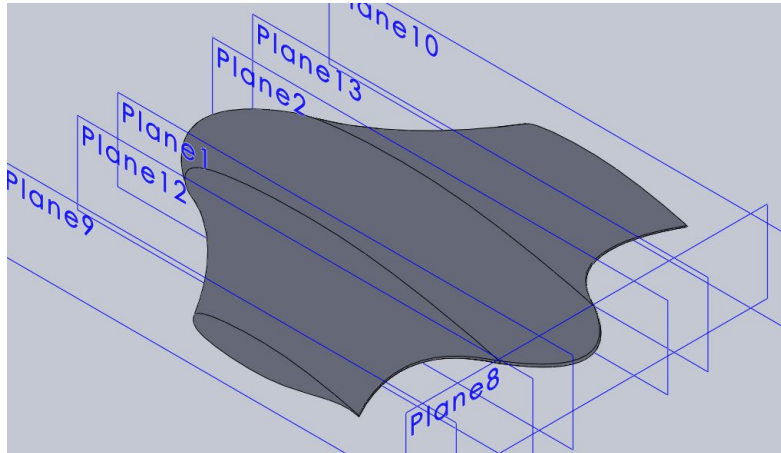

Figure 29: 2nd Iteration

Problems Encountered

Many problems were encountered when attempting to design this aircraft. The first

problem was overall design, this design for commercial use is something that has not been

produced on a large scale. Stealth aircraft F-117 as noted earlier is more suited overall design for

what is envisioned. The next problem that was encountered was selecting the airfoil for aircraft,

initialing thinking 1 airfoil would suit the overall design needs, but through further research the

SWE BWB noted earlier was implementing 2 seperate airfoils. The initial airfoil that was

decided on was the NACA 63015. From the initial research on the aerofoil software the velocity

on top of the airfoil was going supersonic at the given conditions of 344000 feet and a speed of

255.9 m/s.

The airfoil problem was a big cause for concern, if the aircraft can't fly at the given

parameters of a Boeing 747-400 series without going supersonic, the project was destined to fail.

Through further studying as noted above in the airfoil selection, the need for a supercritical airfoil was decided for the design of the airplane.

The next problem was bringing the design to life with software, since Solidworks is free for engineering students at Kennesaw State University. Only being experienced with a couple of CAD classes, a design of this scale would be challenging. Sometimes importing the airfoil data into an XYZ curve in Solidworks proved to be challenging. However, the challenges were overcome and a design was able to be modeled and simulated in Solidworks.

Final Design

The final design was modeled in Solidworks with the SC(2)-0518 for the fuselage and the SC(2)-0610 for the wing. The overall dimensions for the aircraft are a wingspan of 41.2 meters, 24.53 meters long and is 4.4 meters at the aircrafts thickest point.
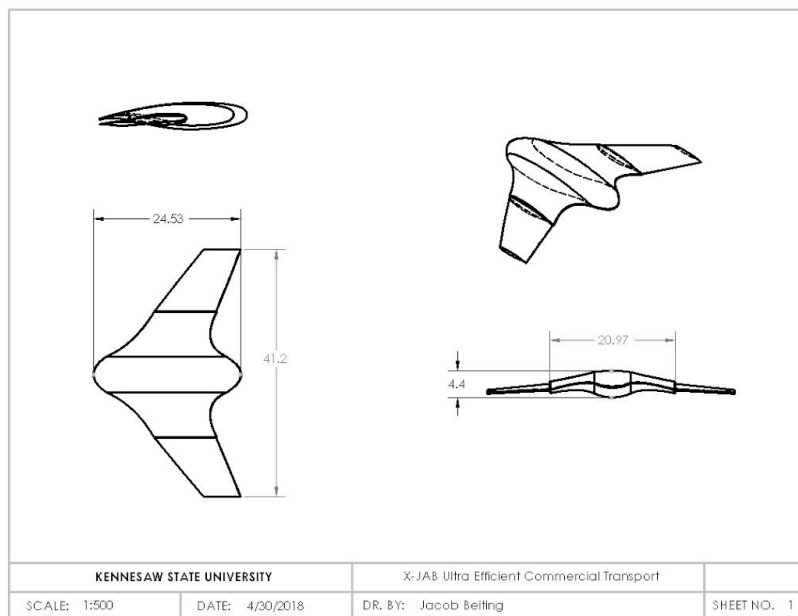

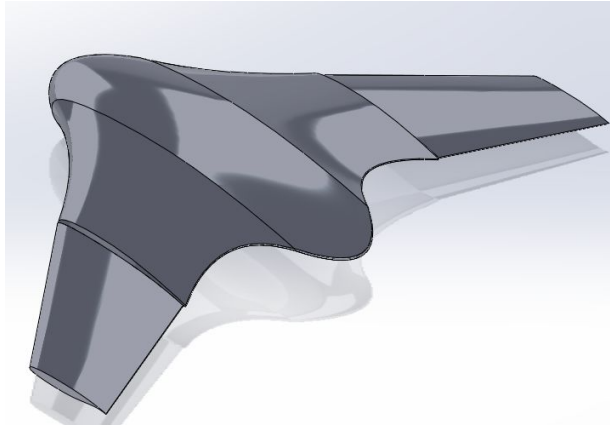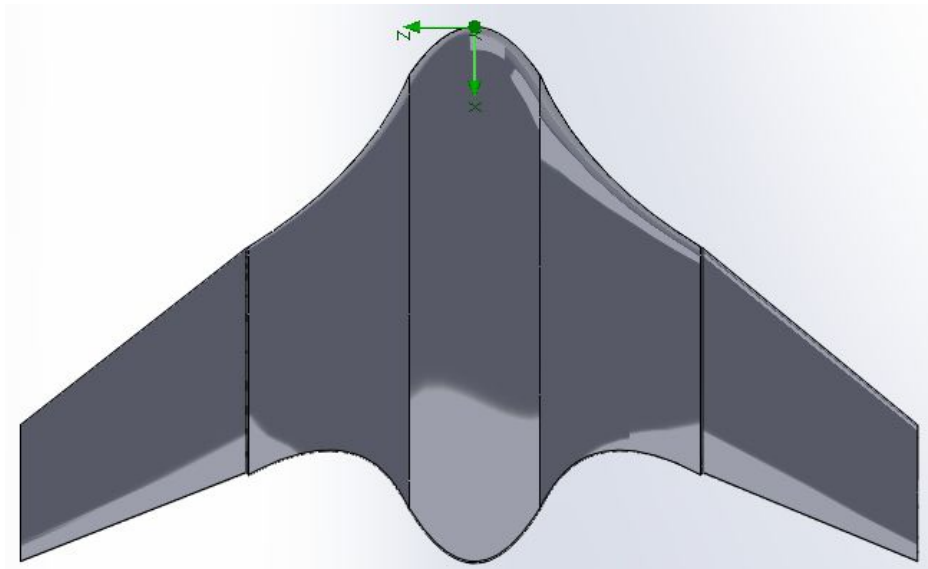Figure 30: Technical Drawing of X-JAB

Figure 31: Isometric View of X-JAB

Figures 32-34: Top, Front , and Right views of X-JAB

Engine Sizing and Design

The engines of X-JAB-EFT were designed through parametric analysis of an ideal turbofan engine. The parametric analysis was done to optimize the engines' thrust specific fuel consumption during cruise. At the cruise velocity of 255.9 m/s, cruise altitude of 10,000 m, and altitude density of 0.38856 kg/cu.m, the drag was determined to be an average of 148,000 N. For 4 engines, the average thrust required from each engine is 37,000 N. Using all assumptions and equations from Appendix A-II, for 4 engines, the thrust specific fuel consumption of the engines was determined to be 0.000013 (kg/s/N).

For this design, the overall core compression ratio is 60. The fan pressure ratio is 1.3, with an optimal bypass ratio of 20.24. The temperature entering the core turbine is 1600 K. Each engine has a core exit velocity of 648.32 m/s, with a bypass exit velocity of 322.6 m/s, a core air intake of 26.09 kg/s, and a bypass air intake of 528.08 kg/s; the total air intake into each engine is 554.16 kg/s. Using continuity principle, the inlet area for the core and bypass are determined to be .264 sq.m and 5.347 sq.m respectively. The pressure ratio across the turbine required to power the engine is 0.4016, and the fuel to air ratio required to produce the thrust from the given engine is 0.01848.

With the current iteration of the engine design, the total fuel consumed for the required range of 11,260 km is 85,397.55 kg. Comparatively, the total fuel consumed for the equivalent range by a Boeing 747-400 is 124,051 kg, resulting in a 31.16% reduction in fuel consumed by the X-JAB-EFT.

**Analysis**

Fuel Consumption Analysis

For the final engine design chosen to power the X-JAB aircraft, calculations were made to compare the fuel consumption on a typical 5 hour cross-country flight from Atlanta, Georgia to Los Angeles, California to that of the Boeing 747-400. On this 5 hour flight, a Boeing 747-400 will consume 68,576.63 L of fuel. Comparatively, X-JAB will consume 49,227.98 L. A per set comparison of fuel consumed shows that the Boeing 747-400 will consume 164.85 liters of fuel per passenger at a max capacity of 416 passengers, compared to X-JAB at 118.37 liters per passenger at max capacity or 416 passengers. At a cost of 56 cents per liter of Jet A-1 fuel, the Boeing 747-400 will use $38,098 on this 3,120 km flight, or $91.58 per passenger. X-JAB will use $27,349 for the same flight, equating to $65.74 per passenger.

The results of a single cross-country flight from Atlanta to Los Angeles show that X-JAB is able to provide a fuel savings of $25.84 per passenger over a Boeing 747-400. On a fully booked flight, the total fuel savings equate to $10,749. This fuel savings is significant; if X-JAB is flown the equivalent of only 3 cross-country flights daily, in a single year, X-JAB will use $11,770,389.87 less fuel than conventional aircraft in the same class.

Flow Simulation Results

Through Solidworks flow simulations, there is an ability to add global goals to the simulation to quantify results, the global goals for these flow simulations were set for Av Total Pressure, Av Velocity, Force is the X direction (drag), and Force in the Y direction(lift). Also knowing the parameters for density and velocity, as stated above, allowed the ability to calculate the lift and drag coefficients for different angles of attack. The main goal was steady level flight for this aircraft to decrease overall fuel consumption by at least 30%. Through flow analysis,

with the given parameters the flow going over the aircraft does not go supersonic and therefore

cannot create too much drag or create structural failure.
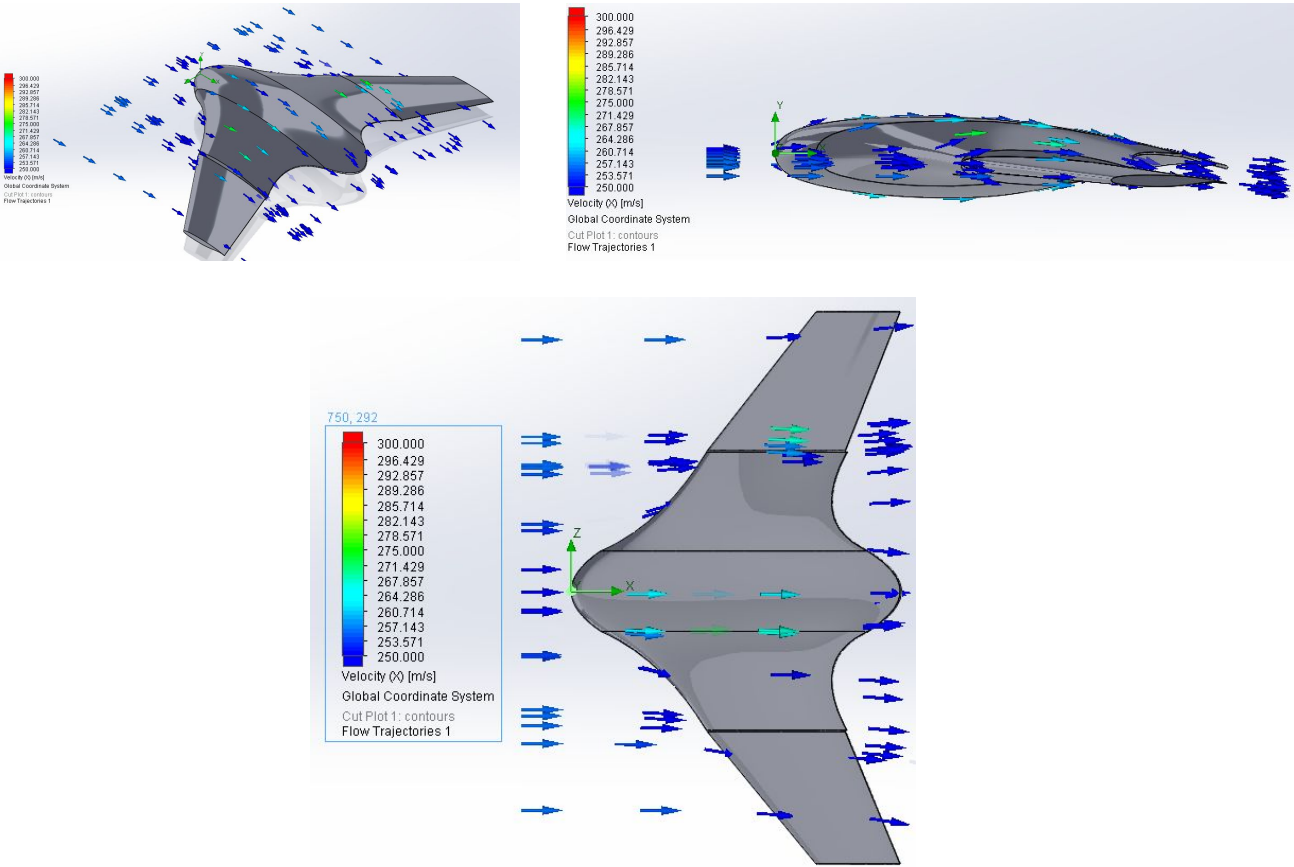
Figures 35-37: Flow during steady level flight

Angle of Attack	Lift (N)	Cl	Drag (N)	Cd	L/D	rho (kg/m^3)	Wetted Area (m^2)	Velocity (m/s)
0	755968	0.05409197905	126164	0.009027446195	5.99194699	0.388452	1098.81	255.9
1	536460	0.03838546484	234789	0.01679991967	2.284860023			
2	1125810	0.08055538189	248261	0.01776388526	4.534783957			
3	1586900	0.1135478771	231934	0.01659563509	6.842032647			
4	1970010	0.1409606487	211392	0.01512578791	9.319226839			
5	2406890	0.1722208393	190712	0.01364606638	12.62054826			
6	2925360	0.2093190609	163680	0.01171183851	17.87243402			
6.5	3132520	0.2241420354	158377	0.01133239154	19.77888203			
7	3376350	0.2415888681	148059	0.01059410494	22.80408486			
8	3893860	0.2786183986	119626	0.008559630945	32.55028171			
9	4274890	0.3058823394	122884	0.008792751484	34.78801146			
10	4681170	0.3349530001	103995	0.007441181851	45.01341411			

Figure 38: Lift and Drag from Flow Simulations

Conclusion

The X-JAB Ultra Efficient Commercial Transport is able to achieve a 31.6% reduction in fuel costs compared to the Boeing 747-400. The design with the given airfoils, produces enough lift to sustain flight, and produces less drag, allowing for better efficiency of the fuel system. The X-JAB compared to the 747 also has a reduction in cost of fuel per person $25.84 for a flight from ATL to LAX.

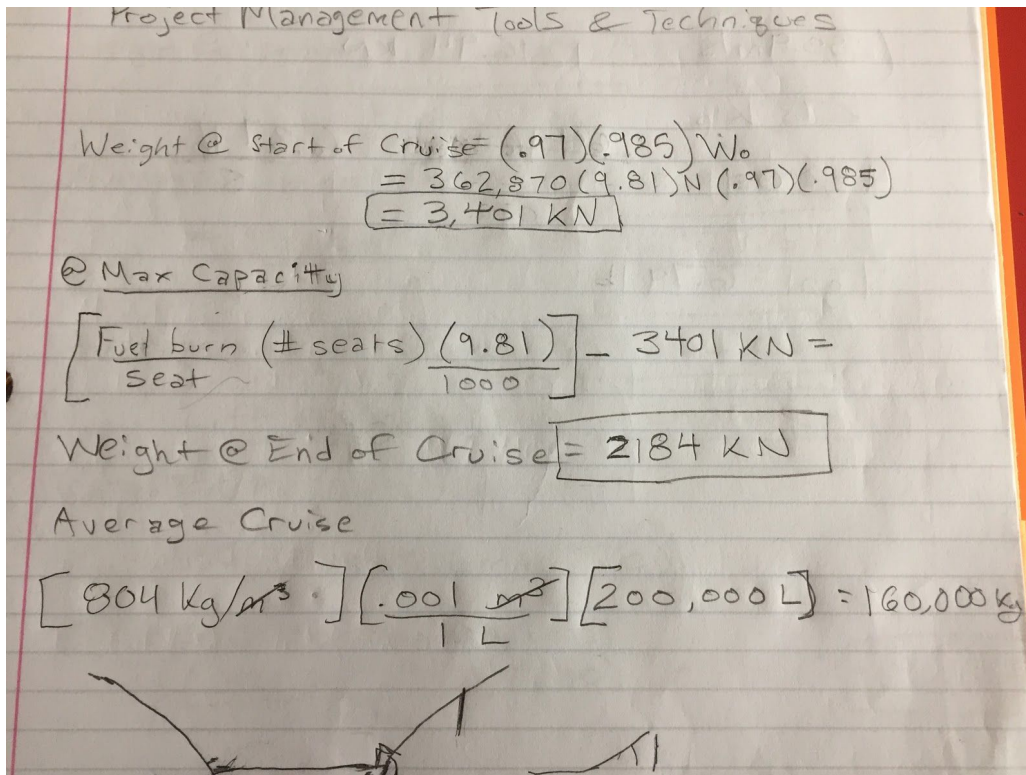|	X-JAB-EFT	Boeing 747-400
Fuel Capacity (L)	162,816	203,520
Fuel Burn per Seat (kg)	205.3	292.8
Fuel Burn [ATL to LAX (L)]	49,228	68,577
Fuel Cost (ATL to LAX)	$27,349.79	$38,098.00
Fuel Cost per Person (ATL to LAX)	$65.74	$91.58

Figure 39: Fuel Savings

Gantt Chart

Appendix

A-I. Calculations

Using 747;
$S_{wet} \approx (70.06m)(2.5m)(\pi)$
$+ 525m^2$
$S_{wet} \approx 760 m^2$
$[.66 \cdot S_{wet}] = S_{bl} = 510 m^2$
$S_{bl}(.5) = 255 m^2$
$\frac{1}{2} b(h) = 255 m^2$
$\tan^{-1}(h/b) = \tan^{-1}\left(\frac{3.25}{2.75}\right)$
$1.18 b = h$
$\Rightarrow b = 20.77m$
$h = 24.55m$

24.55m

41.54m

5.456m

5.456m

24.55m

Image 1 (top-left)
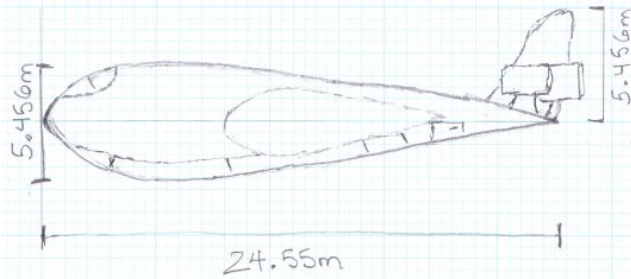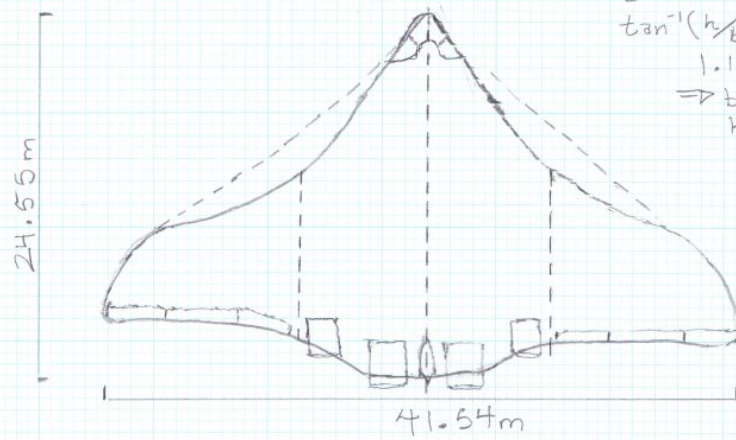
Weight @ start of Cruise = $(.97)(.985)(W_o)$
$= (.97)(.985)(362.07 Mg)(9.81) = \boxed{3401\ KN}$

Weight @ Landing = $260.36 Mg (9.81 \frac{KN}{Mg})$

$\boxed{= 2554\ KN}$

Average Cruise Weight @ Max capacity
$= \frac{3401 KN + 2554\ KN}{2} = \boxed{2977.6\ KN}$

Average Lift in Cruise $= \boxed{2977.6\ KN}$

Lift @ Cruise Start $\boxed{= 3401\ KN}$

$V_\infty = .855\ M\ (c) =$

$V_\infty = .855(331\ m/s + .6 m/s (T^\circ C))$

$T^\circ R\ @\ 34,700 ft\ (standard\ day)$

$7\left[\frac{(397.6 - 394.1)(1100)}{1000}\right] + 394.1^\circ R = 396.85^\circ R$

$\frac{396.55^\circ R - 491.76}{1.8} = {}^\circ C = -52.844^\circ C$

$C = 299.29$

$\boxed{V_\infty = 255.9\ m/s}$

Image 2 (top-right)

Average Lift Cruise = $\boxed{2977\ N}$

Wing Area, $S_{ref} = \boxed{509.9\ m^2}$

$= 2\left(\frac{1}{2} bh\right) = 2\left(\frac{1}{2}(41.54 m)(24.55 m)\right)$

@ 34,000 ft $\rho = .38857\ kg/m^3$

$V_\infty = 255.9\ m/s$

$L = \frac{1}{2}\rho V^2 S C_L$

$C_L = \frac{2L}{\rho V^2 S} = \frac{2(2977.600\ kg \cdot m)}{(.38857 \frac{kg}{m^3})(255.9 \frac{m}{s})^2 (509.9\ m^2)}$

$\boxed{C_L = .45899}$ in cruise

$C_D = .02\ ?$ with NACA 0018

$C_{?} = $ BAC 463

Image 3 (bottom-left)

$C_W = \frac{W_c}{\frac{1}{2}\rho V^2 S_{ref}}$

Wing Wetted Area

$S_{w(wet)} = [2 + 0.5(t/c)_w]\left\{ \frac{Q_w \sqrt{A_w(1 + \lambda_w)}}{K_\theta t/c} \right\}^{2/3}$

$A_w = b_w^2 / S_w$ [Aspect Ratio]

t/c [mean thickness ratio] = ratio of $\frac{frontal\ area}{planform\ area}$

λ = taper Ratio

$K_\theta = .95$

$Q_w = \frac{K_\theta (t/c)_w}{\sqrt{1 + \lambda_w}} S_N \sqrt{\frac{S_w}{A_w}}$

Section I	Section II
$A_w = .55367$	$A_w = 1.4627$
$\lambda = .461$	$\lambda = .411$
$t/c = .3556$	$t/c = .4109$
$t/c = .222$	$t/c = .4047$
$Q_w = 582.564$	$Q_w = 239.64$
$S_{wet} = 399.48\ m^2$	$S_{wet} = 204.8926$

$\left(S_{wet_{total}}\right) = 2(S_{w_1} + S_{w_2}) = 1278.24$

Image 4 (bottom-right)

$\left(\frac{8.28 mm}{15 mm}\right) 11 m = 6.072\ m$ = diameter fuselage

$\left(\frac{62.45 mm}{95.4 mm}\right) 70.66 m = 45.15 m$ = length fuselage

Front cone
$\left(\frac{12.7 mm}{95.4 mm}\right)(70.66 m) = 9.358\ m$ = length

Rear cone
$\left(\frac{21.88 mm}{95.4 mm}\right)(70.66 m) = 16.106\ m$ = length

Fuselage Wetted Area
$2\pi r (L) = 2\pi (6.072 m)(45.15 m) = 861.27\ m^2$
                                        $+$
$\pi r (r + \sqrt{h^2 + r^2})$ $122.79\ m^2$
                                        $+ 185.28\ m^2$
                                        $\boxed{1169.34\ m^2}$
                                        $+$
Wing Area (Ref) $1019.8\ m^2$
$509.9\ m^2$ $\boxed{2189.14\ m^2}$
$2(S_{ref}) =$
Horizontal Stabilizers $+ (239.2\ m^2)(2)$
$\frac{1}{2}\left(\frac{13.54 mm}{89 mm}(70.66 m)\right)(22.17 m)$
                                        $+ 78.7\ m^2 (2)$
Vertical Stabilizer
$\frac{1}{2}\left(\frac{18.98 mm}{89 mm}(70.66 m)\right)\left(\frac{12.13 mm}{22.81 mm}\right)(19.41 m)$

                                        $\boxed{S_{wet} = 2824.94\ m^2}$

$\boxed{(S_{wet})(.66) = 1864.46\ m^2}$

Wing Reference Area

$$\frac{\frac{1026.25}{5283(1+.461)}}{.95(.3556)} \cdot \sqrt{.55367} = S_w^{(3/2)}$$

$$\boxed{S_{w_1} = 582.68\,m^2} \quad \boxed{195.44\,m^2}$$

$$\frac{\frac{533.97}{1775.7}\left(\sqrt{1+.411}\right)\sqrt{1.4627}}{.95(.4109)} = S_w^{(3/2)}$$

$$\boxed{S_{w_2} = 349.54\,m^2} \quad \boxed{156.89\,m^2}$$

$$2(S_{w_1} + S_{w_2}) = \boxed{S_w = 704.66\,m^2}$$

$$\frac{582.6875\left((.95)(.222)\right)^{2/3}}{\frac{\left(\sqrt{.55367}(1+.461)\right)^{2/3}}{2+0.5(.3556)}} = Q_w^{2/3}$$

$$Q_{w_1} = 1026.25\,m^3$$

$$\frac{(349.542)\left(\frac{.95(.4047)}{\sqrt{1.4627}(1+.411)}\right)^{2/3}}{2+0.5(.4109)} = Q_w^{2/3}$$

$$Q_{w_2} = 533.97\,m^3$$

$$\boxed{L = \tfrac{1}{2}\rho V^2 S_{ref}\,C_L}$$

$$\frac{2\left(2,977,600\,\frac{kg\cdot m}{s^2}\right)}{.38857(255.9\,m/s)^2(704.66\,m^2)} = C_\rho$$

$$\boxed{C_\rho = .3321}$$

$$C_{\ell max} = \frac{2\,W_o}{\rho\,V_{takeoff}^2\,S_{ref}} \quad ; \quad \begin{array}{l} V_{takeoff} = 80.467\,m/s \\ S_{ref} = 704.66\,m^2 \\ W_o = 3559754.7\,N \\ \rho = 1.12857\,kg/m^3 \end{array}$$

$$C_{\ell max} = 1.3826$$

Calculations at 5000ft altitude + 20°F offset

Thrust in cruise: 31,000 lb
Thrust in Takeoff: 133,300 lb

	16 Engines	8 Engines	4 Engines
Cruise	5167 lb	3875 lb	7750 lb
Takeoff	22,217 lb	16,662.5 lb	33,325 lb

New $C_{\ell cruise} = .418$

A-II. Parametric Analysis Equations and Assumptions

A-II.1. Equations

$$R = \frac{\gamma - 1}{\gamma} c_p$$

$$a_0 = \sqrt{\gamma R g_c T_0}$$

$$\tau_r = 1 + \frac{\gamma - 1}{2} M_0^2$$

$$\tau_\lambda = \frac{T_{t4}}{T_0}$$

$$\tau_c = (\pi_c)^{(\gamma-1)/\gamma}$$

$$\tau_f = (\pi_f)^{(\gamma-1)/\gamma}$$

$$\frac{V_9}{a_0} = \sqrt{\frac{2}{\gamma - 1} \left\{ \tau_\lambda - \tau_r[\tau_c - 1 + \alpha(\tau_f - 1)] - \frac{\tau_\lambda}{\tau_r \tau_c} \right\}}$$

$$\frac{V_{19}}{a_0} = \sqrt{\frac{2}{\gamma - 1}(\tau_r \tau_f - 1)}$$

$$\frac{F}{\dot{m}_0} = \frac{a_0}{g_c} \frac{1}{1+\alpha} \left[\frac{V_9}{a_0} - M_0 + \alpha \left(\frac{V_{19}}{a_0} - M_0 \right) \right]$$

$$f = \frac{c_p T_0}{h_{PR}} (\tau_\lambda - \tau_r \tau_c)$$

$$S = \frac{f}{(1+\alpha)(F/\dot{m}_0)}$$

$$\eta_T = 1 - \frac{1}{\tau_r \tau_c}$$

$$\eta_P = 2M_0 \frac{V_9/a_0 - M_0 + \alpha(V_{19}/a_0 - M_0)}{V_9^2/a_0^2 - M_0^2 + \alpha(V_{19}^2/a_0^2 - M_0^2)}$$

$$\eta_O = \eta_T \eta_P$$

$$\mathrm{FR} = \frac{V_9/a_0 - M_0}{V_{19}/a_0 - M_0}$$

$$W_{to} = \frac{W_p + W_{fix}}{1 - \dfrac{W_{var}}{W_{to}} - \dfrac{W_f}{W_{to}}}$$

$$C_L = \frac{W}{\dfrac{1}{2} \rho V^2 S}$$

$$T = D = \frac{1}{2}\rho V^2 C_D S$$

$$M = \frac{V_t}{a}$$

A-II.2. Assumptions

$$h_{PR} = 42{,}800 \, \text{kJ/kg.}$$

$$\gamma = 1.4,$$

$$c_p = 1.004 \, \text{kJ/(kg} \cdot \text{K)}$$

$$\tau_d = \tau_n = 1$$

$$\pi_d = \pi_n = 1$$

$$\tau_c = \pi_c^{(\gamma-1)/\gamma}$$

$$\tau_t = \pi_t^{(\gamma-1)/\gamma}$$

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