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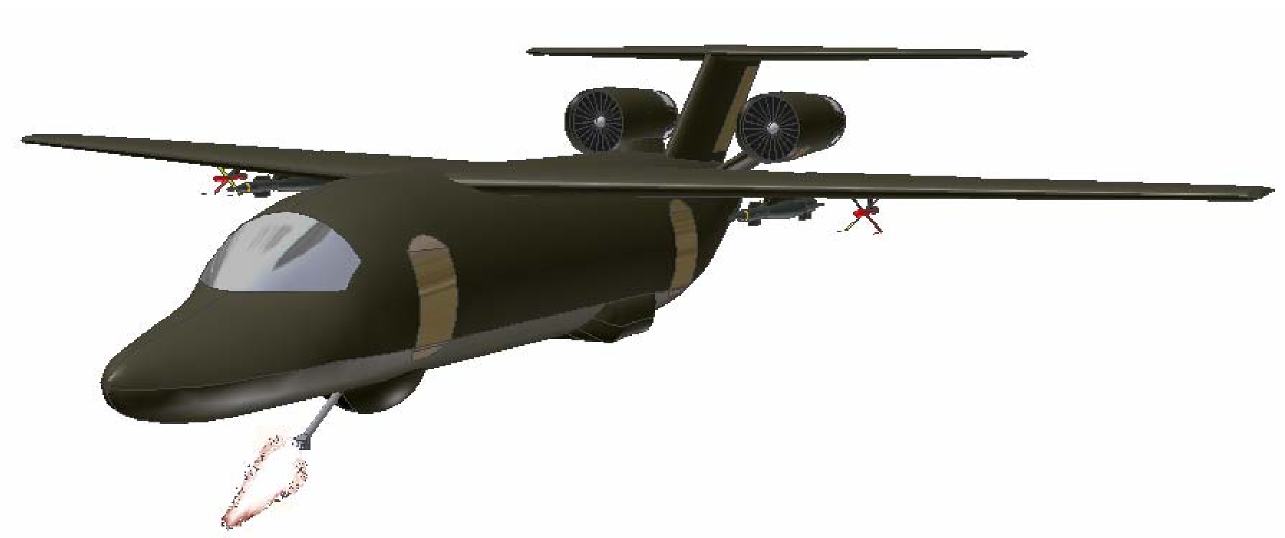

"PHOENIX"

Advanced Gunship Proposal
2004-2005 AIAA Aircraft Design Competition

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Very special Thank You to Nikolai Vozza and Michael Sherman

Executive Summary

HokieWorks, a Virginia Tech design team, is proud to present Phoenix in response to the 2004-2005 AIAA Foundation Undergraduate Team Aircraft Design Competition Request For Proposal (RFP).

Phoenix makes use of a conventional configuration with the incorporation of a high-wing, T-tail, and external fuselage-mounted engines. It is equipped with a weapons package including a 40mm cannon and a 105mm Howitzer cannon, as well as 2 wing-mounted GBU-12 Paveway II laser-guided bombs and 2 “Viper Strike” BAT munitions. Access to ammunition canisters is available through two easily accessible doors, one on the forward fuselage behind the 40mm cannon and one just behind the 105mm cannon near the rear of the aircraft, allowing for quick turn-over time between missions.

Phoenix also employs state-of-the-art target acquisition systems capable dual targeting/tracking in both all light and infrared modes. A top-of-the-line navigational system completes the aircraft.

Coming in at just under 70,000 pounds, Phoenix has a wingspan of 76.9 feet and a length of 68.9 feet. With an estimated acquisition cost of roughly $33.1 million per aircraft, Phoenix is cheaper and smaller than anything currently maintained by the Defense Department for this given application.

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Symbols

α	Angle of attack
Λ	Sweep angle
η	Efficiency
λ	Taper ratio
ρ	Density
AR	Aspect ratio
b	Wing span
c	Chord length
$\bar{c}$	Mean aerodynamic chord length
C_D	Drag coefficient
C_{D0}	Zero-lift drag coefficient
Cfe	Equivalent skin friction coefficient
CL	Lift coefficient
Cl_α	Lift curve slope
Cm_α	Pitching moment derivative
c_{root}	Root chord length
D	Drag
F	Fuselage lift factor
h	Center of gravity location
h_n	Neutral point location
L	Lift
L/D	Lift to drag ratio
M	Mach number
$P_{K/E}$	Prob. of a kill for N number of shots
$P_{K/SS}$	Prob. the aircraft is killed (by a hit), given a single shot
P_K	Prob. the aircraft is killed in a single-shot scenario
$P_{S/E}$	Prob. the aircraft survives the N (identical) shot engagements
P_{SS}	Prob. the aircraft will be engaged by a single shot threat
S	Reference area
S_{wet}	Wetted reference area
T	Thrust
V	Velocity
W	Weight

Acronyms

AAA	Anti aircraft artillery
ABL	Airborne laser
ACG	Adaptive configurable EGI
AIAA	American Institute of Aeronautics and Astronautics
ALLT	All light level television
BAT	Brilliant anti-tank
CFC	Carbon fiber composite
CG	Center of gravity
CNI	Communication/Navigation/Identification
COTS	Commercial off-the-shelf
DGL	Digital laser gyroscope
EGI	Embedded global positioning and inertial navigation
FLOPS	Mission analysis program
GBU	Guided bomb unit
GPS	Global positioning system
HE-P	High explosive-plugged
IDS	Infrared detection system
INS	Inertial navigation system
JSF	Joint strike fighter
JSOW	Joint standoff weapon
LAIRCM	Large aircraft infrared countermeasures
LAV	Light armored vehicle
LGB	Laser guided bomb
MANPADS	Man-portable air defense system
IR	Infrared
RDT&E	Research, development, test and evaluation
REVS	Radar enhanced vision system
RF	Radar frequency
RFP	Request for proposal
SAM	Surface-to-air missiles
SBC	Single board computer
SFC	Specific fuel consumption
SR	Signature reduction
TADS	Target acquisition designation sight
TOGW	Take-off gross weight
TSFC	Thrust specific fuel consumption
UAV	Unmanned aerial vehicle

Compliance Matrix

RFP Requirement	Section and Page Number(s)
Survivable against MANPADS and AAA threats with $P_{K\|E}$ less than 0.10 for both threat encounters	Chapter 5, Pages 22-26
Mission radius of 500 nm with minimum 4 hours on station unrefueled	Section 13.1, Page 78
Aircraft capable of aerial refueling	Section 12.1.4, Page 72-73
Counter/kill threats including personnel, trucks, light armored vehicles, and buildings	Section 4, Page 16
Payload of 15,000 lbs or more	Section 4.4, Page 20
Avionics and Sensors required to accomplish the mission	Chapter 12, Pages 69-76
Initial cruise ceiling of 30,000 ft at a speed no less than 400 knots	Section 13.4, Pages 80-82
Structural load limit of at least 3.5 g's, with a FS of 1.5 for the ultimate load factor	Section 7.2, Page 39-40
2,600 nm cruise to austere base unrefueled	Section 13.2, Pages 78-79
Landing distance over 50 ft obstacle with 1 engine out at operating weight empty plus 40% fuel and max payload shall be less than or equal to 5,000 ft.	Section 13.3, Pages 79-80
Optimization carpet plots	Section 6, Pages 31-32
3 view general arrangement drawing	Section 1, Pages 4-5
Inboard profile with internal arrangement	Section 4.1, Page 17
Primary load bearing structure and material selection rationale	Section 7.1 Pages 38-39, Section 7.3 Pages 40-45
V-n Diagram	Section 7.2, Page 40
Estimated drag build up for cruise	Section 8.4, Page 51
Component weight breakdown	Section 9, Pages 56
Performance and stability estimates	Chapter 11, Pages 63-68
Life Cycle costs of 100, 200, and 400 planes	Section 14.5, Pages 87-88
Fly-away and acquisition cost for 100, 200, and 400 planes	Section 14.3, Pages 85-86

1. Introduction

Recent events in the Middle East involving US military engagements have shown the need for a new, more modernized gunship capable of dealing with low-cost threats, to be operated over a varying terrain and/or combat situation in the place of American infantry units. The war on terrorism and the hunt for the Al-Qaeda terror network has taken US soldiers into lands of extremely rough terrain where they have encountered enemy guerrilla tactics that have put them in harms way. Finding these rebels has proven to be difficult for units on the ground. Aerial reconnaissance and subsequent strike is therefore deemed to be ideal for this military operation. With the development of a new gunship, our armed forces would be capable bringing the fight right to the enemy while keeping the majority of their personnel out of immediate danger.

This year, the AIAA RFP[1] calls for the design of an Advanced Gunship capable of responding to rapidly changing combat situations. The key focus is the development of a highly-survivable aircraft against low-cost threats, these being Anti-Aircraft Artillery (AAA) and Man-Portable Air Defense Systems (MANPADS). It is requested that the aircraft be capable of carrying weapons that provide *"precision and persistent firepower, affordably"*. It is also desired that the aircraft have a low weapon cost per shot/kill, as well as a low acquisition and life-cycle cost to accommodate the Defense Department budget.

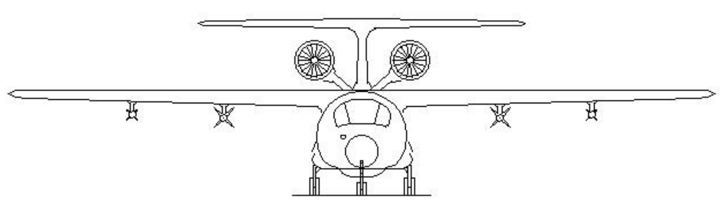
In Egyptian mythology, the Phoenix was a bird that lived in the desert and consumed itself with fire only to rise again reborn. Today, our modern Phoenix occupies the role of the Advanced Gunship specified by the AIAA Foundation Competition RFP. The aircraft is equipped with two cannons; a M2A1 40mm cannon with 400 rounds of ammunition on a forward-mounted turret capable of ± 90° lateral movement, and a 105mm Howitzer cannon with 80 high-fragmentation steel shells that descends from the belly of the aircraft, capable of ± 35° of lateral movement. Advanced targeting systems, including the AAQ-26 IDS, ALLT-IDS, and TADS sight, are capable of all types of detection and allow for easy target acquisition and destruction. In additions to the guns, Phoenix is equipped to carry a mixed wing-mounted guided ordinance consisting of 4 GBU-12 Paveway II laser-guided bombs and 2 “Viper Strike” BAT munitions.

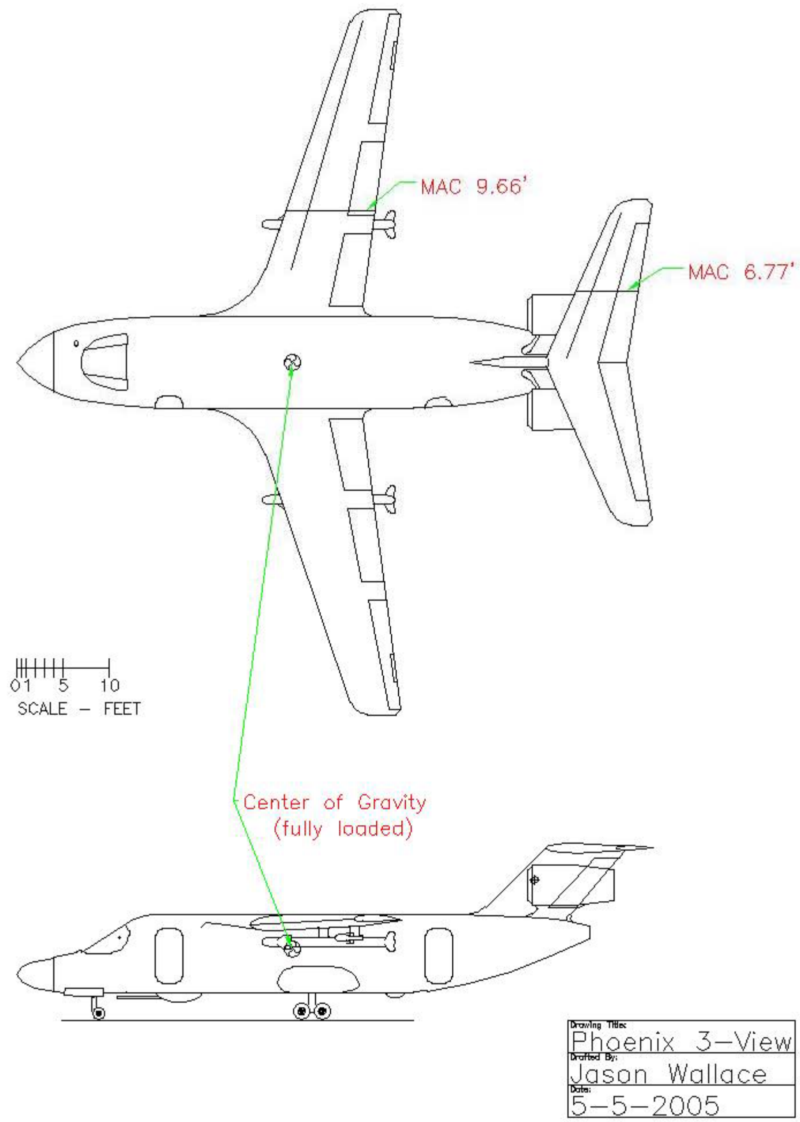
While extremely lethal, Phoenix is also well protected from the dangers that it may encounter. The aircraft is extensively protected with a combination of metal and composite armor. Twin engines, redundant systems, and the LAIRCM countermeasures system all help to ensure that the Phoenix will make it home safely from each mission.

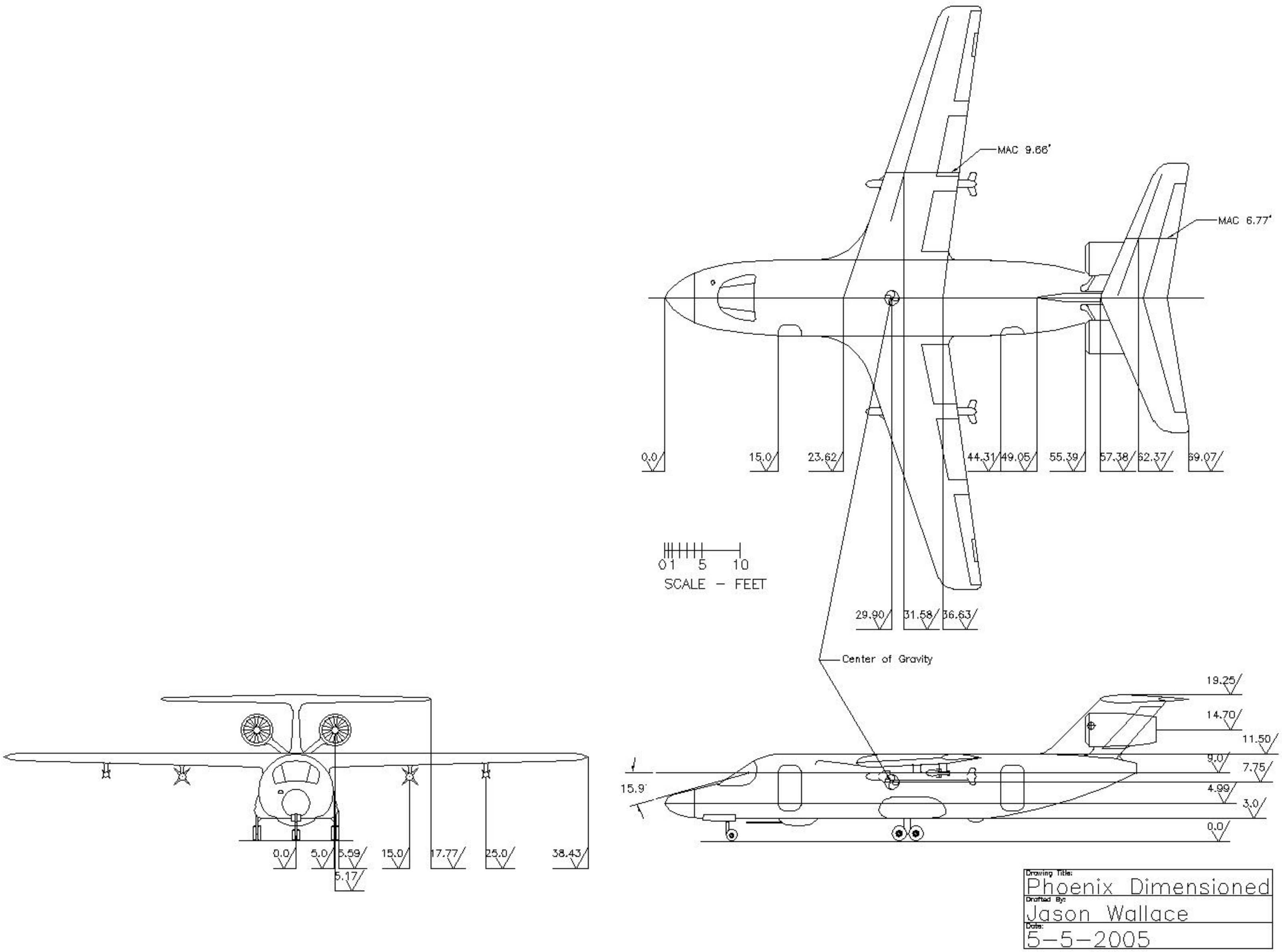
Upon landing, access doors located in close proximity to both onboard cannons, as well as the pylon-mounted wing ordinance, reduce turn-around time and allow the Phoenix to return to its appointed station. There is a vast flexibility in the types of ammunition and ordinance that can be comprised in the aircraft’s payload making the Phoenix not only extremely versatile, but a formidable opponent.

The "Phoenix"

PHOENIX	
Length	69.07'
Span	76.85'
Height	19.25'
Root Chord	13.01'
Tip Chord	5.20'
Aspect Ratio	8.44
Sweep Angle (1/4c)	15.9
Max Lift Coeff.	2.3
Max Speed	0.7 @ 36,000'
Static Thrust	44,000lbs
TOGW	69,984lbs
Empty Weight	32,513lbs
Payload Weight	15,568lbs
T/W Ratio	0.629



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Drafted By:
Jason Wallace
Date:
5-5-2005

2. Understanding the Problem

The overall objective for this project is to design a survivable and economical aircraft that has the ability to deliver precision firepower at a persistent rate. The design mission for the project requires the aircraft to remain on station for a minimum 4 hours, waiting to respond to any immediate threats in the area.

The aircraft must also have a $P_{K|E}$ lower than 0.10 against the AAA threat and a $P_{K|E}$ lower than 0.10 against MANPADS. These are the main drivers for the aircraft and were considered throughout the design process. The design mission for this aircraft, seen in Figure 2.1, is composed of a cruise period for at least 500 nautical miles at an altitude above 30,000 feet, a four hour minimum loiter period at 20,000 feet, weapons release at 10,000 feet, and finally a cruise back to base.

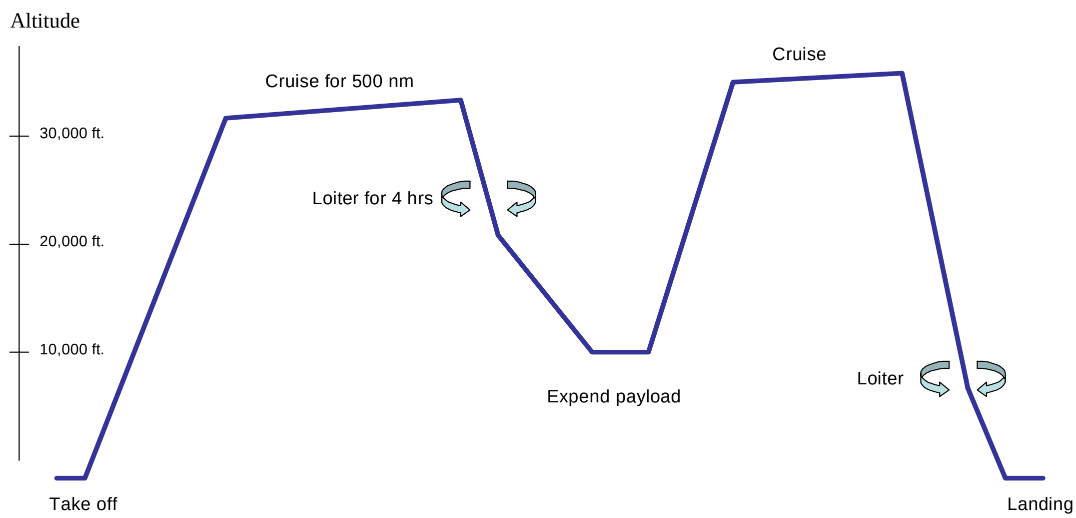

Figure 2.1: Design Mission Profile

Because the extended loiter period fuel and weight considerations take precedence in the design of the aircraft, a high *L/D* ratio upwards of 10-15 would be needed to provide the aircraft with enough endurance to complete the loiter period while conserving fuel.

The secondary mission shown in Figure 2.2 requires the aircraft to cruise to an austere base at least 2,600 nautical miles away.

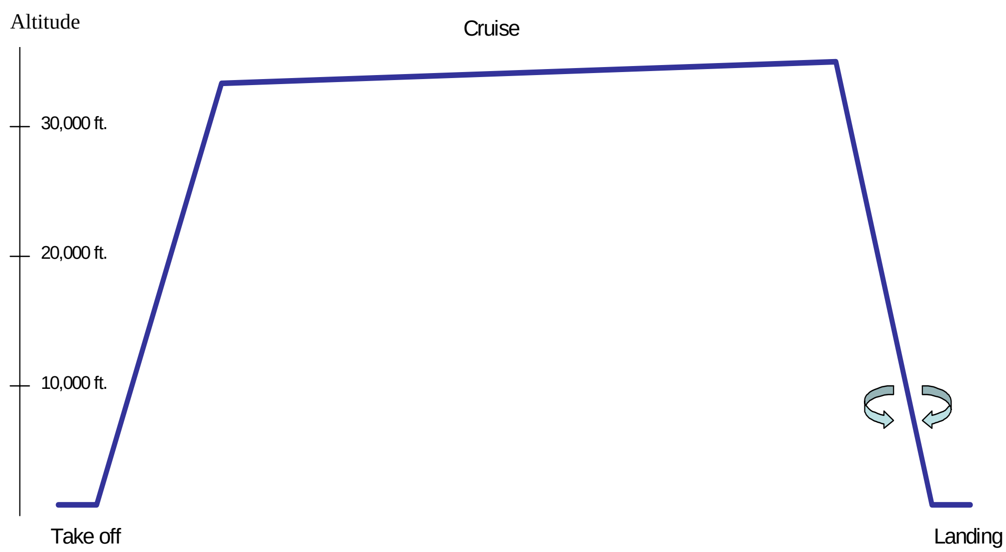

Figure 2.2: Secondary Mission Profile

While fuel and endurance are main driving forces for this project, the aircraft should be designed around its weapon platforms.

The aircraft must be able to counter/kill personnel, trucks, light armored vehicles and buildings in the most cost effective manner available. All of these targets can be destroyed using four weapons systems: one M2A1 40 mm cannon, one M102 105mm howitzer, four GBU-12 Paveway II laser-guided bombs, and two "Viper Strike" BAT munitions. The 40mm and 105mm guns can be used to eliminate personnel, trucks and LAVs while the Paveway II and "Viper Strike" would target bunkers or buildings. All of these weapons, with the exception of the new

"Viper Strike" technology, have been around for years and are inexpensive, yet accurate. The 40mm gun can deliver persistent fire while the 105mm howitzer can destroy larger targets effectively. The Paveway II guided bombs are also cheap but have laser targeting, making them extremely accurate. Other munitions, such as the JSOW guided bomb and cluster bombs were not used because they saturate a large area with smaller bomblets at a high cost. Since this aircraft must provide close-air support it would not be logical to drop cluster bombs in areas close to friendly troops.

Survivability was another main consideration when designing our aircraft. To meet $P_{K|E}$ requirements the aircraft would have to be able to react to and survive AAA and MANPADS threats. Using active countermeasures provides a large part of this deterrence. Also, material selection for the wings, fuselage, control surfaces and areas housing the main guns is essential to the design. Composites, such as carbon fiber epoxy will be used on the wings since it has a high strength-to-density ratio.[4] Composites are lighter than most metals, hold up under high stress, and localize damage. Titanium would be used in regions on the bottom of the fuselage to protect the 40mm and 105mm guns and their personnel, along with the pilot and co-pilot.

Another main survivability issue was the decision between one or two engines. The decision was made to use two engines with space in between so that the aircraft would be able to survive if one engine was damaged during combat. The engines will be placed on the top of the fuselage on either side of the vertical tail instead of on the wings or under the wing on the side of the fuselage. By moving the engines above the fuselage, they become less susceptible to enemy fire from the ground.

When investigating initial aircraft concepts one of the most controversial decisions was in making the design manned or autonomous. It was concluded that for our design, a manned aircraft would be the best choice for a number of reasons. First, the environment that the aircraft would be operating in would be one where reaction time and ability are critical. Close-air support calls for individuals to react to combat situations that are changing every minute and require a crew that can do so effectively. Today, many unmanned aerial vehicles (UAVs) are used for reconnaissance or individual strike missions with predetermined targets. The best way to provide friendly troops with support is to have on-board pilots flying the aircraft so that weapons personnel can effectively find and neutralize enemy targets. Secondly, on today's battlefield communication is critical. UAVs have been proven to be susceptible to jamming from enemy ground stations.[25] If this were to occur the mission would be compromised and the aircraft would be useless. Also, having remote operators flying the aircraft and controlling the weapons and targeting and making all these systems work in unison could be extremely cumbersome. During combat, which could possibly be a close-air support mission, it might be difficult for all these systems (and people) to work together to react in an effective manner when they are hundreds or thousands of miles away from the battlefield. For these reasons it is necessary to have a crew onboard for flying the aircraft, each with specific responsibilities. A crew of five is necessary to carry out the intended mission effectively. Alongside the pilot will be the co-pilot/navigation officer who will be responsible for radar, countermeasures, navigation, communication and assisting the pilot. Also in the cockpit will be a gunner for the 40 mm cannon. He/she will operate the gun through a helmet targeting system. Finally, two crew members will be located in the rear of the plane where they will man the 105 mm weapon. One person will target and fire the weapon and the other will load and remove empty shells. In combat, all of these individuals could work together to respond to a rapidly changing situation more effectively than an autonomous or remote-operated vehicle.

3. Configuration Concepts and Selection

The RFP calls for the design of a new, survivable military aircraft that is capable of providing persistent, precision firepower economically. In short this entails the design of well armored and highly redundant aircraft, equipped with the most effective low cost weapons available. Looking at a more specific design driver from Sections 3.211 and 3.231 from the RFP, a required 4 hour loiter time and take-off and landing distances less than or equal to 5000 feet, we determined that a reasonably high *L/D* and *AR* would be necessary to help increase our fuel economy and allow for maximum lifting force.

3.1. Baseline Configurations

Based on these initial decisions the following three configurations, seen in Figure 3.1, were examined for their feasibility in approaching the design.

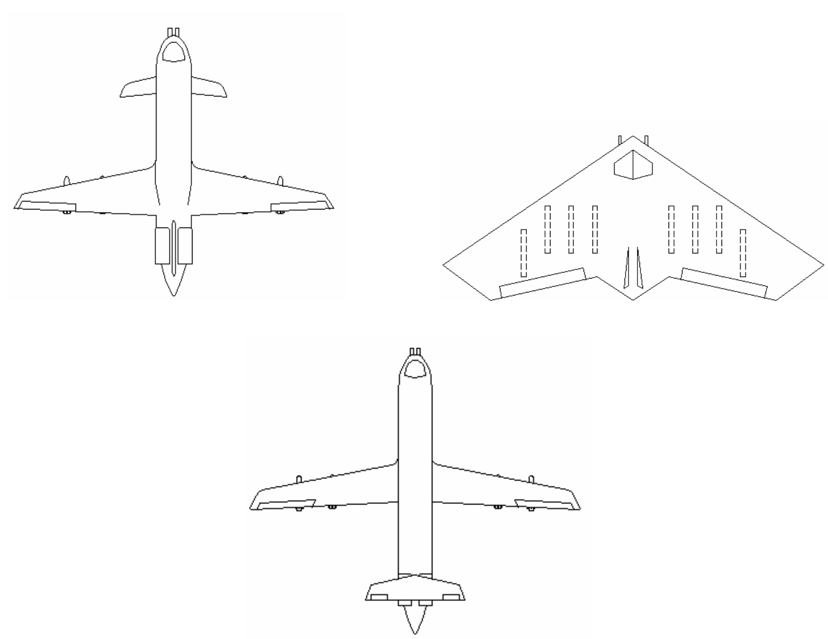

Figure 3.1: Initial configuration concepts

Of the shown configurations, the first two were eliminated after some consideration. The flying wing configuration raised stability and control concerns, while the canard configuration was predicted to generate downwash on the wing. The canard-downwash would prove dually unfavorable by reducing the wing-loading and requiring a technically complex and expensive control system.

3.2. Conventional Concept Variation

Having chosen our preferred configuration we then drew three separate variations, with an emphasis on survivability, payload capability, aircraft autonomy (manned or unmanned) and the wing design.

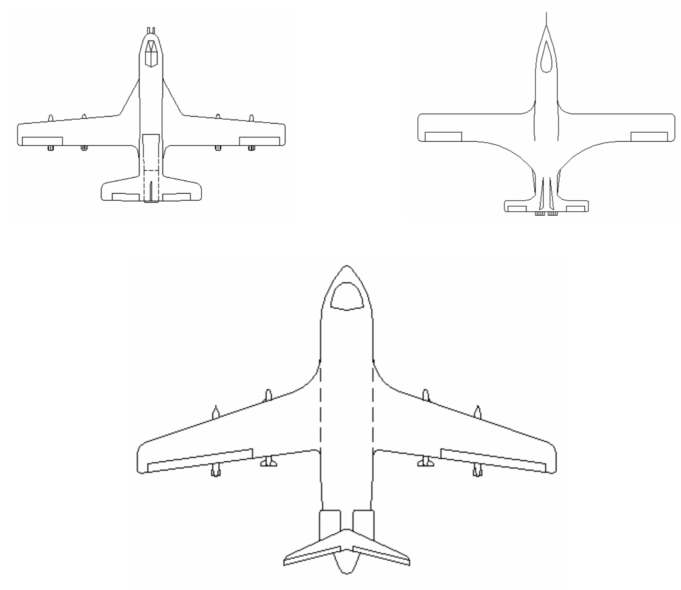

Figure 3.2: Conventional design variations

As shown in figure 3.2, the first two conventional ideas (top) were smaller, and were imagined as A-10 type aircraft. The second of the two smaller aircraft (the picture is not to scale) was mostly distinguished from the first by it being unmanned. The third idea (bottom) was to be relatively larger than the other two and designed as an AC-130 type aircraft.

The first aircraft idea to be eliminated was the small unmanned aircraft. The decision was based on a few deciding points, the first being a UAV's susceptibility to jamming and their inability to act quickly and decisively when cut off from base control. The lack of human control over aircraft operations also greatly limits the aircrafts payload capability. Large, normally man-operated guns like a 105 mm howitzer, an excellent choice for destroying light vehicles and trucks, can not be used. The cost of designing and manufacturing an unmanned control system for such a weapon would be prohibitively expensive.

In addition to the disadvantages in mission performance and payload capacity the aerodynamic inefficiencies that would accompany its lack of leading edge sweep were deemed prohibitive. The RFP quoted a minimum flight speed which allowed for the possibility of sonic or supersonic flight which requires wing sweep for reduced drag.

3.3 Conventional Concept Variation – 2nd Iteration

For the final decision we looked at the configurations, affectionately known as the "Havoc," the smaller A-10 like aircraft, and the "Phoenix," the larger AC-130 like aircraft seen in Figure 3.3 below.

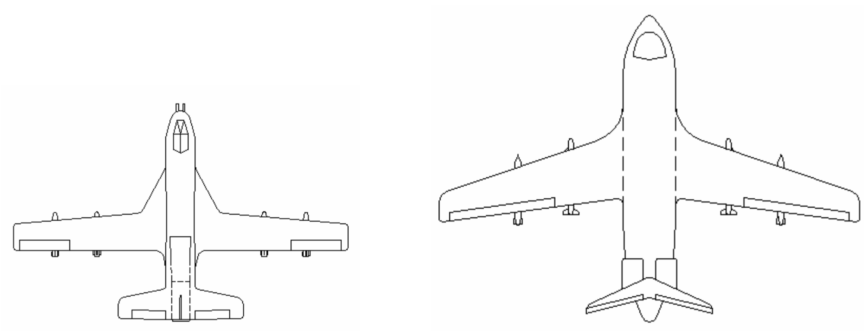

Figure 3.3: Final decision concepts, "Havoc" (left) and "Phoenix" (right)

It was decided that a larger aircraft with the ability to carry large manned cannons would be the best way to meet the RFP requirement of providing persistent, precision firepower economically. This caused us to size up "Havoc" to the scale of "Phoenix" and make a decision based on engine placement and number, wing placement and tail configuration. Table 3.1 shows a decision matrix for the three initial conventional concepts.

	UAV	Design #1	Design #2	Weight %
	Archangel	*Phoenix*	*Early Havoc(small)*	
Survivability	5	8	7	35
Weapons	9	5	7	35
Total Cost	3	9	7	15
Maneuverability	7	4	6	10
Aerodynamics	4	5	6	5
	4.55	7.35	6.75	

Table 3.1: Decision Matrix for Conventional Concepts

3.4 Conventional Concept Variation – Final Concept Selection

The major differences in Havoc in Phoenix during the final iteration, which scaled-up Havoc, are the wing placement (specifically high or low) the tail configuration and the number of engines and their placement. Figure 3.4 shows the scaled-up version of Havoc and Phoenix. Clearly the mid-wing configurations would present trouble in integrating the wing and fuselage due to the location of any large onboard cannon/s or vice-versa. A high-wing like that of the Phoenix solves this issue, creating the ability to place cannons or other weapons that point downward out from the fuselage without having to worry about designing around a wing structure.

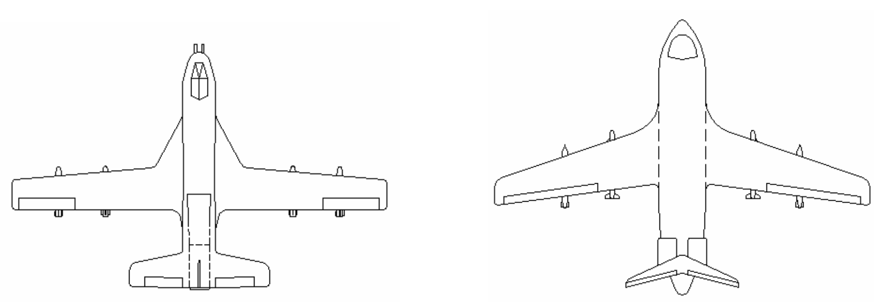

Figure 3.4: Scaled up Havoc and Phoenix

The next issue in deciding between the Phoenix and the Havoc is the number of engines and their placement. Havoc was designed with having one internal engine, though seemingly more protected in the fuselage a direct hit to any engine would certainly be disastrous and so being in the fuselage does not provide any appreciable increase to survivability. Also, having only one engine leaves the aircraft without any options but to glide in the event of an engine failure, which is not a survivable situation. The two engine configuration used on the Phoenix was chosen as the best choice since in an engine out event there would still be some thrust generation to theoretically allow the aircraft to safely land. Also the RFP requires that when landing the aircraft should be able to stop within 5,000 ft on wet pavement, something that would be difficult without a working engine. In regards to the engine placement, having external engines like on the Phoenix was chosen as the best choice for the mission since it allows more room inside the fuselage for cannons or other weapons and eases maintenance work.

Finally the issue of the tail was debated. It was decided that a T-tail would be the better choice since it takes the tail out of the downwash of the wing rendering it more effective in stabilizing the aircraft. This was an important consideration considering that the use of large weapons would cause significant recoil which would need to be counteracted by control structures. Table 3.2 shows some of the advantages and disadvantages of both the concepts.

Aircraft	Advantage	Disadvantage
Havoc	• Aerodynamically efficient • Internal engine (hidden) • Lighter Tail Configuration	• One engine • Low wing (less flexibility with weapon placement) • Tail in downwash
Phoenix	• Aerodynamically efficient • High wing • More Stable (good for recoil) • Twin engine • Easy engine maintenance • Increased firepower	• Higher TOGW • T-tail is heavier than conventional tail

Table 3.2: Comparison between Havoc and Phoenix

It is clear that the Phoenix has the characteristics desirable for the mission profile. It was chosen as the final design concept to optimize.

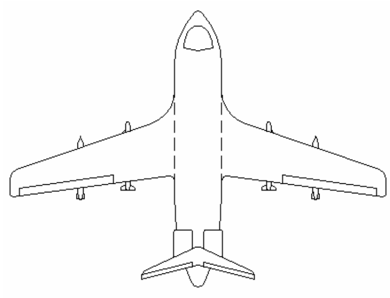

Figure 3.5: Phoenix concept to be optimized for gunship application

4. Payload

Since the purpose of this project is to design an advanced gunship, lots of thought and consideration went into selecting the weapons. The AIAA RFP states that "this aircraft must be capable of carrying weapons that provide precision and persistent firepower affordably." In order to select the most suitable weapons, careful attention must be paid to the targets. As seen in Table 4.1 a weapon has been selected to answer to every threat stated in the RFP.

Target	Weapon
MANPADS/ Personnel	40mm Cannon
AAA	40mm Cannon/ 105mm Cannon
Trucks	40mm Cannon/ 105mm Cannon
Light Armored Vehicles	105mm Cannon
Buildings	Paveway II Laser Guided Bomb (LGB)

Table 4.1: "A weapon for every target"

As can be seen from Table 4.1, a gatling gun will not be used for this aircraft, even though it has been a staple of the AC-130 arsenal. The reason for not using this proven weapon is cost and precision. The further the aircraft is from a target, the larger the bullet dispersion would be. Rather than using thousands of five dollar rounds to disable a target, the Phoenix will utilize more costly 40mm and 105mm rounds; however it will only require a few rounds to disable a target. This weapon selection played a key role in selecting Phoenix as our aircraft, rather than Havoc, which had been designed with two 25mm Gatling guns mounted on a turret.

A great deal of the research done for this project was spent investigating unconventional weapons. The weapon that stood out the most for potential use was the airborne laser (ABL). Currently, the Air Force has been testing the use of ABLs in Boeing 747s to shoot down enemy missiles. Though there is a potential for the use of ABLs in an attack aircraft, there are far too many drawbacks for practical use. The amount of chemicals required to create a potent laser beam is large. Several truckloads of chemicals are required to generate enough laser shots for one mission. Although Phoenix is not equipped with an ABL, the aircraft may still be used as a platform when the technology is available.

4.1 Weapons Description and Layout

A schematic of the weapons layout appears in Figure 4.1. The figure shows the 40mm and 105mm cannons, along with the ammo racks, with appropriate dimensions in feet. The 105mm M101 cannon will be fully enclosed in the fuselage of the aircraft when flying at cruise altitude, to allow for cabin pressurization. The Paveway II laser guided bombs will be pylon-mounted on the aircraft's wings.

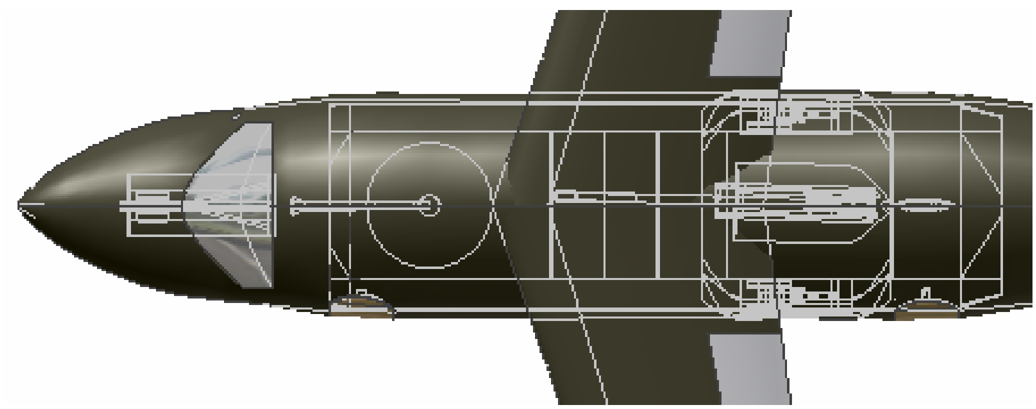

Figure 4.1: Cannon layout inside the fuselage

4.2 40mm Cannon

To respond to low armored threats (personnel, AAA, trucks), a modified M2A1 40 mm cannon will be mounted in a turret near the nose of the aircraft. The turret, seen in Figure 4.2, will utilize an electronic chain feeder system which will supply the cannon with the high explosive-plugged (HE-P) rounds which are ideal for personnel targets.

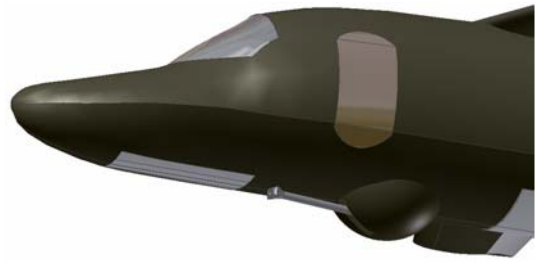

Figure 4.2: 40mm gun turret and TADS sight

The two ammo stores for the 40mm each hold 200 rounds, for a total weight of about 2,000 lbs. The turret, 40mm cannon and feeder system are estimated to weigh around 1,800 pounds. The 40mm weapon system will use the same Target Acquisition Designation Sight (TADS) as seen in the AH-64 Apache. Coupled with an All Light Level Television and Infrared Detection System, the copilot will have total control over the turret when engaging enemies.

4.3 105mm Cannon

HokieWorks was privileged enough to be able to arrange a meeting with various personnel doing ballistics studies at NSWC Dahlgren in Dahlgren, Virginia last November 2004. When asked what was the most cost effective weapon for a gunship application, AC-130H pilot Col. Scott Stephens (ret.) answered, "The 105mm high fragment steel cannon". The 105mm cannon is the primary weapon of this gunship for its ability to provide consistent firepower. The rounds, pictured in Figure 4.3, have a blast radius greater than 30 yards and can be shot 10 times per minute. The primary advantage of these rounds are their relatively low cost, at $500 per round, capable of providing persistent affordable firepower.

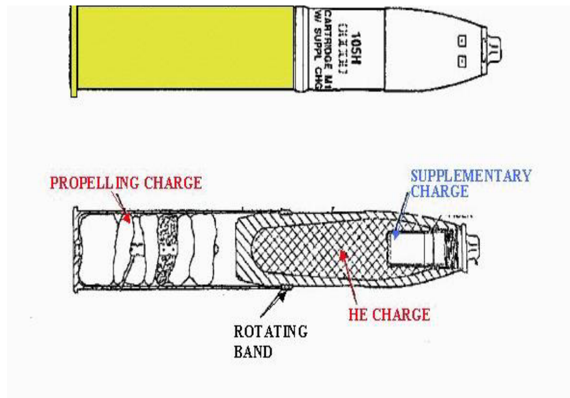

Figure 4.3: 105mm High Fragment Steel round

The main feature of this cannon is its ability to be fully enclosed in the fuselage. Figure 4.4 shows a schematic of the cannon enclosed in the fuselage and in operational mode.

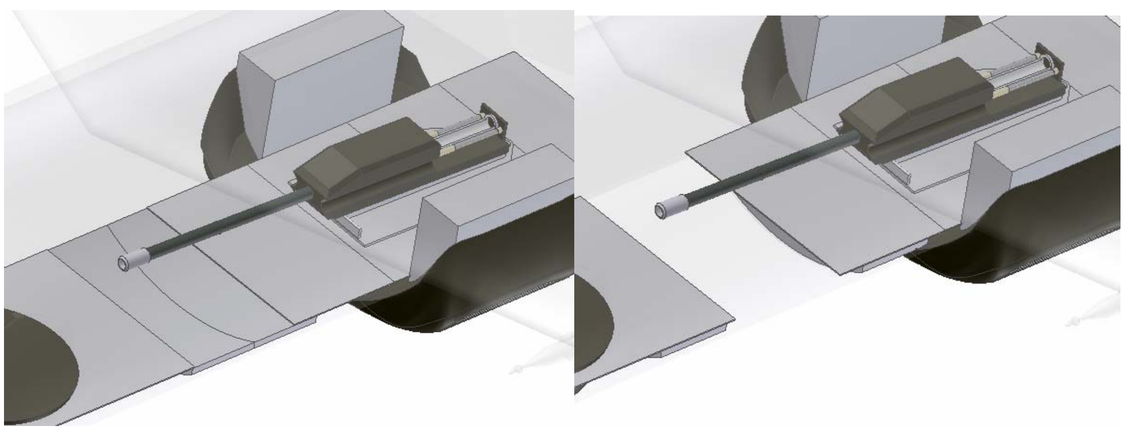

Figure 4.4: 105mm cannon operation

The cannon will have the ability to track targets from ±35º in the horizontal direction, and 20 to 70º in the vertical direction. The ability to be concealed in the fuselage is important for many reasons. Since the aircraft will be flying at 40,000 feet, pressurization of the cabin is important. Also, during cruise and loiter the gun will not influence the aerodynamics of the aircraft. 120 rounds of the 44 pound high fragment steel will be supplied in Phoenix, making for 5,280 lbs of 105mm ammunition. The targeting system used for the 105mm cannon will be the Advanced AAQ-26 Infrared Detection Set (IDS). What makes this system unique is its ability to simultaneously track targets. In other words, as the cannon fires on one target, the system will automatically track other targets in the vicinity, allowing for persistent firepower.

4.4 Laser Guided Bombs (LGB)

To provide precision firepower, and as the primary weapon for buildings, Phoenix will be equipped with four pylon hardpoints on the wings to carry laser guided bombs. The primary bomb used will be the GBU-12 Paveway II.

Since this weapon's primary target will be buildings, this is the ideal laser guided munition. An eight nautical mile range, lightweight at 800 lbs and inexpensive at 19,000 dollars per unit, the Paveway II is the cost effective solution for precision firepower. The targeting system used in conjunction with this LGB is the Pave Tack AN/AVQ-26, which will allow for tracking day or night and even in adverse weather conditions.

In addition to the Paveway II, Phoenix will have the ability to carry the Viper Strike laser guided weapon. This cutting edge weapon is intended to be dropped on targets when they are directly below the aircraft, making an ideal weapon for loitering. The warhead uses only 4 pounds of explosive charge in order to reduce collateral damage. This weapon is a derivative of the Brilliant Attack Munitions (BAT) sub-munitions and will provide precise firepower from a safe altitude.

Item (Quantity)	Weight
40mm Cannon (1)	1,800 lbs
40mm Ammo (400)	2,000 lbs
105mm Cannon (1)	4,800 lbs
105mm Ammo (120)	5,280 lbs
Paveway II (2)	1,600 lbs
Viper Strike (2)	88 lbs
	Total Weight = 15,568 lbs

Table 4.2: Weapon payload weight

Table 4.2 summarizes the weapons payload. The total payload was 15,568 pounds, which met the requirement stated by the RFP.

5. Survivability

The RFP states that the airplane should be designed with a $P_{K/E}$ less than 0.1 for both anti-aircraft artillery (AAA) and man-portable air defense system (MANPADS) threats. The $P_{K/E}$ value is the probability the aircraft will be killed in an engagement consisting of N shots fired by a particular threat. In the following analysis an aircraft is considered killed if it is lost or destroyed. The $P_{K/E}$ is given by the equation,

$$P_{K/E} = 1 - (1 - P_{K/SS})^N \tag{5.1}$$

where $P_{K/SS}$ is the probability the aircraft will be killed by a single shot fired by a particular threat.

The survivability $P_{S/E}$ of an aircraft is the inverse of the kill-ability and is defined as the ability of an aircraft to resist man-made dangers. It is given in terms of $P_{K/E}$ by

$$P_{S/E} = 1 - P_{K/E}\,. \tag{5.2}$$

To increase survivability or conversely reduce the killability of an aircraft, a design must take into account the vulnerability and the susceptibility of the aircraft to any particular threat. Designing aircraft with survivability in mind has become a mainstream design criteria[5]. Designing a survivable aircraft reduces repair costs because less aircraft will be hit and also reduces replacement costs because less aircraft will be lost. Table 5.1 shows possible enhancements used to reduce the vulnerability and susceptibility to enemy weapons fire.

Survivability Enhancement Features		
Speed and altitude	Maneuverability/agility	Chaff and flares
Fire/explosion protection	Terrain following	Fighter escort
Self-repairing flight controls	No fuel adjacent to air inlets	Rugged structure
Redundant and separated hydraulics	Self defense missiles and guns	Good target acquisition capability
Night-time capability	Crew situational awareness	Threat warning system
More than one engine – separated	Hydrodynamic ram protection	Mission planning system
Low signatures	Crew training & proficiency	Anti-radiation weapons
Tactics	Nonflammable hydraulic fluid	Armor
On-board electronic attack equipment	Lethal launch-and-leave or stand-off weapons	Stand-off electronic attack equipment

Table 5.1: Vulnerability and Susceptibility Enhancements[6]

Acquiring how the killability changes with each enhancement is a daunting task. In industry simulations are done for thousands of different scenarios and statistics showing the effectiveness of a particular enhancement against a particular threat or combination of threats. Probabilities measuring the survivability of a particular enhancement are then determined from those simulations.

In the analysis for the killability of the aircraft against the AAA and MANPADS threats historical data from the gulf war was used. To determine which enhancements to use, historical kill rates from the gulf war were analyzed along with the particular enhancements used by each aircraft. During the gulf war allied aircraft flew nearly 65,000 sorties and only lost 38 aircraft. This translates into low values of P_K for all the allied aircraft that participated in the conflict. The P_K for an aircraft is the probability the aircraft will be killed in a scenario. It can be given by the following equation,

$$P_K = P_{K/SS} P_{SS} \tag{5.3}$$

Where P_{SS} is the probability the aircraft will be engaged in a scenario by a single shot coming from a particular threat. Table 5.2 shows the P_K for various aircraft during the gulf war.

Aircraft	P_K
A-10	0.0005
AC-130	0.0099
F-16	0.0002
A-6E (USN)	0.0006
F/A–18 (USN)	0.0005
AV-8B	0.0015
Tornado GR-1	0.0036

Table 5.2: P_K of Allied Aircraft during the Gulf War[5]

Although the P_K value given in Table 5.2 is only the total number of that type of aircraft killed divided by the total number of missions flown by that type of aircraft without considering what type of weapon caused the kill, the majority of the allied aircraft that were killed were shot by either Infrared surface-to-air missiles (IR SAM) or radar frequency surface-to-air missiles (RF SAM).[5] Statistics showing the type of weapon that caused damage on each aircraft type are also available from Reference 5. The majority of the aircraft that were damaged but still returned to base were damaged by AAA fire suggesting that vulnerability to these threats is much lower than the vulnerability to SAM fire.

The highest value for P_K in Table 5.2 is for the AC-130 at about 0.01. This value is misleading because the AC-130's only flew 101 missions, a miniscule mission burden when compared to the total number of missions at nearly 65,000. The A-10, an aircraft with a mission similar to the mission stated in the RFP, flew nearly 8,700 missions and had a P_K of 0.005. The A-10's low killability reflects on the emphasis on survivability used in its design, a characteristic the AC-130 lacks.

In determining what kind of countermeasures are needed to obtain a $P_{K/E}$ below 0.1 for the aircraft design, an estimation of the P_K value for MANPADS and AAA threats must be obtained. This was done by comparing performance characteristics of MANPADS and SAMs. Missiles fired from SAMs are more accurate and have much higher ranges than MANPADS.[7, 8] This results in aircraft having an arguably higher P_K for SAM threats than MANPADS threats. Also, since most of the kills during the gulf war were made by SAMs and not AAA fire, the P_K value for AAA fire is less than that of the SAMs.

By assuming a P_{SS} of 1 (meaning if there is an AAA site along the mission it will fire at the aircraft), a conservative estimate, the P_K becomes equal to the $P_{K/SS}$ value in Equation 5.1. Figure 5.1 shows the $P_{K/E}$ values for the various gulf war aircraft plotted versus the number of shots made by a particular threat which for this data is primarily SAMs.

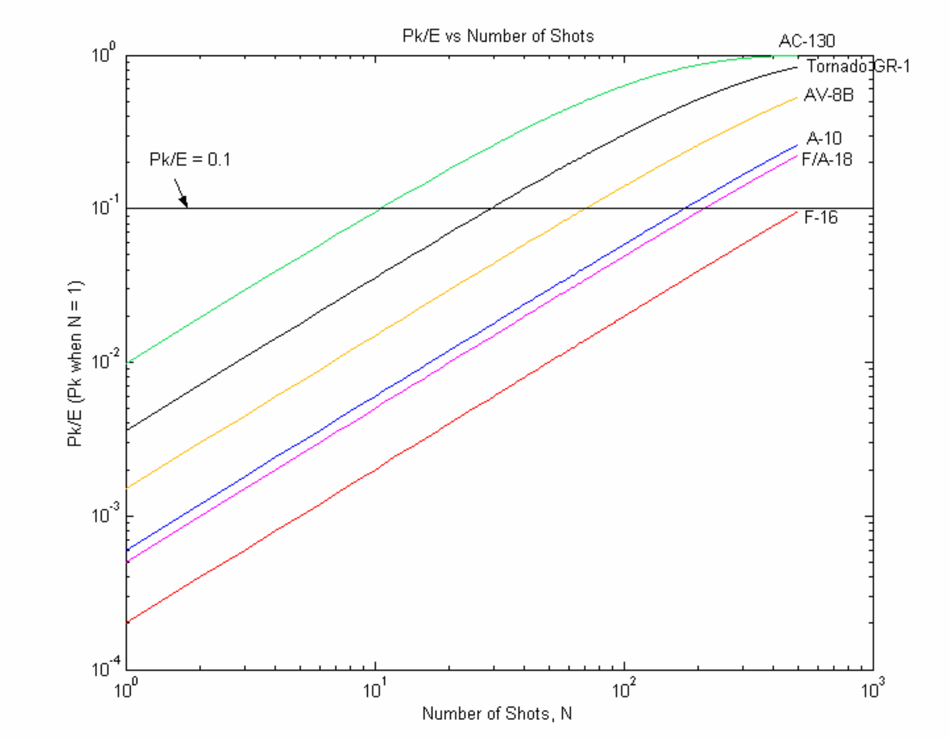

Figure 5.1: $P_{K/E}$ vs. Number of Shots Fired

The constraint that the $P_{K/E}$ be less that 0.1 is shown as the horizontal line labeled accordingly on Figure 5.1. This plot shows conservatively the number of shots that can be fired by AAA or MANPADS threats at the 7 listed allied aircraft based on the historical kill rate. As mentioned before the AC-130 did not have a high P_K and consequently can not take a large number of shots and still satisfy the 0.1 value for $P_{K/E}$. Figure 5.1 shows that the A-10 and F/A-18 can take a very large number of enemy shots, around 150, due to their much lower P_K value. When expending the payload at the required altitude of 10,000 feet, it is unlikely that it will encounter 150 threats from AAA and MANPADS.

Because the data presented in Figure 5.1 is conservative, due to the assumption of $P_{K/SS}$ = 1 and the fact that MANPADS are less accurate and less powerful than the SAMs faced by the allied aircraft during the gulf war, it can be assumed that by designing an aircraft with similar features to the F/A -18 and A-10, a survivable aircraft can be developed to meet the RFP requirement. Table 5.3 lists the major survivability enhancements used on the F/A-18 and the A-10.

Aircraft	Vulnerability Enhancement	Susceptibility Enhancements
A-10	Dual fire walls	Expendables (chaff, flares)
	Self-Sealing Engine Fuel Lines	Low Signature (IR, Radar, Visual)
	Two independent, separated, jam-free flight control systems	Threat warning
	Fuel transfer lines inside tanks	Noise jamming and deceiving
	Bullet/Spill resistant panels and canopy	
	Armor tub for pilot	
	Ammunition drum for gun ballistically protected	
	Closed-cell foam in dry around fuel tanks	
	Both fuselage tanks can feed both engines	
	Two shot fire detection extinguishing system	
	Two independent, separated hydraulic systems	
	aircraft can be flown without hydraulics	
F/A-18	Damage tolerant wing design	
	Fan, compressor, turbine blade containment	
	No fuel over or between engines	

Table 5.3: Survivability Enhancements used on F/A-18 and A-10[5]

The vulnerability enhancements in Table 5.3 are included in the design of the Phoenix and most will not cost any additional money since they are merely designed into the aircraft. Enhancements like the two flight control systems and the two fire suppression systems will increase the cost since they are outside packages that need to be obtained from a seller and integrated into the aircraft.

Adding susceptibility features will increase the cost of the aircraft since, like flight control systems, they are systems that need to be obtained from a seller. The jamming and deceiving equipment and the threat warning equipment as well as the cost is discussed below and also in the avionics section of the report.

Figure 5.4 shows how much can be spent on survivability as survivability is increased and as the number of aircraft ordered is increased. The assumption made is that a lost aircraft must be replaced at cost. Using the different costs, derived in the cost section of this report, for the various order sizes, a limit for how much should be spent on survivability enhancements was developed.

Figure 5.4 shows that as the order size is increased, the cost savings from the survivability enhancements diminishes. It also shows that more survivable aircraft can spend more on enhancements. The idea is that eventually, spending for increased survivability becomes too expensive to justify. A P_k a tenth lower than the P_k of a non-enhanced aircraft for example can be reached and still is cost effective for a 400 airplane order by spending $2 million on enhancements. This limit of $2 million, which is the lowest of all the aircraft order bundles, was used to determine which vulnerability and susceptibility enhancements to include on the Phoenix.

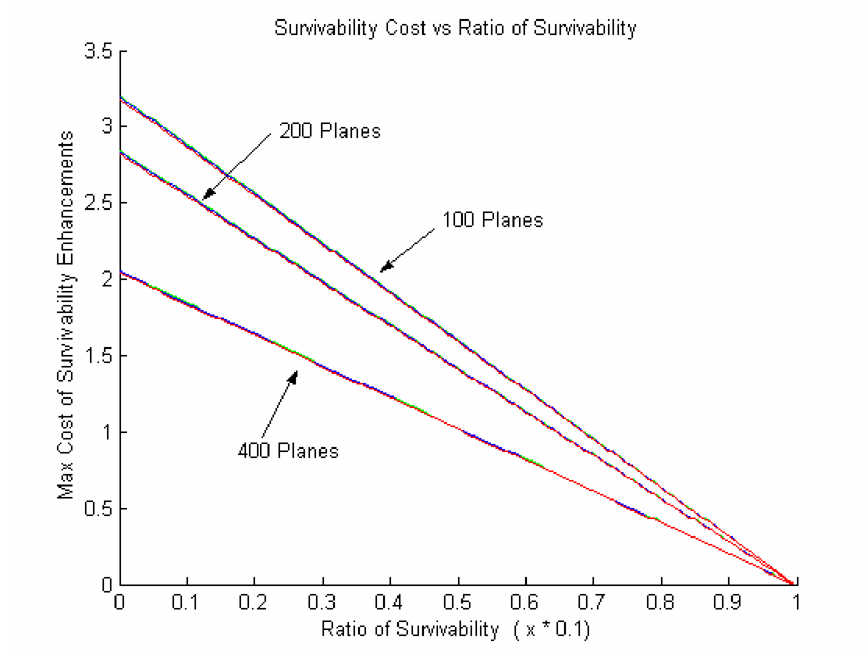

Figure 5.4: Survivability Enhancement's Cost vs. Effectiveness of Enhancements

Table 5.4 lists the enhancements that must be purchased as outside systems or added components that cost additional money and add unaccounted for additional weight.

Enhancements	Approximate Weight, lbs	Approximate Cost, $
Large Aircraft Infrared Countermeasures	< 50	$1,300,000
Extra Flight Control System	< 50	$73,000
Chaff and Flare	< 500	< $30,000
Titanium Armor under Pilot	2,000	$56,000
Titanium Armor under Ammunition Stores	2,000	$56,000
2 x Fire Detection and Extinguishing Systems	< 1000	< $500,000

Table 5.4: Enhancements and Approximate Cost

The need for signature reduction (SR) was discussed and decided against due to the increase price of materials and design work and flight control integration inherent to a stealthy design (i.e. non-aerodynamic shapes). Since the RFP states that the design needs to expend its payload, and thus attack, at 10,000 feet SR was deemed unimportant. Aircraft drop to lower altitudes to attack for the sole purpose of enhanced survivability against high altitude SAMs. At this lower altitude aircraft are observable and susceptible to AAA gun fire and MANPADS systems which depend little on radar for guidance.[5] The above describes a situation where SR has little use.

6. Sizing

Using the constraints given in the RFP and the type of configuration chosen as best for the mission (high aspect ratio, T-tail) the take-off-gross-weight (TOGW) and size for the Phoenix were determined. The landing constraint in the RFP states that *"landing distance over 50 ft obstacle at operating weight empty plus 40% internal fuel and maximum payload shall be less than or equal to 5,000 ft, at sea level, with one engine inoperative and an ICAO Standard Day and wet runway".* It was assumed that with one engine out, the other engine equipped with a thrust reverser and wet pavement the take off distance would be increased by a quarter of the original distance. Figure 6.1 shows a carpet plot of the landing constraint given in the RFP which depends on the C_{Lmax} and wing loading (W/S) normalized to takeoff conditions with the RFP weight constraint accounted for. This relationship is given by equation 6.1,

$$S_{landing} = 80\left(\frac{W}{S}\right)\left(\frac{1}{\sigma C_{L\max}}\right) + S_a \tag{6.1}$$

where S_a is the obstacle-clearance distance. The landing wing loading was assumed to be 85% of the take-off wing loading. This percentage falls within the RFP's landing weight constraint when checked using the final aircraft TOGW with the fuel and payload weights presented earlier in this report.

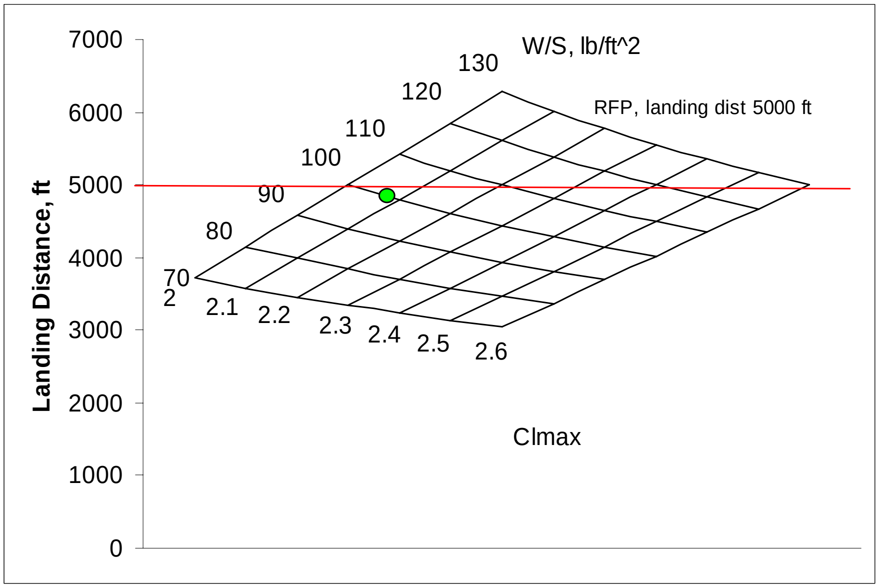

Figure 6.1: Landing Constraint

A *W/S* of 100 lb/ft2 was chosen as reasonable. The highest Cl_{max} should be at landing and thus all other flight regimes should not require a Cl_{max} greater than 2.1. Equations from Reference 4, the 1.5 g maneuver at 20,000 ft constraint given in the RFP and the landing constraint described above were used and a TOGW of 69,250 lbs and a thrust-to-weight ratio (*T/W*) of at least 0.3 was determined for the wing loading (*W/S*) of 100 lb/ft^2. All values are normalized to takeoff conditions. These values are shown in figure 6.2. The optimal direction along the wing loading axis is towards higher values because it means a smaller wing will be needed, meaning less weight and thus cost. The optimal direction along the thrust-to-weight ratio axis is towards lower values since for a given weight a lower thrust would be needed to satisfy the constraints.

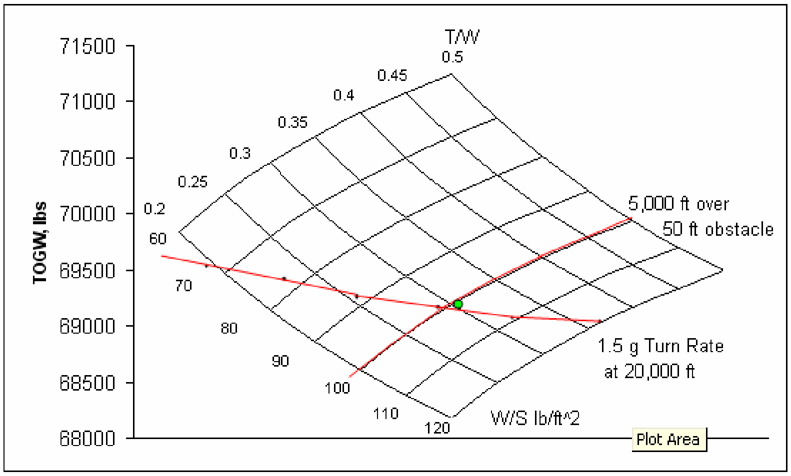

Figure 6.2: Sizing Plot

This analysis required an initial weight guess which is described in the weights section of this report. The initial weight estimation was determined from historical data and estimations of payload and fuel weight and the structural weight needed to support the payload and fuel.

6.1 Wing

With the wing loading and TOGW determined and a range of aspect ratios and the wing shape decided upon, the size of the wings was determined. Selection of the wing characteristics is described in the aerodynamics section of this report. Table 6.1 lists the wing specifications.

	Wing
Area (ft)	699.84
Span (ft)	76.85
Aspect Ratio	8.44
Leading Edge Sweep (deg)	18.6
Quarter Chord Sweep (deg)	15.95
t/c	0.12
Taper Ratio	0.4
C_{root} (ft)	13.01
C_{tip} (ft)	5.202

Table 6.1: Wing Specifications

6.2 Fuselage

The fuselage width was sized to accommodate the 40 and 105 mm cannons and the necessary support equipment and personnel needed for those cannons while remaining compatible with the wing size and the conventional configuration. Table 6.2 lists the fuselage specifications.

	Fuselage Dimensions
Largest Width (ft)	10.0
Largest height (ft)	8.5

Table 6.2: Fuselage Specifications

6.3 Tail

A T-tail was selected to be used on the Phoenix in order to remove the elevators from the wing's downwash. In addition this tail configuration utilizes what is known as the "end plate effect" allowing for increased rudder effectiveness and better handling qualities. The vertical tail however must be strengthened in order to support the weight of the horizontal tail, though the horizontal tail may be smaller than is standard because of its position in the free stream.

Phoenix's T-tail was sized using the method of tail volume coefficients found in Reference 4, based upon previously determined geometries of the wing and fuselage. The sizing went through several iterations and eventually the size of the horizontal tail was significantly increased so that its span was greater than that of the engine nacelles. This concerned stemmed from case study of the DC-9, a similar configuration in which the issue of recovery in "deep stall" at very high AoA was a concern due to the tail being blanketed by the wing wake.[24] The tail specifications can be seen in the following table.

	Horizontal Tail	Vertical Tail
Area (ft)	229.55	136.82
Span (ft)	35.53	7.23
Aspect Ratio	5.5	1.55
Sweep (deg)	23.6	45.0
Taper Ratio	0.45	0.90
C_{root} (ft)	8.91	9.90
C_{tip} (ft)	4.01	8.91

Table 6.3: T-Tail geometry

7. Structures

This section of the report describes the materials selected for each component of the aircraft, the basic structural layout of the aircraft and both the maneuver and gust V-n Diagrams.

7.1 Materials Selection

Two categories of materials stand out as ideal candidates for an aircraft structure, composites, specifically carbon fiber composites (CFC), and aluminum alloys. Aluminum is a classic material used in aircraft structures because of its light weight, high strength and toughness and low cost. Though aluminum has been in use for over fifty years, new alloys like aluminum-lithium are still being developed as stronger, tougher alternatives to their predecessors.

Composites were used before metals in aircraft construction, wood is a composite, but only in the past twenty years have manmade composites begun to play a significant role in aircraft design. Composites are lighter and stronger than aluminum alloys and are thus more appealing to use in aircraft structures since they ideally can save weight for a given configuration.

Other materials such as magnesium and titanium were also examined. Magnesium is extremely light and has a tensile strength comparable to that of some aluminum; however, it is flammable rendering it almost useless in any but the most protected of areas on an aircraft. Titanium is the ideal metallic material for aircraft because of its low density, high tensile strength, ductility, toughness and high performance at increased temperatures. The cost of titanium and difficulty in forming it restricts its use as a high percentage of an aircraft's structure.

After studying the material use of current and new aircraft it is apparent that composites are being increasingly integrated into aircraft design. Europe's newest fighter, the Eurofighter, is almost 85% composite material, using only 15% metal components for hardening of key areas.[9] Boeing's new jet liner, the 787 - Dreamliner, is almost entirely constructed of composite materials.[10]

The advantages of composite materials include higher strength, stiffness and lower density. This means that a composite structural element at the same weight of a metallic element can withstand greater stresses than a metallic one. Composites are also relatively insensitive to flaws. Fatigue testing has shown high resistance to cracking and the propagation of those cracks.[11] They are also highly resistant to corrosion; however, attaching composites to metals must be done cautiously because the galvanic interaction between the two materials can cause accelerated corrosion in the metal. Titanium is and ideal candidate for joints since it is not susceptible to galvanic corrosion.[4]

Composites are also more customizable. The amount of stress that can be carried by a composite member can be optimized in the design to further reduce weight needs. Composites can more easily be molded into a desired shape than a metal allowing for a more streamlined outer skin. Composites also reflect less radar than metals allowing for a more stealthy radar profile.

The major disadvantage of composites is their production costs. Specialized equipment and skilled personnel are required for composite manufacturing and add additional cost to production.[4] It is inevitable, however, that as composites become more widely used the cost will drop. Table 7.1 shows the density to strength and cost to strength ratios for various materials. All costs are considered to be high estimates.

Material	Strength to Density ratio, m-Pa/g	Strength to Cost ratio, MPa-kg/$
Aluminum Alloys	60.26	42.73
Titanium	264.56	9.02
Carbon Continuous Fiber (high Modulus)	447.06	2.76
Aramid (Kevlar)	985.71	22.26

Table 7.1: Density to Strength and Cost to Strength ratios[12]

Table 7.1 shows the huge difference in strength to density ratios between aluminum and carbon fiber composites. Carbon continuous fiber has a strength-to-density ratio almost 7.5 times that of aluminum. Aramid, which is marketed under the name Kevlar®, has the highest strength to density ratio. Aramid is not often used in aircraft because it is not flexible enough, Airbus has even established a design principle that states Kevlar® will not be used in loaded structures.[11] For this reason Aramid was not chosen to be used in the design.

Table 7.1 also shows the strength to cost ratios for the various materials considered for the design. Aluminum, with its relatively low cost has the best cost-to-strength ratio followed by Aramid. The CFC has such a low cost-to-strength ratio because the price per kilogram was quoted at around $275/kg.[12] Because the comparison was made to be a very conservative estimate of prices, due to the lack of information on composite prices, it is possible for this price to be significantly lower. Looking at the prevalence of composite use in new and current aircraft structures, it reasonable to assume the price of CFCs is significantly lower.

Table 7.2 lists various structural components of Phoenix and the material selected for those components.

Component	Material	Color	Reasons
Wing (skin & spar)	Carbon Fiber - Epoxy Resin Composite	Black	Light, Strong, fatigue/corrosion resistant
Leading edges (horizontal tail, wing,	Aluminum-lithium	Blue	tough, light
Vertical Tail & Fin	Titanium	Gray	Heat resistant (near engines), light, strong
Horizontal Tail	Carbon Fiber - Epoxy Resin Composite	Black	
Nose / Radome	Glass / Epoxy	Green	Light, excellent electrical characteristics
Control Surfaces	Carbon Fiber - Epoxy Resin Composite	Black	
Fuselage	Carbon Fiber - Epoxy Resin Composite	Black	
Other Considerations			
Shielding underneath pilot	Titanium	Gray	Pilot protection/survivability
Shielding underneath weapon stores	Titanium	Gray	Survivability

Table 7.2: Component Material Makeup

The majority of the structure is carbon fiber/epoxy composite. This composite is light, strong and resistant to fatigue and corrosion. The CFC is used in the wings for the skin and spars, the fuselage structure, horizontal tail and the control surfaces for the wing and horizontal tail. Titanium is used for the vertical tail and fin and engine nacelles due to its close proximity to the nearby engines. The nose is constructed of E-Glass/epoxy composite due to the materials excellent electrical properties.[11] The leading edges on the wing and horizontal tail are constructed of aluminum-lithium. The leading edges that take on the brunt of the air flow experience the most damage from debris during landing and taking off or flying in adverse weather conditions (i.e. hail damage). It is important for these surfaces to be durable; composites are known to be more easily damaged from impact damage than are metals.[11] Aluminum-lithium is used because it has exceptional strength and toughness making it ideal for areas prone to impact damage. Figure 7.1 shows graphically the location of the materials selected for the Phoenix.

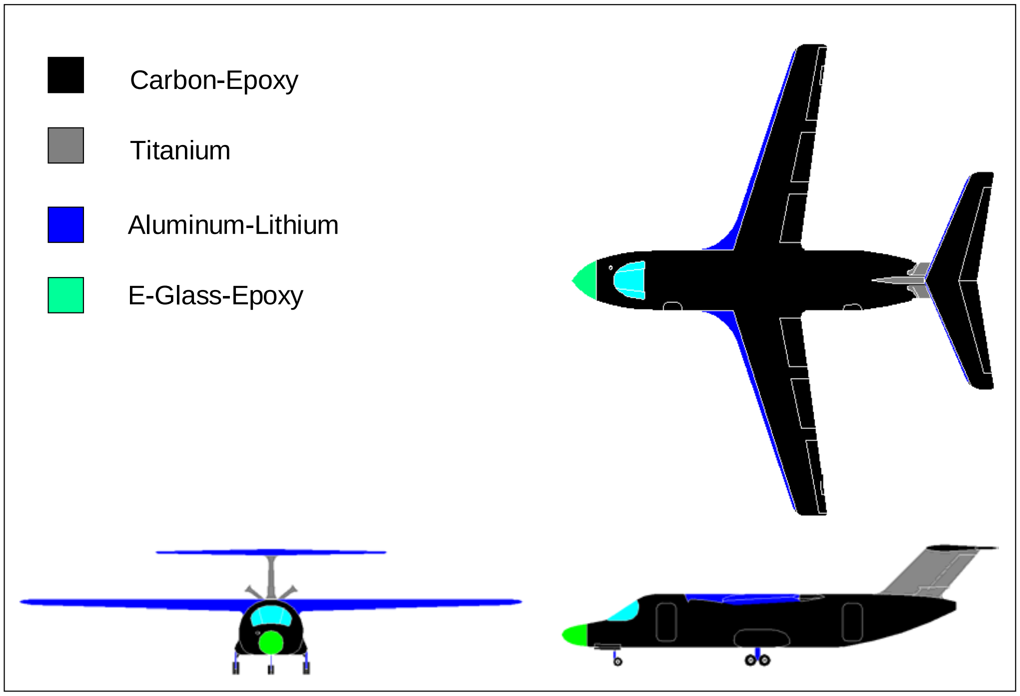

Figure 7.1: Materials Selection

Aluminum-lithium is also used for floor and firewall bulk heads (discussed below) in the interior of the fuselage where the 105 and 40mm guns are installed since these areas will need to also be tough and able to withstand constant impacts from crewman and weapons operation. Although composites are more easily damaged by impacts there have been great advances in composite impact damage resistance that make this less of an issue.[11]

7.2 V-n Diagram

V-n Diagrams are used to graphically show the structural limit loads and the loads associated with stall and various gust loads that are experienced during flight. The aircraft must be designed so that no part of the aircraft is stressed beyond its yield point at the limit load. These limit loads are determined by either the structural limit load, which is given by the RFP as 3.5 g's, or by the gust loads laid out by government regulations. A factor of safety of 1.5 should be multiplied to the ultimate load. The NACA discrete gust conditions were used to define the gust constraint. They are defined as follows.[22]

1. Rough air gust: U = 66 ft/sec at a speed related to the stall speed
2. High speed gust: U = 50 ft/sec at cruise speed V_C.
3. Dive speed gust: U = 25 ft/sec at dive speed V_D

Figure 12.2 shows the V-n Diagram for the Phoenix.

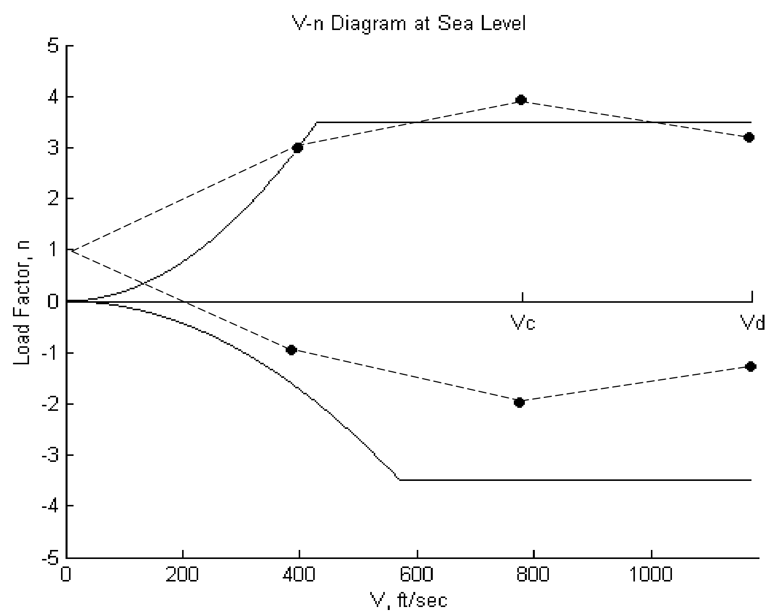

Figure 7.2: V-n Diagram

The V-n diagram shows that the aircraft's structural design should be driven mostly by the maneuvering diagram (solid line). A small portion of the gust diagram (dotted line) stretches above the maneuvering diagram.

7.3 Structural Layout

The structural layout includes the basic structural member layout for the various sections of the aircraft. Figure 7.3 shows a 3-D view of the structural member layout and figures 7.4 and

7.5 show the top and side views of the structural member layout respectively. Members have not been assigned a specific thickness.

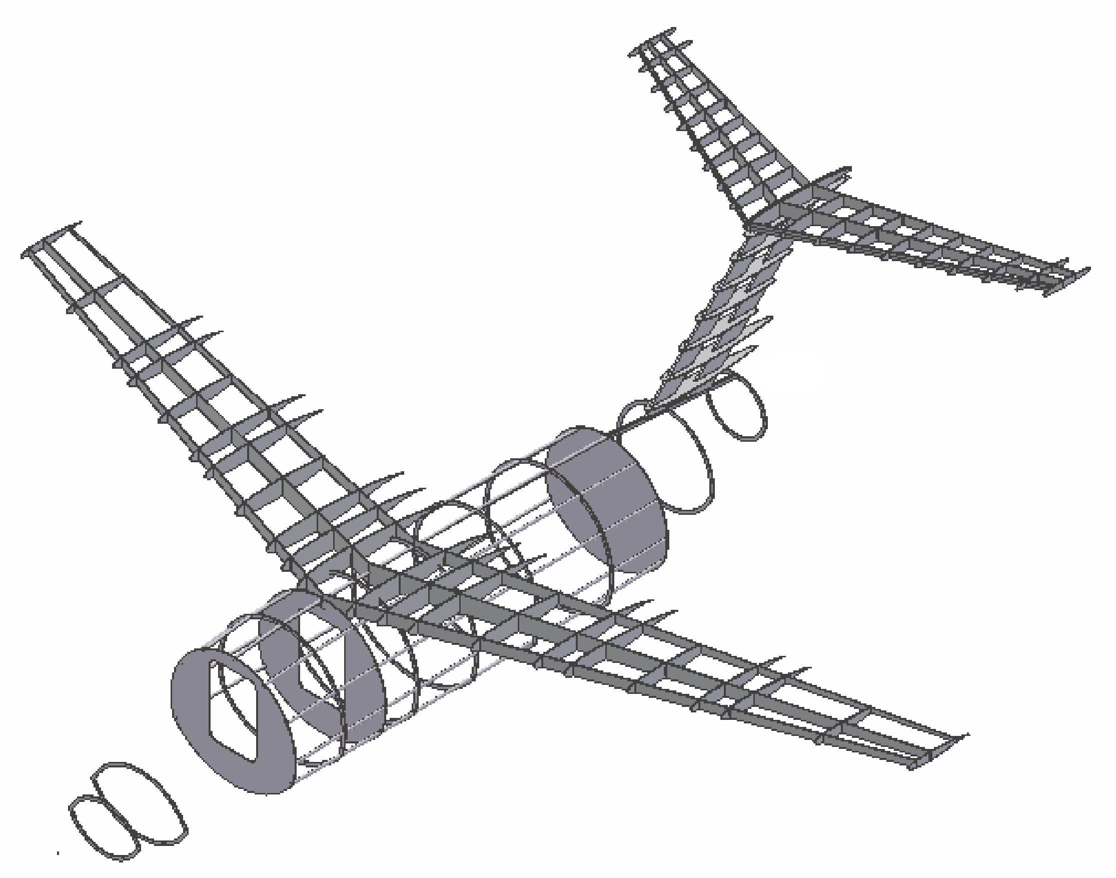

Figure 7.3: Structural Member Layout

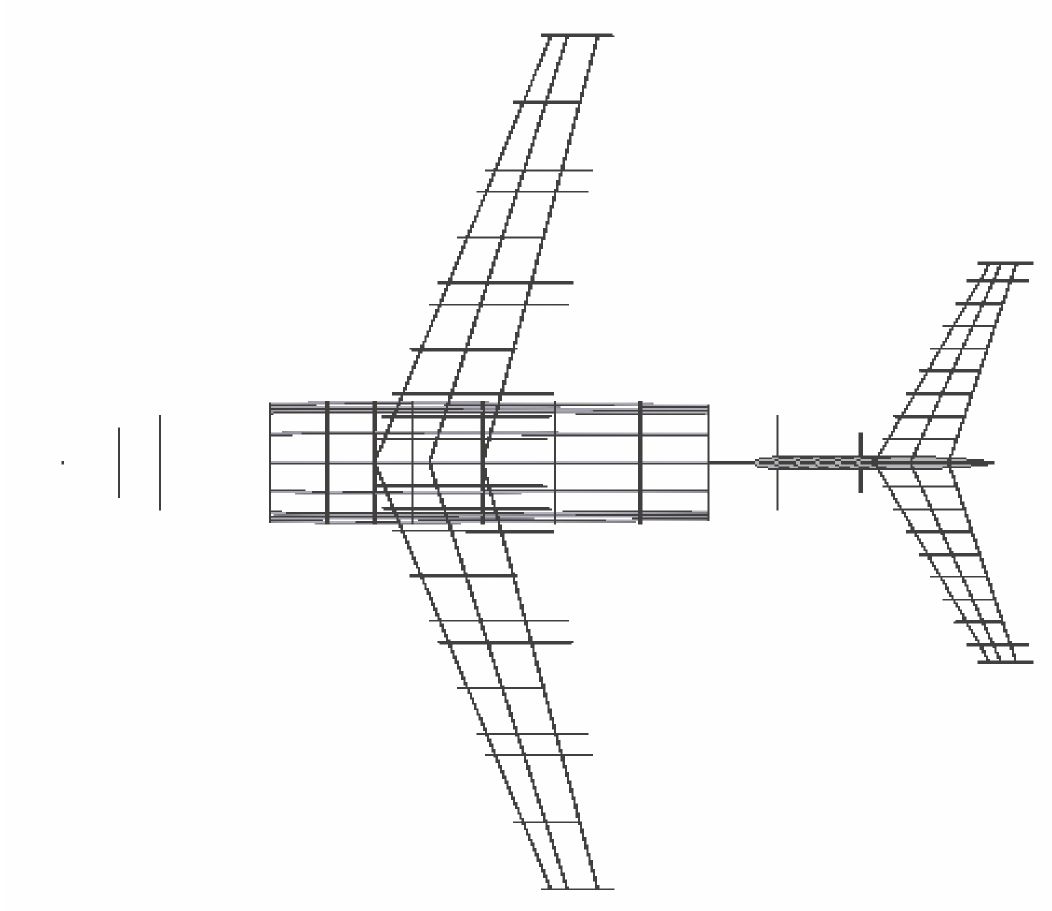

Figure 7.4: Structural Layout - Top View

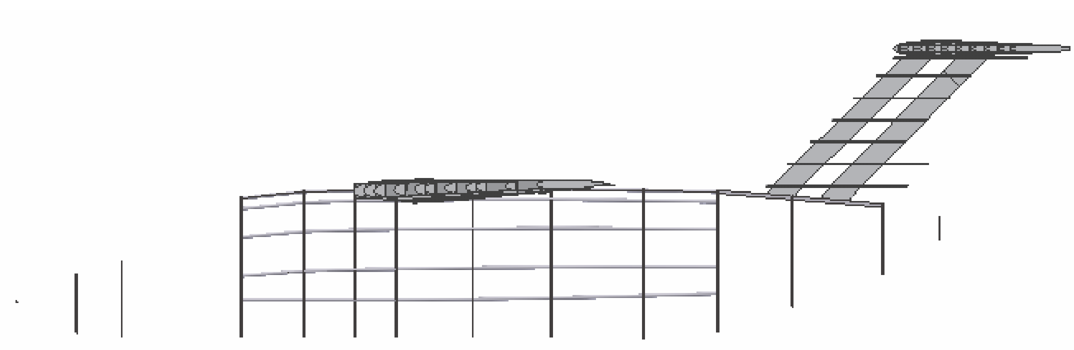

Figure 7.5: Structural Layout - Side View

7.3.1 Landing Gear

Dimensions for the landing gear were estimated using the buckling load and compressive yield load for an aluminum column with a circular cross section as constraints. A solid column was assumed the best choice but further analysis found a weight savings in making the members hollow (a ring cross section). Figures 7.6 and 7.7 show the front and back landing gear respectively and show how they fit into the fuselage.

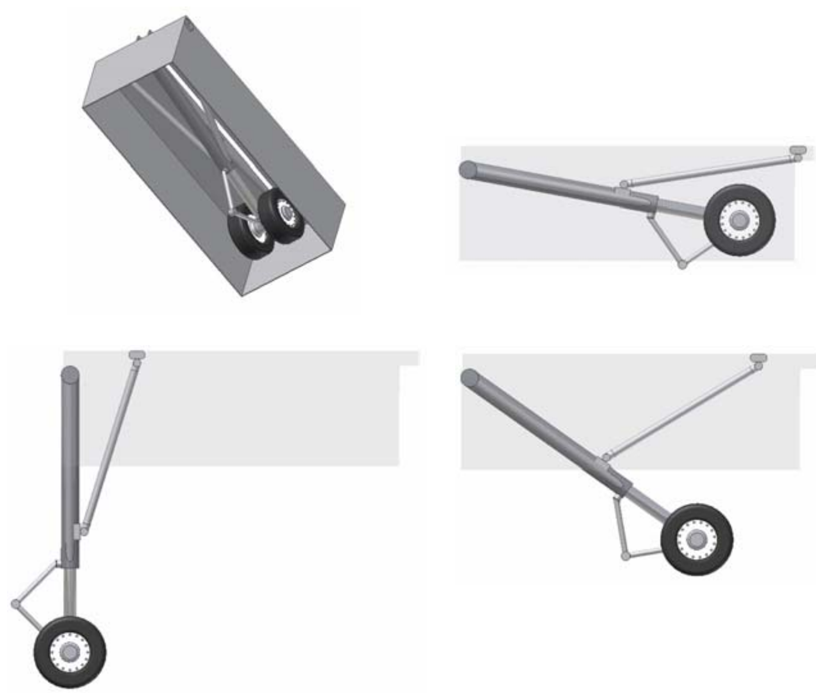

Figure 7.6: Front Landing gear configuration (2 wheels)

Figure 7.7: Rear Landing Gear Configuration (4 wheels)

A three point landing gear configuration was chosen for space and simplicity reasons. The front landing gear assembly is housed in the nose under the cockpit. Blisters were used for the two rear gear to provide extra room in the fuselage for the cannons, ammunition and personnel and to provide increased lateral stability.

The mechanics of the landing gear are simple. Both the front and back landing gear are gravity assisted. When deployed, a piston connected to a sliding wedge extends and locks the gear into place. Referring to Figure 7.6, the front gear, main piston and sliding wedge are evident. This configuration was chosen due to its simplicity. The wheels are Goodyear ® 34 x 9.25 - 16 - 18, which have been tested for up to 20,000 lbs. Since Phoenix will be using 10 wheels, a factor of safety of over 2.0 will be more than sufficient.

7.3.2 Wing

The wing is supported by three spars running its length. The first spar runs near the leading edge of the aircraft providing a point to connect the aerodynamically curved aluminum leading edge and carbon-epoxy skin of the main wing body. Another spar runs along the trailing edge and provides the support structure for the flaps and ailerons. The third spar runs along the middle of the other two providing redundant support for the wing.

There are nine ribs in each wing providing torsional stiffness. The ribs are placed on each side of each flap/aileron and also in the middle of each flap/aileron. This setup provides additional support for the two weapon mounts on each wing.

7.3.3 Fuselage

The fuselage is supported by eleven transverse supports and eleven longitudinal supports. The longerons are placed in important spots around the cross section. These sections include the height above and below the floor, the height along where the blister meets the main fuselage skin and where the wing intersects with the fuselage.

The transverse supports are placed closer in areas where loading is higher. These areas include where the wings attach to the fuselage and the two gun positions. Three of the transverse supports are bulk heads, used to separate the two gun areas and the cockpit. These bulk heads serve as firewalls protecting the individual sections from spreading fire and also allowing for each section to control its individual pressurization.

7.3.4 Tail

The horizontal tail is supported with the same spar arrangement as the wing with ribs placed every 2 ft. The vertical tail has two spars with one running along the leading edge and the other running along the fin to support the fin structure. The spars change angle slightly after extending into the fuselage and attaches to the keel beam (not shown) which runs the length of the bottom of the fuselage. Ribs are placed every 1.5 feet providing additional stiffness.

8. Aerodynamics

8.1 Lifting Capabilities

The design focus for an improved and advanced gunship is the weapons systems. The weapons were chosen and the size and the shape of the aircraft were then fitted to the weapon layout. Therefore the resulting gunship is rather conventional in appearance. The lift analysis and flap selection were based on the RFP requirements. The requirements state that the maximum landing weight is specified at 80 percent the maximum take-off ground weight and the balanced field length is less than or equal to 5000 ft at sea level for an ICAO standard day, over a 50 foot obstacle.

Based on Equation 8.1 (Raymer) $C_{L_{max}}$ for landing can be computed at this

$$S_{Landing} = 80\left(W/S\right)\left(\frac{1}{\sigma C_{L\max}}\right) + S_a \qquad (8.1)$$

scenario where the landing wing loading is 80 percent of the maximum take-off wing loading. Therefore the landing wing loading is equal to 80 $\frac{lbs}{ft^2}$. The minimum value for $C_{L\max}$ at landing for this RFP requirement is equal to 1.45 at sea level. $C_{L\max}$ can easily be increased by landing at a higher altitude or with a shorter runway distance. From this information the maximum $C_{L\max}$ needed for this mission is approximately 2.1. This is shown in the carpet plot, Figure 6.1: Landing Constraint, where RFP specifies landing over a 50 ft obstacle, one engine operative, at empty weight plus 40 percent internal fuel on an ICAO Standard Day and wet runway.

At take-off the $C_{L\max}$ can be estimated from Equation 8.2.[4]

$$\left(\frac{W}{S}\right) = (TOP)\sigma C_{L_{TO}}(T/W) \qquad (8.2)$$

This estimates a take-off lift coefficient of 1.33 and a maximum take-off lift coefficient of 1.61. It is approximated that the maximum take-off lift coefficient is 80 percent that of the maximum landing lift coefficient therefore making the maximum take-off lift coefficient approximately 1.7.

8.2 Flap Analysis

Since we need to obtain a maximum landing lift coefficient of 2.1, flaps will be needed. Two types of flaps analyzed were single slotted and Fowler flaps, shown in Figure 8.1.

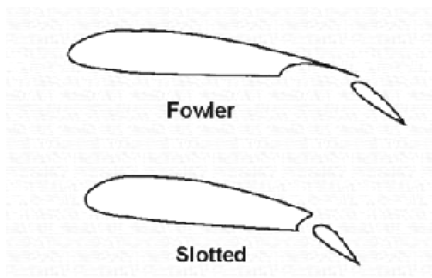

Figure 8.1: Fowler and Single Slotted flaps

To obtain the difference in the maximum lift coefficient Equation 8.3 is used.[4] Table 8.1 summarizes the results. On the wing, the flap is divided into two flaps leaving room for the pylon. The span for each flap is 8.074 ft and 7.941 ft and the flap chord is 30 percent the length of the wing chord.

$$\Delta C_{L\max} = 0.9 \Delta C_{l\max} \left(\frac{S_{flapped}}{S_{ref}} \right) \cos \Lambda_{H.L.} \tag{8.3}$$

	Takeoff	Landing
Single-slotted	0.432	0.617
Fowler	0.496	0.712

Table 8.1: Change in maximum lift coefficient at take-off and landing for certain flaps

The Fowler flap is very similar to the slotted flap. The main advantage to the fowler flap is that when deployed the camber as well as the chord are being increased by both backward and downward motions. This causes an increase in surface area of the wing and allows for more lift. Since the Fowler flap is an extension of the single-slotted flap and has a greater increase in the maximum lift coefficient, the Fowler flap was selected.

8.3 Wing Geometry

The RFP states that the aircraft may cruise with speeds no lower than 400 knots with an initial cruise ceiling of at least 30,000 ft. Therefore the aircraft must fly at a cruise Mach number of at least 0.68. Supercritical airfoils will be analyzed since the aircraft is flying at transonic speeds. Supercritical airfoils are designed with a large amount of aft camber, large leading edge radius, and less curvature on the upper surface, which lead to weaker shock waves and greater lift than the original 6-series airfoils. To obtain values for the thickness to chord ratio a modification of the Korn equation with an additional term, sweep, is used, shown in Equation 8.4.

A plot in Figure 8.2 shows the maximum thickness to chord ratio at different cruise mach numbers. Large leading edge sweep for our aircraft is not necessary because we are flying at such a low Mach number and adding sweep increases the weight of the aircraft, although during the sizing of the aircraft we thought that sweep helped in the appearance of our aircraft. Using historical trends and sizing technique, the leading edge sweep is 18.6 degrees and the quarter chord sweep is 15.9 degrees.[4] With sweep of 15.9 degrees at the quarter chord, and flying at a cruise Mach number of 0.7 the maximum thickness to chord ratio is 0.2.

$$M_{DD} = \frac{K_A}{\cos\Lambda} - \frac{t/c}{\cos^2\Lambda} - \frac{C_L}{10\cos^3\Lambda} \qquad (8.4)$$

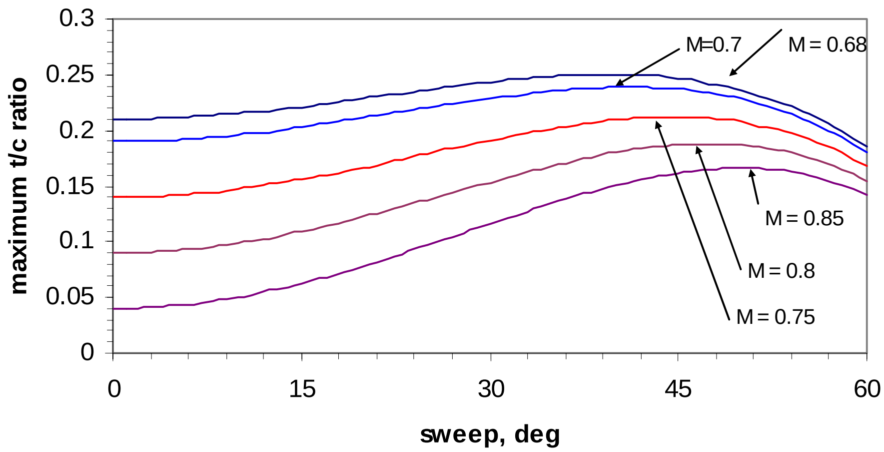

Figure 8.2: Plot of maximum thickness to chord ratio vs. sweep using Korn Equation

In NASA Supercritical Airfoils, a study by Charles D. Harris, it shows that for transport aircraft the thickness to chord ratio is between 10 and 14 percent and the design lift coefficient is either 0.6 or 0.7.[26] The airfoils chosen to be analyzed include the SC(2)-0612 and the SC(2)-0714, where the design mach number is 0.6 and 0.7 and the thickness to chord ratio is 0.12 and 0.14 respectively.

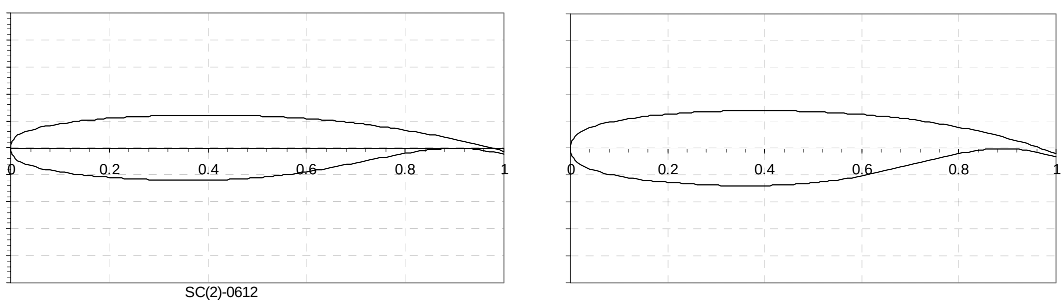

Figure 8.3: SC(2)-0612 and SC(2)-0714 airfoil shapes

The pressure distribution, computed in TSFOIL2.exe, of the two airfoils can be seen below at a Mach of 0.7 and an angle of attack of zero and two degrees.[2] In both distributions you can see the effects of the aft camber and the large leading edge radius. Since these airfoils are so similar, there is little difference in the pressure distribution.

Our mission is to loiter for four hours, therefore we want a high lift to drag ratio, as the thickness to chord ratio in the airfoil increases, so does the drag and the weight of the wing. Therefore we want to have the smallest thickness to chord ratio but still have enough room for the necessary fuel. The amount of fuel needed to be placed in the wings is satisfied using a wing thickness to chord ratio of 0.12. From analysis on the two supercritical airfoils the SC(2)-0612 supercritical airfoil was selected.

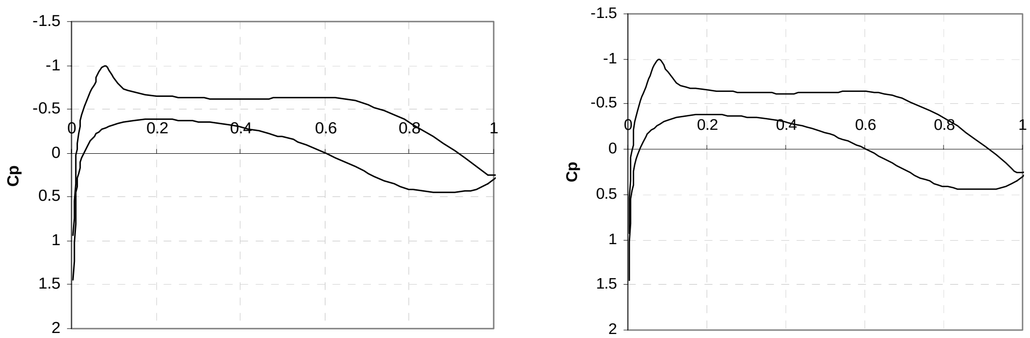

Figure 8.4: Pressure distribution for supercritical airfoils SC(2)-0612 and SC(2)-0714 respectively at an angle of attack of zero degrees and Mach of 0.7

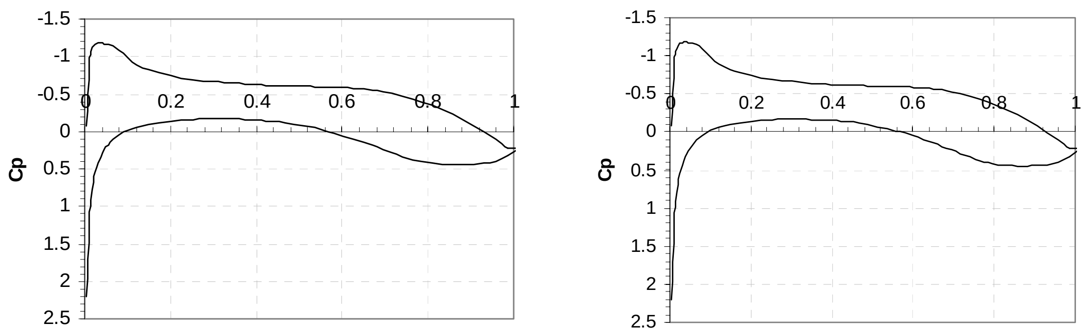

Figure 8.5: Pressure distribution for supercritical airfoils SC(2)-0612 and SC(2)-0714 respectively at an angle of attack of two degrees and Mach of 0.7

8.4 Drag Build-Up

The drag on the aircraft was calculated using Roskam's Method[17] and the Friction program.[2] A breakdown of this drag is tabulated in Table 8.2.

	Takeoff	Landing	Cruise
Wing	0.00509	0.00528	0.00483
Fuselage	0.00608	0.00631	0.00576
Horizontal Tail	0.00193	0.00201	0.00183
Vertical Tail	0.00085	0.00088	0.00080
Viper Strike Missile	0.00035	0	0.00033
Paveway Missile	0.00032	0	0.00031
Flaps	0.00145	0.00151	0
Pylons	0.00025	0.00026	0.00024
Landing Gear	0.00047	0.00049	0
Total	0.01679	0.01673	0.0141

Table 8.2: Drag breakdown for Phoenix

Assuming a parabolic drag polar, the maximum lift to drag ratio is computed at takeoff, cruise and landing using Equation 8.5.

$$C_D = C_{Do} + \frac{C_L^2}{\pi A e} \tag{8.5}$$

where A is the aspect ratio, and e is the Oswald efficiency factor. For landing conditions need to account for the ground effect, when the wing is near the ground the Oswald efficiency factor increases, Equation 8.7 accounts for the change.

$$K = \frac{1}{\pi A e} \tag{8.6}$$

$$\frac{K_{effective}}{K} = \frac{33(h/b)^{1.5}}{1+33(h/b)^{1.5}} \tag{8.7}$$

The Oswald efficiency factor is based on the Aspect Ratio and is 0.798. At landing approximately 30 ft off the ground and a wing span of 76.8 ft, the Oswald efficiency is 0.897. The drag polars, Figure 8.6 through Figure 8.8, show the maximum lift to drag ratio for take-off, cruise, and landing. Table 8.3 summarizes the results.

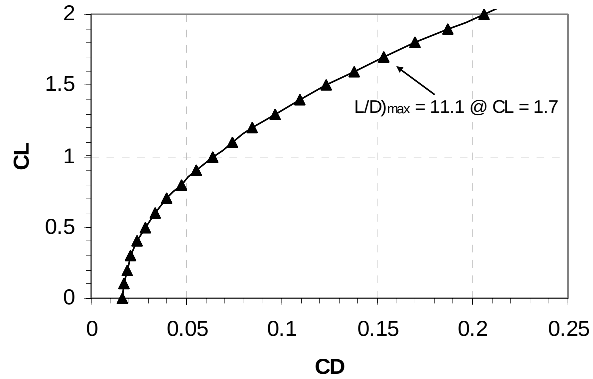

Figure 8.6: Drag Polar for take-off conditions

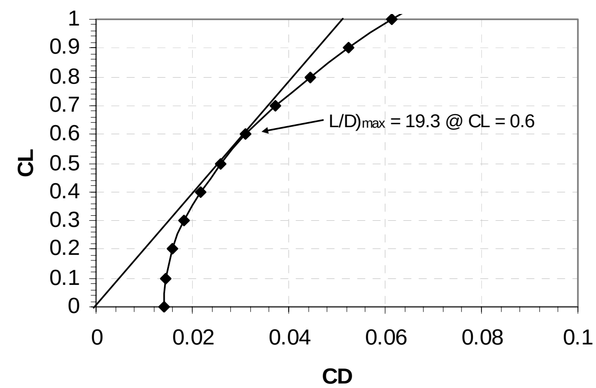

Figure 8.7: Drag Polar for cruise conditions

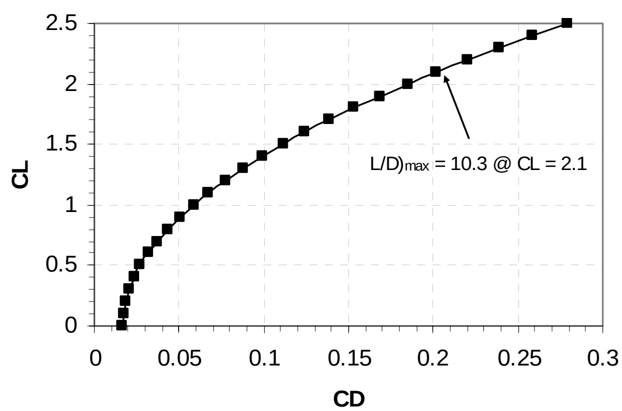

Figure 8.8: Drag Polar for landing conditions

	Maximum L/D	Lift Coefficient
Takeoff	11.1	1.7
Cruise	19.3	0.6
Landing	10.3	2.1

Table 8.3: Results of Drag Polars

9. Weights

The initial sizing done on our concepts was done using two separate methods. The first method used is the sizing from a conceptual sketch method described in Aircraft Design a Conceptual Approach, 3rd edition.[4] This method used a combination of historical data and our initial sketches to determine the component weight of all of our designs. In order to verify and optimize the weight breakdown found using Raymer's method the FLOPS program was used. By using this program the correct fuel weight was determined to complete the mission.

By using the methods described above the take off gross weight for the Phoenix was found to be 69,984 lbs. This take off gross weight includes 20,903 lbs of fuel, 15,000 lbs of payload, and a crew of five people weighing 1000 lbs. The take off gross weight for the Phoenix is in the range of the take of gross weight of currently used gun ships.

The major component weight breakdown is shown in Table 9.1. In order to reduce the weight of the aircraft composite materials are used in various structures. The aircraft is constructed from a mix of standard aircraft metals like aluminum and composite materials such as carbon fibers with epoxy resin. The materials section of this report discussed in greater detail the type and location of the materials used. Table 9.2 shows the weight savings in major components due to the use of composites. The most weight savings is found in the wings and fuselage due to the size of each of these components. The total weight savings by using composite materials is greater than 2,300 lbs.

When designing the Phoenix great care was taken to ensure that the center of gravity would not travel much during a mission. In order to meet this requirement the weapons were placed in a location such that there weight was evenly balanced around the fully loaded center of gravity location. The missiles and bombs are placed on hard points on the wings. By doing so the longitudinal center of gravity will not move much when the payload is released. The 105 mm cannon is placed towards the center of the plane and is as close to the wings as possible. The weight of the 40 mm cannon placed in the front of the aircraft is balanced out by the weight of the two-turbofan engines located on the empennage of the Phoenix. The majority of the fuel was also placed in self-sealing tanks in the wing in an effort to reduce the center of gravity travel during flight. There is 300 cubic feet of fuel stored in the tanks in the wings that are placed around the main wing strut and extend almost to the tip of each wing. Two smaller reserve fuel tanks containing 145 cubic feet of fuel are mounted on the inside of the fuselage close to the 105 mm cannon. The fuel is first pumped out of the wings and then out of the tanks inside of the fuselage. Five percent of the total fuel weight of 20,903 lbs is for reserve purposes. Figure 9.1 shows the center of gravity travel during a mission where the fuel and weapons are used. The center of gravity for the fully loaded aircraft is 24% the mean aerodynamic chord. The center of gravity only travels 0.4 ft or 4.37% the mean aerodynamic chord due to fuel consumption. As shown in Figure 9.1 the center of gravity will move aft during flight when the fuel is being pumped out of the wings and the internal fuel tanks are full. When all fuel tanks are empty the center of gravity will move forward of the totally loaded center of gravity location. Deploying the wing mounted weapons and the shells from the internally mounted cannons also causes the center of gravity to move forward of the fully loaded center of gravity location. When the aircraft is completely empty with no weapons or fuel the center of gravity shifts forward 4.2 ft or 45.9% the mean aerodynamic chord. This of course is a very extreme case in which the aircraft will never operate. During each of the missions this aircraft is expected to perform the center of gravity shifts a very small percentage of the mean aerodynamic chord and remains very close to the fully loaded center of gravity location. By limiting the movement of the center of gravity the flight characteristics of the Phoenix remain near constant throughout the required missions.

Component	Weight (lbs)
STRUCTURE	
Wing	8015.3
Horizontal Tail	1139.6
Vertical Tail	1105.8
Fuselage	8307.2
Main Landing Gear	1222.1
Nose Landing Gear	392.3
Nacelle Group	660.9
PROPULSION GROUP	
Engine(s)	1730.6
Engine Controls	46.8
Starter	66.2
Fuel System	245.6
EQUIPMENT GROUP	
Flight Controls	781
Hydraulics and Electronics	1374.3
Instruments and Avionics	1522.2
USEFUL LOAD GROUP	
Crew	1000
Fuel	20903.9
Payload	15568
TOGW	69984.9

Table 9.1: Component weight breakdown.

Component	Metal Weight (Lbs)	Composite Weight (Lbs)	Weight Savings (Lbs)
Wing	9213	8015.3	1197.7
Fuselage	9029.6	8307.2	722.4
Horizontal Tail	1340.7	1139.6	201.1
Vertical Tail	1300.9	1105.8	195.1
Nacelle Group	710.6	660.9	49.7

Table 9.2: Component weight savings due to the use of composites.

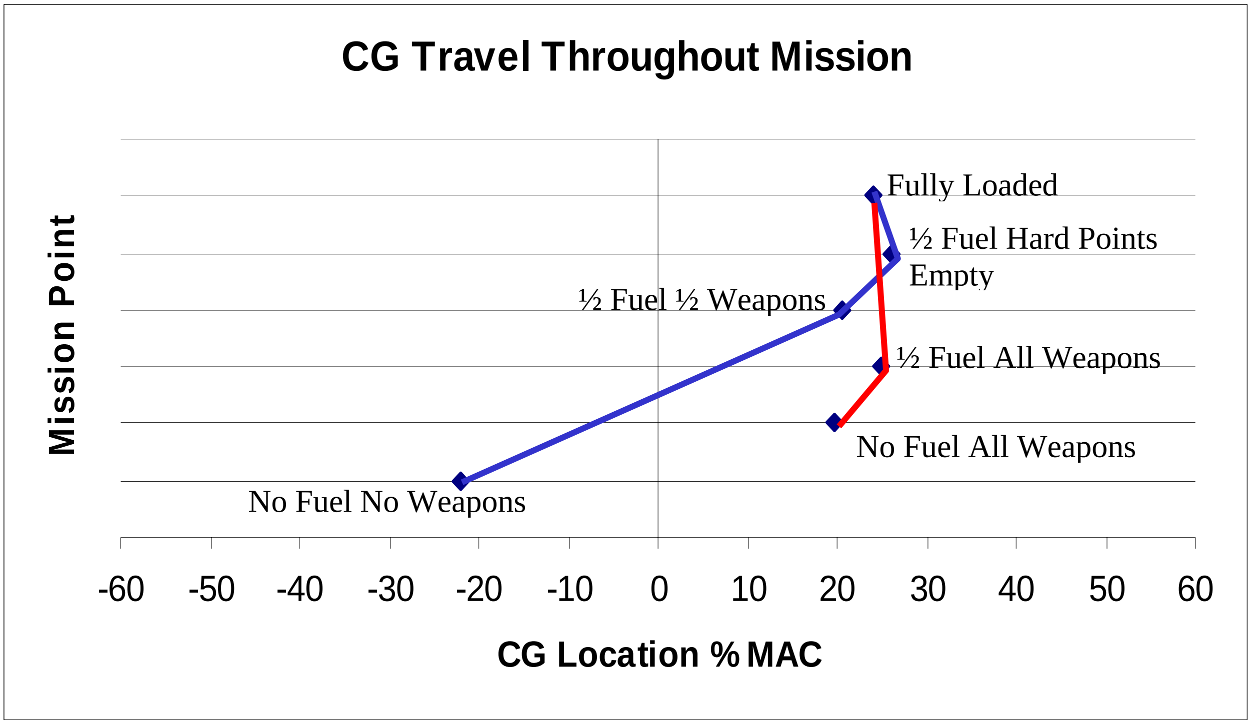

Figure 9.1: CG travel throughout mission.

10. Propulsion

The Phoenix will use two high bypass ratio turbofan engines for propulsion. These engines will be mounted on the fuselage of the aircraft on either side of the vertical tail. Due to the fact that most of the weapons fire this aircraft will encounter will come from the ground the engines are placed above the fuselage to remove them from the line of fire. The high location of the engines also reduces the chances of the engines ingesting debris from the runway. The engines were placed on the empennage of the aircraft to counterbalance the heavy 40 mm cannon placed in the front of the aircraft. Most importantly the location of these engines allows for the greatest variety of weapons systems on the aircraft. Weapons can be mounted on the wings and inside the fuselage due to the empennage mounted engines. Two engines were chosen rather than one for survivability reasons. Also related to survivability, the high bypass ratio was chosen for these engines due to the fact that high bypass ratio engines can diffuse heat into the environment at a quicker rater than lower bypass ratio engines. This will reduce the thermal signature produced by the aircraft and increase the aircrafts survivability. The high bypass ratio engines can also produce more thrust and are more fuel-efficient than low bypass ratio engines.

It was determined that the AIAA engine deck produced too much thrust for the Phoenix, so a scaled down AIAA engine was used. The scaled down engine has an inlet diameter of 4 ft and has a length of 7.8 ft. Each engine weighs 865.3 lbs and produces a maximum sea level thrust of 21,999.5 lbs. These engines give a combined thrust of 36,380 lbs at takeoff, which gives the Phoenix a takeoff thrust to weight ratio of 0.52. The scaled engine allows for a more compact installation on the Phoenix and meets the maximum thrust requirements better than the AIAA engine deck. The nacelle for each engine has a maximum diameter of 4.75 ft and is 9.17 ft long. Each nacelle weighs 369 lbs. The engine inlet was designed in a manner such that at the maximum cruise Mach number of 0.7 the inlet area is greater than the inlet area required to produce a shock. By assuring that there will not be a shock in the inlet at transonic speeds the overall performance of the turbofan is increased. There is an access door on the bottom of the nacelle so that there is maximum accessibility to perform maintenance and inspections on the engines. The bottom of the nacelle is located 12.5 ft from the ground so the maintenance crew will have to use a cherry picker to work on the engines. The engine support struts connect to the fuselage and extend the nacelle far enough away from the vertical tail so that the rudder is functional.

Table 10.1 displays the thrust, fuel flow, and thrust specific fuel consumption at a number of different altitudes for the optimum operating Mach number. The optimum Mach numbers used in this chart were determined for a given altitude and flight activity. The task the aircraft is performing is displayed underneath the altitude that it is occurring at in Table 10.1. Figure 10.1 shows the maximum available thrust and the optimal operating thrust at the altitudes, Mach numbers, and activities mentioned above in Table 10.1. It can be seen from this chart that the optimum thrust at each part of the mission is less than the maximum available thrust. The optimum thrust was determined by examining a number of charts of the thrust versus fuel flow at a given altitude and speed, but different power levels. Due to this fact our aircraft will have excess thrust if it would need to perform an evasive action or any other uncharacteristic activities throughout the course of the mission. There is enough thrust available at take off so that the Phoenix will be able to take off inside the required take off field length. There is also enough available thrust to meet the desired cruise mach number of 0.7 at an altitude of 37,000 ft. There is a 5% increase in the fuel flow due to installation losses and engine wear.

A clamshell thrust reverser was selected for each of the engines as shown in Figure 10.2. The clamshell configuration was selected over the cascading thrust reverser configuration for many reasons. Most importantly the clam shell thrust reversing system will reverse both the bypass and jet flow where as the cascading system will only reverse the bypass air flow. The clamshell thrust reverser system is also a mechanically simpler system and requires less moving parts, which also reduces the weight of the system. The clamshell thrust reverser is also very compact and can easily be installed on the exit nozzle of the engine. The clamshell thrust reverser works by using two actuators to open the two flaps shown in Figure 10.2. These flaps divert the exhaust of the jet perpendicular to the direction of the engine inlet flow. This causes the engines to not only produce nearly no positive thrust, but also increases the drag and reduces the stopping distance. By using a thrust reverser the Phoenix will be able to meet the landing field distance requirement of 5,000 ft. when there is 40% of the fuel left in the aircraft.

The nozzle exit on the engines has a diameter of 3.5 ft. A mixing nozzle was selected due to a number of reasons. The mixing nozzle will reduce the engine exhaust temperature because it will mix the hot jet air with the cooler bypass air. By reducing the engine exhaust temperature heat seeking weapons will become less effective and the survivability of the aircraft is increased. The mixing nozzle also reduces the noise that the engine exhaust produces. Once again this increases the survivability of the aircraft. The mixing nozzle is shown in Figure 10.3.

Altitude Mission Segment	Mach	Thrust Per Engine (LBS)	Fuel Flow Per Engine (LBS/HR)	TSFC Per Engine (1/HR)
0 Takeoff	0.20	18191	7862	0.432
10000 Climb	0.48	6091	3720	0.611
20000 Loiter	0.31	4752	2167	0.456
30000 Climb	0.54	2571	1467	0.571
36000 Cruise	0.70	1935	1336	0.690

Table 10.1: Thrust, fuel flow, and TSFC per engine at various altitudes and optimum mach numbers.

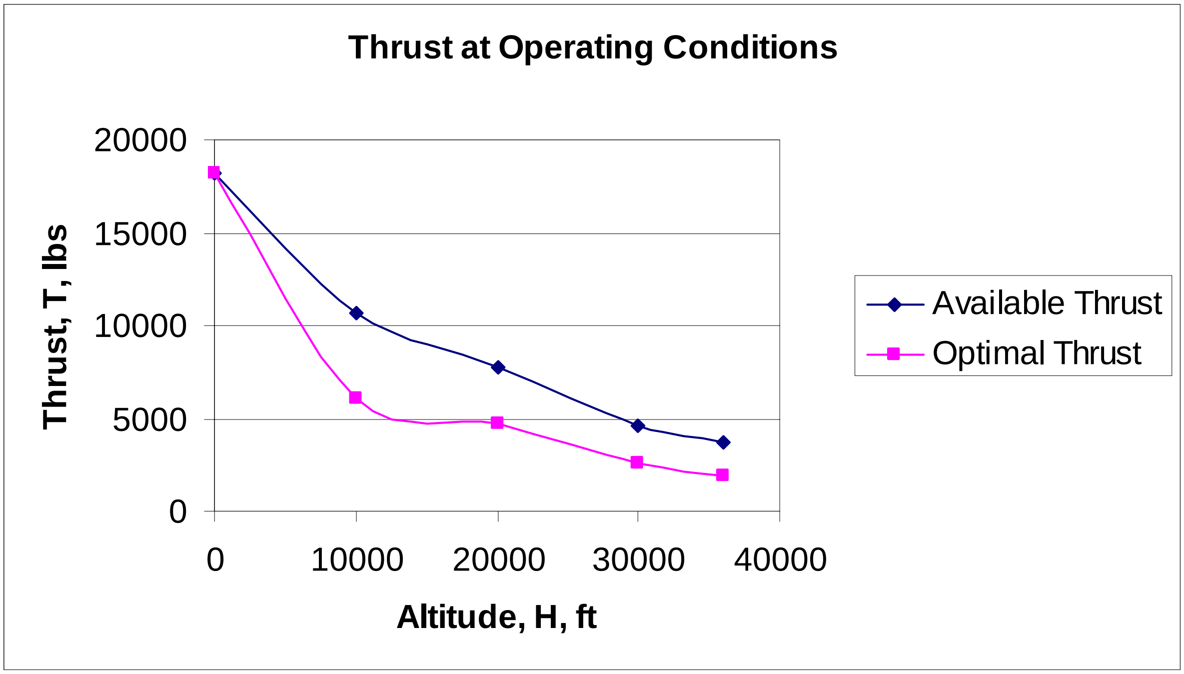

Figure 10.1: Operating thrust and maximum available thrust for the operating conditions described in Table 10.1.

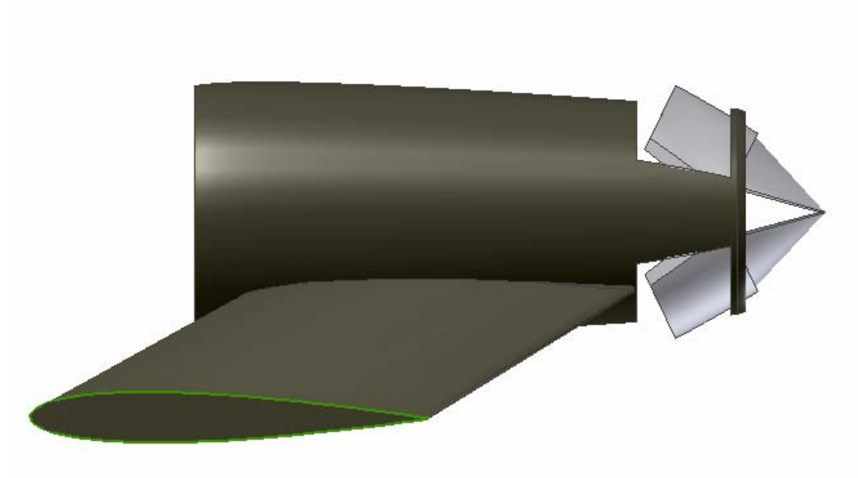

Figure 10.2: Clamshell thrust reversing system

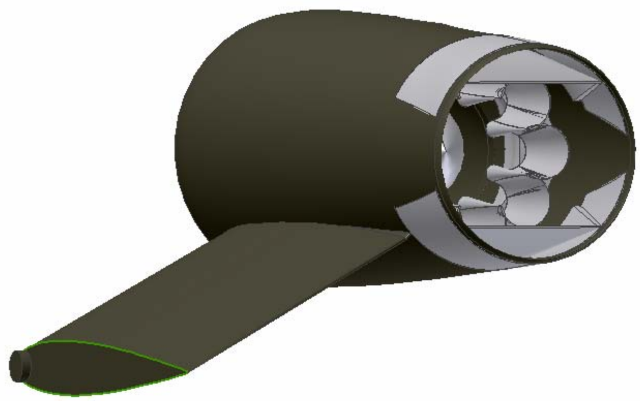

Figure 10.3: Mixing nozzle

11. Stability and Control

The Phoenix control system operates using a Fly-By-Light system. This was chosen for its inherent faster speed of operation and insusceptibility to jamming. In addition to this, care was taken to design and size a tail that would be capable of balancing the heavy loads near the nose of the aircraft as a result of the 40mm cannon placement. While the T-tail may seem larger than is required the benefits outweigh the structural weight penalty. With a tail our size the static margin of the Phoenix is reduced and the aircraft is placed in a state of low static stability, allowing for more control authority due to lower required deflections of the elevators to trim the aircraft. This in turn also helps lessen the trim drag the Phoenix would encounter. A summary of the Phoenix's static margin can be seen in Table 11.1:

	Takeoff	Cruise	Loiter	Landing
Static Margin	5.6%	5.5%	4.5%	10.3%

Table 11.1: Static Margin

As one can see, the static margin decreases through takeoff, cruise, and loiter. However upon landing it has been assumed that roughly half the payload has been expended. Due to the distribution of fuel, ordinance, and ammunition about the aircraft center of gravity, as well as the order of the pumping of the fuel tanks, our cg actually moves forward throughout the flight, thus increasing the stability of the Phoenix during the terminal phase of the mission.

11.1 Tail Design

As previously mentioned a T-tail arrangement, seen in Figure 11.1, was chosen for the Phoenix. This type of tail allows for the horizontal tail to be placed above the fuselage, which helps create a larger moment arm with the wing and thus greater control power. In addition the tail is removed from the wake of the wing.

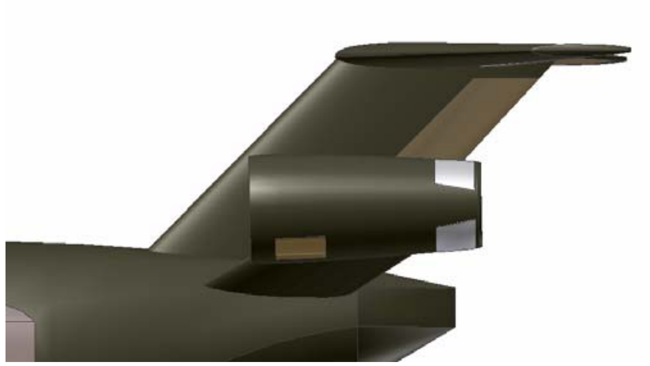

Figure 11.1: Phoenix T-tail arrangement

Due to the aft position of the engines on the fuselage, the horizontal tail span has been increased such that it extends beyond the nacelles in order to ensure control authority in the event of a deep stall.[24] As you can see in Figure 11.1 the tail has also been placed such that the rudder is forward of the engine exhausts to allow for maximum effectiveness. The tail geometry has been summed up in Table 11.1, seen below:

	Horizontal Tail	Vertical Tail
Area (ft)	229.55	136.82
Span (ft)	35.53	7.23
Aspect Ratio	5.5	1.55
Sweep (deg)	23.6	45.0
Taper Ratio	0.45	0.90
Croot (ft)	8.91	9.90
Ctip (ft)	4.01	8.91

Table 11.1: T-tail geometry

11.2 Control Surfaces

The control surfaces were sized based on historical guidelines found in Reference 4 and from comparator aircraft analysis. A summary of their sizes is seen below in Table 11.2:

	% Span	% Chord	Area (ft^2)
Ailerons	30	25	19.3
Elevators	85	35	34.1
Rudder	75	30	15.4

Table 11.2: Control surface geometry

11.3 Stability and Control Analysis

The stability and control analysis for the Phoenix was done using a combination of programs including VLMpc, a NASA-Langley vortex lattice program, and JKayVLM, an analysis program developed by Virginia Tech faculty members.[2] User defined trapezoidal sections are used to model the lateral and longitudinal geometry of the aircraft and then a vortex lattice analysis is done to obtain the required derivatives. The model for Phoenix can be seen in Figure 11.2.

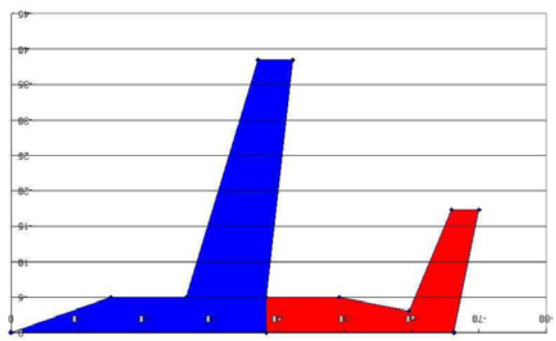

Figure 11.2: Phoenix VLMpc/JKayVLM model used for analysis

Analysis was done for four key flight conditions; takeoff, cruise, loiter, and landing. The flight conditions can be seen in Table 11.3 and the resulting derivatives can be found in Table 11.4.

Flight Phase	Takeoff	Cruise	Loiter	Landing
Altitude (ft)	0	36,000	20,000	0
Mach No.	0.48	0.68	0.25	0.15
CG location (%mac)	24.0	25.2	20.4	19.0

Table 11.3: Evaluation conditions

Flight Phase	Takeoff	Cruise	Loiter	Landing
C_{L_α}	8.163	9.586	7.474	7.354
C_{m_α}	-3.947	-4.616	-3.542	-3.862
C_m / C_L	-0.483	-0.482	-0.474	-0.525
C_{L_q}	19.902	22.651	18.337	18.872
C_{m_q}	-37.303	-41.746	-34.615	-35.592
$C_{L_{\delta e}}$	1.2587	1.3906	1.1867	1.1716
$C_{m_{\delta e}}$	-4.0844	-4.5531	-3.8175	-3.8249
$C_{\ell_{\delta a}}$	0.0461	0.0461	0.0461	0.0461
$C_{n_{\delta a}}$	0.0064	0.0064	0.0064	0.0064
$C_{Y_{\delta r}}$	-0.0710	-0.0720	-0.0704	-0.0702
$C_{\ell_{\delta r}}$	0.0001	-0.0034	-0.0007	0.0005
$C_{n_{\delta r}}$	0.0313	0.0307	0.0310	0.0310
C_{Y_β}	-0.592	-0.599	-0.587	-0.586
C_{n_β}	0.037	0.039	0.035	0.039
C_{ℓ_β}	-0.063	-0.066	-0.062	-0.062
C_{Y_r}	0.361	0.368	0.354	0.361
C_{n_r}	-0.105	-0.108	-0.103	-0.105
C_{ℓ_r}	0.041	0.042	0.040	0.041
C_{ℓ_p}	-0.766	-0.870	-.712	-0.700
C_{n_p}	-0.325	-0.347	-0.312	-.308

Table 11.4: Stability and Control Derivatives

11.4 Handling

Because the Phoenix is a military aircraft it is subject to the MIL-F-8785C requirements. Using the control derivatives from JKayVLM and utilizing Roskam's methods the handling qualities were assessed.[18] Classes A, B, and C flight categories were looked at as a result of Phoenix performing both terminal and non-terminal maneuvering. It was assumed that the Phoenix would perform under the Level 1 category. As one can see from Tables 11.5 and 11.6, the Phoenix is well within the operating requirements set forth.

Flight Categories	MIL-F-8785C Requirements		Takeoff	Landing
	Minimum	Maximum		
ζ_{SP}	0.35	1.3	0.51	0.52
ω_{SP}	0.28	3.6	1.16	1.22
ζ_{Ph}	0.04	-	0.30	0.32
ζ_{DR}	0.19	-	0.29	0.30
ω_{SP}	0.4	-	0.45	0.47
τ_r	-	1.4	1.11	1.15
t_{30deg}	-	1.4	1.29	1.37

Table 11.5: Class A and C qualities for Level 1 aircraft

Flight Categories	MIL-F-8785C Requirements		Cruise	Loiter
	Minimum	Maximum		
ζ_{SP}	0.3	2.0	1.67	1.36
ω_{SP}	0.085	3.6	1.39	0.97
ζ_{Ph}	0.04	-	0.11	0.08
ζ_{DR}	0.08	-	0.52	0.43
ω_{SP}	1.0	-	1.78	1.42
τ_r	-	1.4	0.76	0.61
t_{30deg}	-	1.9	1.04	0.97

Table 11.6: Class B qualities for Level 1 aircraft

11.5 Engine Out Performance

The RFP calls for the Phoenix to be able to land over 50 ft. obstacle at operating weight empty plus 40% internal fuel and maximum payload with a landing distance less than or equal to 5,000 feet, at sea level, with one engine inoperative. The Phoenix was designed with its engines closely located together and symmetric about her centerline so that engine out yawing moment was minimized.

Our engine out analysis was conducted using LDstab from the Virginia Tech design software library.[2] Analysis was done for all crucial flight conditions, and as one can see from Table 11.7 the Phoenix is capable of handling an engine out emergency with little trouble. It should be noted that for all flight conditions a five degree bank angle and max rudder of 25 degrees is required, as well as the listed aileron deflections and yaw angle adjustment.

	Takeoff	Cruise	Loiter	Landing
Bank Angle	5.00°	5.00°	5.00°	5.00°
Yaw Angle	10.92°	2.59°	9.08°	11.96°
Aileron Deflection	10.51°	-0.49°	6.26°	13.35°
Rudder Deflection	25.00°	25.00°	25.00°	25.00°

Table 11.7: Necessary control surface deflections and attitude adjustments for engine out

11.6 Trimming the Phoenix

It's important that our aircraft be able to trim itself during all phases of flight, including during both terminal and non-terminal maneuvers. Calculations to find the elevator deflection necessary to trim the Phoenix during takeoff, landing, and at C_{Lmax} were done using methods shown in References 1 and 18. It was found that for takeoff the elevators would need to be deflected 18.4 degrees, and 31 degrees while landing. Please note that the maximum lift coefficient is expected at the landing condition, flaps down. These deflections are all well within the capabilities of the aircraft's tail.

12. Systems and Avionics

12.1 Major Systems

The major systems were designed to service the major functions of the aircraft so as to facilitate effective operation of the aircraft. The major systems described below include the electrical system, flight control system, hydraulic system, and fuel system.

12.1.1 Electrical System

The electrical system for this aircraft, shown in Figure 12.1, will be provided by Hamilton-Sundstrand. The main source of power will be acquired through two Integrated Drive Generators, each producing 40 kVA from the turbofan engines. The power produced by the drive generators is distributed throughout the aircraft by left, right, and auxiliary power distributors to service the Power Distribution Assemblies (PDAs) and Secondary Power Distribution Assemblies (SPDAs). The PDAs are responsible for primary power distribution to critical electrical components such as General Control Units (GCUs), Transformer Rectifier Units (TRUs), and circuit protection modules, as well as high power secondary loads including exterior lighting, and fuel and hydraulic pumping. The SPDAs are used to service components responsible for interior lighting, actuation control, thrust reverser deployment, and cabin pressurization control, to name a few.

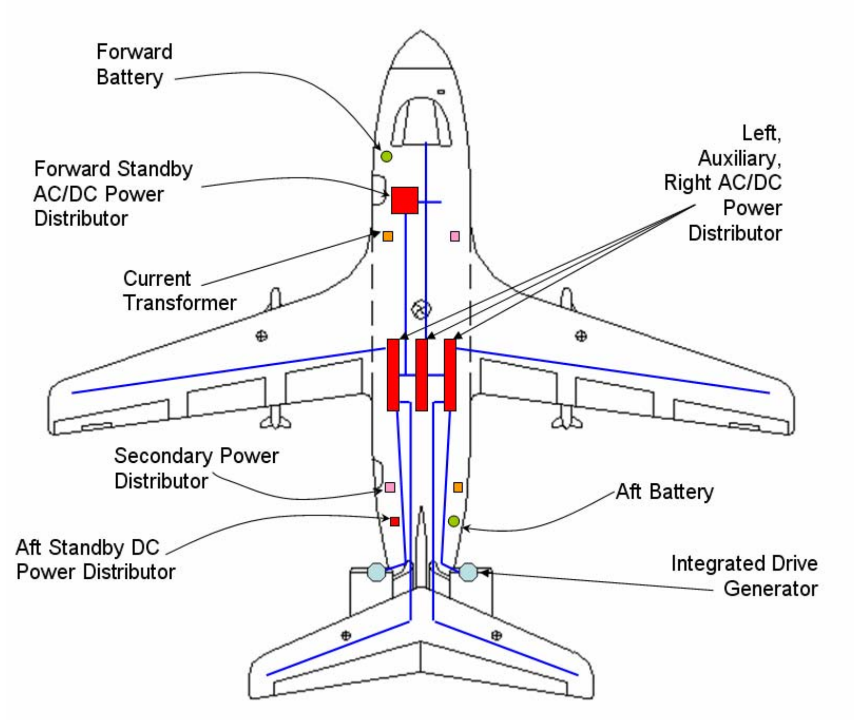

Figure 12.1: Electrical System Layout

12.1.2 Flight Control System

The flight control system for this aircraft, shown in Figure 12.2, is a fly-by-light (FBL) adaptation to a current Hamilton-Sundstrand fly-by-wire (FBW) configuration. Because FBL systems use fiber-optics to replace conventional electrical wiring, FBL systems are lighter in weight, capable of faster and larger data transfer, and resistant to electromagnetic interference (EMI), electromagnetic pulse (EMP), lightning, and high energy radio frequency (HERF). The advantages gained by using an FBL system are evident in the realms of safety, reliability, weight, maintenance, and life cycle cost.

The flight control system contains both linear and rotary actuators used to control the ailerons, flaps, and rudder, all of which are driven by the electro-hydrostatic power drive unit. The electro-hydrostatic drive unit allows for quicker response than conventional electrical motor actuators. Also, since the system is electrically powered instead of hydraulically powered, weight-savings are gained so that hydraulics can be more appropriately used on other components of the aircraft.

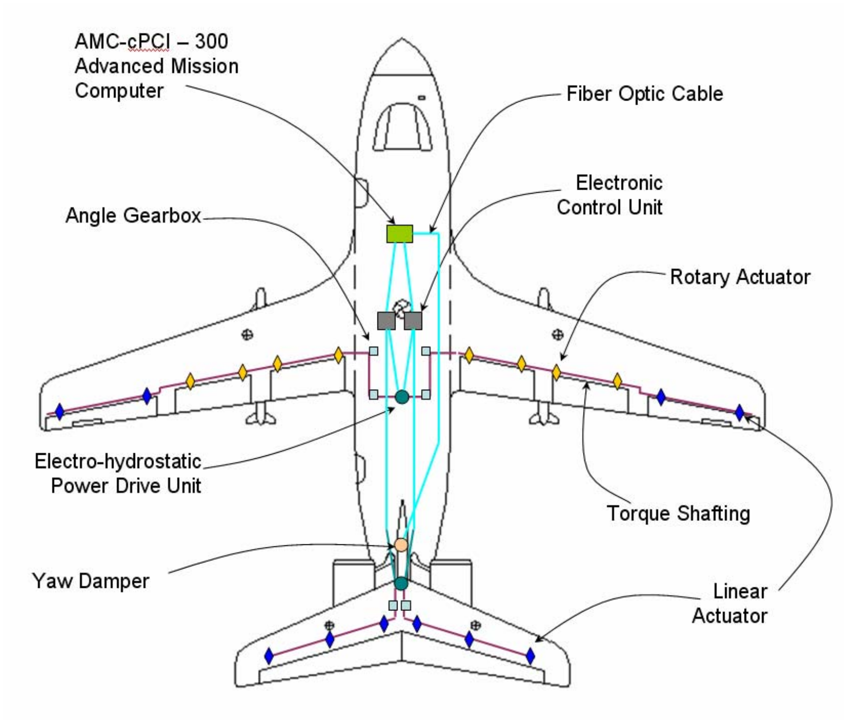

Figure 12.2: Flight Control System Layout

12.1.3 Hydraulic System

The hydraulic system for this aircraft, shown in Figure 12.3, is used to control many of the major systems of the aircraft. Its primary use is to provide rotational capabilities to both the 40 mm and 105 mm canons. Electric systems for inducing rotational motion are too slow and susceptible to burn-out, whereas hydraulic systems are more dependable and provide almost instantaneous response. Although the use of a hydraulic system adds more weight, its use is absolutely necessary in reaping the maximum possible performance of the weapons systems. Furthermore, with the hydraulic system already spanning the full length of the aircraft, it is easy and advantageous to service other major components such as landing gear (including steering and braking), weapons ejection, and the moveable hatch for the 105 mm cannon.

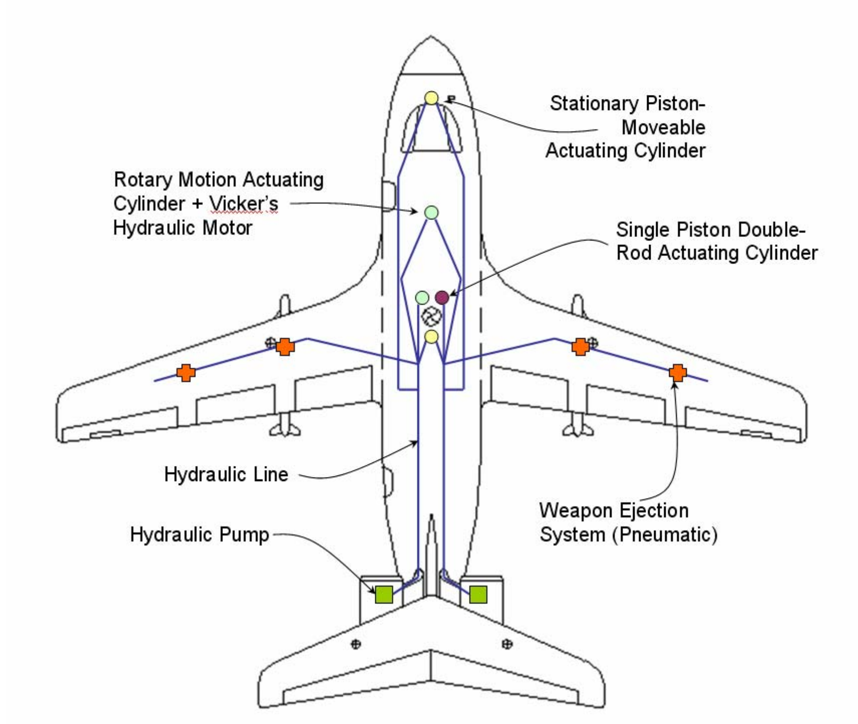

Figure 12.3: Hydraulic System Layout

12.1.4 Fuel System

The fuel system for this aircraft, shown in Figure 12.4, is used to provide fuel storage, air refueling, ground refueling, and fuel flow to the engines. The fuel will be stored in re-sealable bladders inside the wings to minimize fuel loss in the event of wing damage, and in fuel tanks located just aft of the center of gravity inside the fuselage . Approximately 300 ft^3 can be stored in the wings and 150 ft^3 can be stored in the inboard tanks. A refueling port is located at the nose of the aircraft to enable mid-air refueling capabilities, while fuel ports on the underside of each wing allow ground refueling.

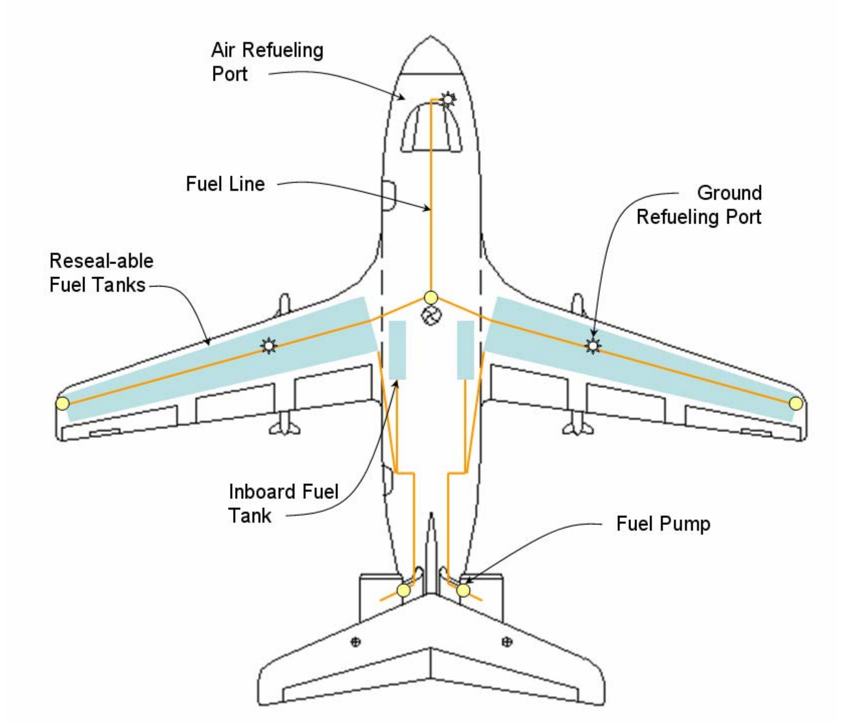

Figure 12.4: Fuel System Layout

12.2 Avionics

The avionics packages for this aircraft were selected with the objectives of self-protection, navigation, power, communication, pilot comfort, and integration of said components in order to control every aspect of its flight. Furthermore, newly developed products were chosen to construct a state-of-the-art vehicle capable of the latest technological skills.

12.2.1 Countermeasure System

The Phoenix will utilize the Large Aircraft Infrared Countermeasures (LAIRCM) system.[13] It is an active countermeasures system used to defeat advanced IR missiles quickly, effectively, and autonomously. It uses advanced laser technology to jam the missile seeker of engaged threats, primarily man-portable missiles. Without any operation of the crew, the system defeats the threat and preserves the full attention of the crew for other important tasks.

This system is a multi-band laser variant of the popular and dependable AN/AAQ-24, of which there 190 units in use on various United States and United Kingdom aircraft. Although somewhat expensive at 1.3 million US dollars, this investment is crucial to the survivability of the aircraft. In 1999, the US Transportation Command identified man-portable missiles as the number one threat to large, slow-flying aircraft. Since the mission profile requires the aircraft to loiter while expending payload in a hostile environment, the defense against man-portable missiles is a primary concern.

12.2.2 Navigation System

The navigation system selected for the Phoenix is Honeywell's H-764 Adaptive Configurable EGI. The main component of this system is the tri-navigation configuration allowing for position and velocity measurements from its Global Positioning System (GPS), Inertial Navigation System (INS), or blended GPS and INS (GPS/INS) mode. The most accurate mode is the blended configuration GPS/INS, which gives position and velocity accuracy to less than 10 meters and 0.05 meters per second, respectively. The pure INS system, which is based on Honeywell's Digital Laser Gyroscope (DGL), has position accuracy of less than 0.8 nautical miles per hour and velocity accuracy of less than 1.0 meters per second. It is small in size and weight, measuring 7 x 8 x 9.8" and 23.5 pounds, and has an operating temperature range of -54°C to +71°C. Finally, the flexible software and hardware nature of the system allows for unique missionization.

12.2.3 Communication and Identification

Our aircraft will also be equipped with a TRW Communication/ Navigation/Identification (CNI) system. This is an advanced avionics system designed to enable communication from air to ground, navigation processing, and friend-or-foe identification. The system is considered the best in avionics and is currently used on the F-22 Raptor, Joint Strike Fighter (JSF), and

Commanche attack helicopter. Its unique design allows for constant communication and data sharing with the ground station, and is reconfigurable to counteract failures that may arise from battle damage. This system is vital in securing close communication between pilot and ground crew, and ensuring the ability to navigate the aircraft despite suffering damage.

12.2.4 Mission Computer

The AMC - cPCI - 3000 Advanced Mission Computer by BAE Systems is the main computer used to integrate all the sytems of the aircraft. It boasts a ruggedised 3U cPCI PowerPC-based RL4 or CM4 single board computer (SBC), Fast Ethernet, 16 general-purpose bidirectional discrete channels, and a high-speed serial card, all used to handle flight management, mission computing, information management, and display processing. It is a commercial-off-the-shelf (COTS) item, which increases ease of acquisition and generally means a decrease in cost relative to similar non-COTS items. The system measures 3.5 x 10.75 x 12.8", weighs approximately 9 pounds, and costs 73,000 US dollars.

12.2.5 Radar Enhanced Vision System (REVS)

The Radar Enhanced Vision System (REVS) by BAE Systems will be used to ensure pilot visibility in 0/0 conditions that may arise from sand-storms, smoke, or fog. The system uses a forward looking low-light display that can be head-up or helmet mounted. This system is also small, weighing only 24 pounds.

12.2.6 Environment

The Hamilton-Sundstrand Air Management System (AMS) will be used to provide ventilation, heating, cooling, humidity control, and pressurization for the occupied sections of the aircraft.

12.2.7 Emergency Battery

In the event of aircraft power failure, the aircraft will be equipped with a BF Goodrich Avionics Systems PS-855 Emergency Power Supply. This 24V DC system will ensure the operation of the main computer.

12.2.8 Cockpit Control Panel

A diagram of the cockpit control panel for the pilot and co-pilot/gunner is shown in Figure 12.5. The pilot will be seated on the left side of the aircraft and is supplied with various controls for maneuvering the aircraft, as well as deployment and extraction of the landing gear. Also, the pilot's Head-up Display (HUD) will utilize the Radar Enhanced Vision System (REVS) to minimize pilot distraction. Seated to the right of the pilot is the co-pilot/gunner whose primary purpose is to operate the weapons systems. The gunner is provided with a gun stick to control the movement of the 40 mm canon and 105 mm cannon, a control stick in case of emergency, a radar screen and HUD for the REVS to detect potential targets and threats, and arming switches for the Paveway II laser guided missiles and Viper Strike missiles.

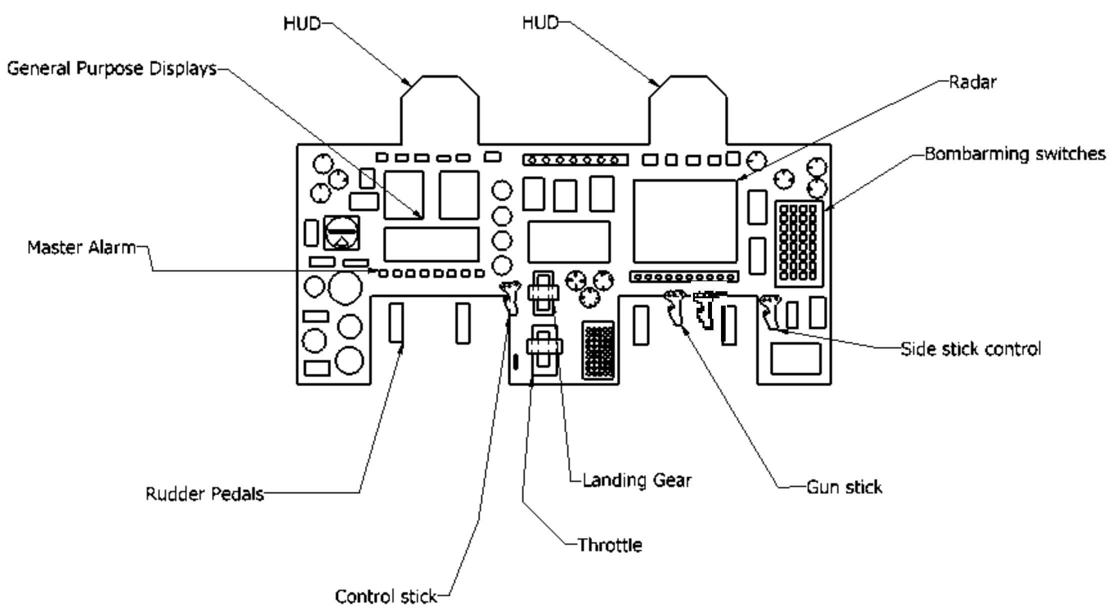

Figure 12.5: Cockpit Control Panel

13. Mission Performance

The RFP outlines two missions that the aircraft must be able to complete. The primary mission, or design mission, requires the aircraft to cruise to a region where it will loiter above the battlefield for a period of at least four hours, descend to 10,000 feet where it will expend its payload, and then cruise back to base. The ferry mission requires the aircraft to cruise to an austere base at best cruise altitude and speed. Matlab mission software written by Mike Morrow[2], along with methods outlined in Raymer[4] were used to analyze both missions.

13.1 Design Mission

The design mission, seen in Figure 13.1, is the primary mission for this aircraft and is comprised of 10 segments.

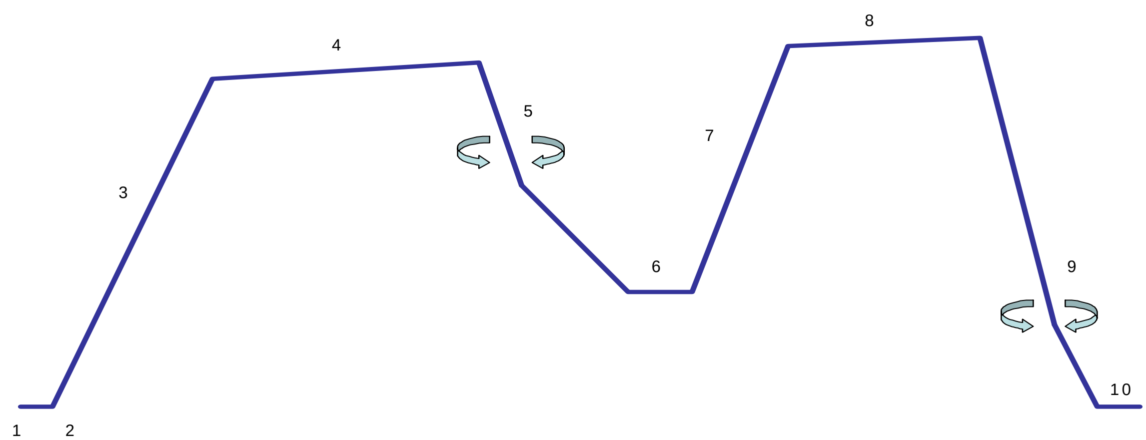

Figure 13.1: Design Mission Profile

The aircraft will taxi, takeoff, climb at max power to cruise altitude, cruise for at least 500 nm at best cruise speed and altitude, descend to 20,000 feet and loiter for at least four hours, descend to 10,000 feet for target identification and payload drop, climb at max power to cruise altitude, cruise at best cruise altitude and speed back to base, descend to sea level and loiter for 30 minutes and land with 5% reserve fuel.   Using the mission program, speed, altitude, lift to drag ratio, time, fuel usage, and range were calculated and are shown in Table 13.1.

Mission Segment	Speed (kts)	Altitude (ft)	L/D	Time (min.)	Fuel (lb)	Distance (nm)
1. Taxi	-	0	-	20	1,078	-
2. Takeoff	-	0	-	2	438	-
3. Climb to cruise	316	36,000	7	16	1,670	106
4. Cruise	463	36,000	10	54	3,490	500
5. Descend/Loiter	165	20,000	12	240	8,197	464
6. Descend/Drop	275	10,000	5	-	-	-
7. Climb to cruise	377	36,000	8	8	534	35
8. Cruise	463	36,000	10	54	3,489	500
9. Descend/Loiter	111	0	12	30	857	35
10. Land	-	-	-	-	-	-
TOTAL				424	19,753	1,640

Table 13.1: Design Mission

For the design mission, the takeoff gross weight is 69,984 lbs, fuel weight is 20,903 lbs and the payload is 15,568 lbs.   The wing loading for cruise is 100 lb/ft^2 and the thrust to weight ratio is 0.33.

13.2 Ferry Mission

The ferry mission is comprised of five segments shown in Figure 13.2.

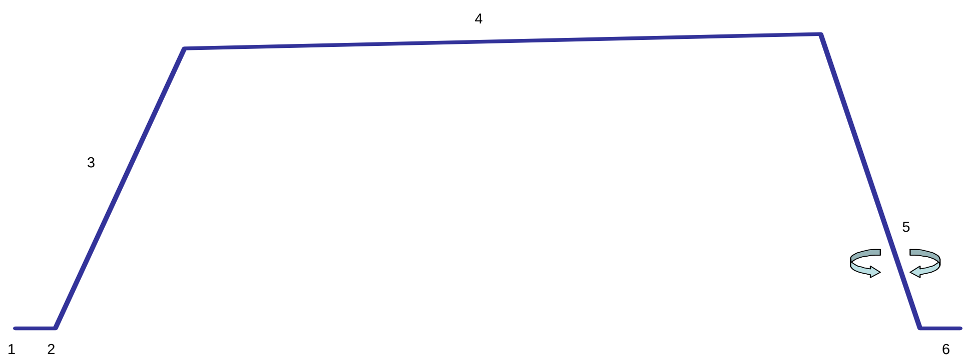

Figure 13.2: Outline of ferry mission

The aircraft is required to taxi, takeoff, climb at max power to cruise altitude, cruise at best cruise speed and altitude to an austere base at least 2,600 nm. The results from the mission program are shown in Table 13.2.

Mission Segment	Speed (kts)	Altitude (ft)	L/D	Time (min.)	Fuel (lb)	Distance (nm)
1. Taxi	-	0	-	20	1,078	-
2. Takeoff	-	0	-	2	438	-
3. Climb to cruise	316	36,000	7	16	1,670	72
4. Cruise	463	36,000	10	291	15,508	2600
5. Descend/Loiter	165	20,000	12	30	857	41
6. Land						
TOTAL				359	19,551	2,713

Table 13.2: Ferry Mission

13.3 Takeoff and Landing

The RFP requirements stipulate that the aircraft must have a balanced field length at max TOGW less than 5,000 feet and be able to land over a 50 foot obstacle on a wet runway less than 5,000 feet long with one engine out.

The balanced field length for the aircraft at sea level and maximum TOGW is 4,779 ft. At takeoff, the aircraft is at a speed of $1.2V_{stall}$ at 130.1 kts which results in a $C_{L\max}$ of 2.11. The balanced field length could have been decreased by increasing the $C_{L\max}$ by means of larger Fowler flaps, however, it would result in over-designing the aircraft and add to the cost and weight.

The landing constraints for this aircraft included clearing a 50 ft. obstacle with one engine out on a wet runway while carrying 40% internal fuel and the maximum payload. At sea level, the landing distance had to be less than 5,000 ft. Methods from Reference 4 were used to calculate the landing distance for the one engine out requirement. This equation was multiplied by 1.25 to account for the one-engine out scenario and resulted in a total landing distance of 4,560 ft. Increasing the distance 25% was an assumption made by the group to account for one lost engine. The obstacle clearance distance was set at 600 ft. assuming a general aviation-type power-off approach.[4] The wing loading used is 80% of the takeoff wing loading. During landing, the aircraft achieves a $C_{L\max}$ of 2.1 and has an approach speed of 127.8 kts ($1.2V_{stall}$) and a touchdown speed of 117.2 kts. ($1.1V_{stall}$). This is consistent with the landing distance carpet plot in Figure 6.1.

13.4 Cruise and Climb Performance

The design mission calls for two cruise periods that must occur at an altitude of at least 30,000 ft. and speed of at least 400 kts. To find the optimal cruise altitude and speed, specific range can be plotted against Mach number for various altitudes. In Figure 13.3, it is clear that at 36,000 ft. the highest specific range is obtained. By multiplying the max specific range by 99%, the cruise Mach number can be obtained. Therefore, the ideal cruise altitude and Mach number are 36,000 ft. and 0.7, respectively.

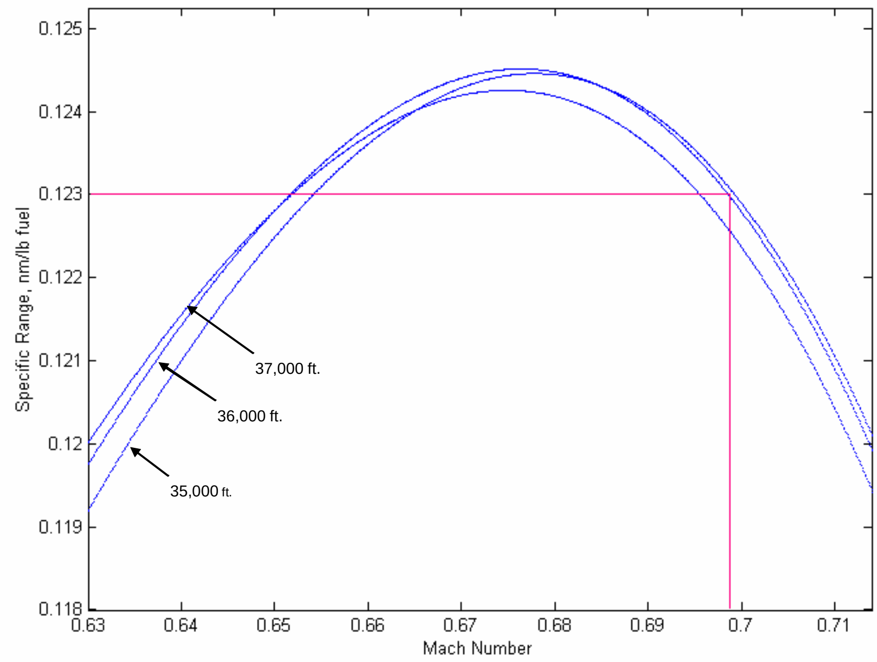

Figure 13.3: Specific range plot for various altitudes

The range for the aircraft is 5,185 nm, assuming constant speed cruise at Mach 0.7, specific fuel consumption of 0.6613 lb/hr/lb. and *L/D* of 10.

Prior to the initial cruise segment, a climb segment from sea level to 36,000 ft. is required. The rate of climb during this period is shown in Figure 13.4. Two important points that determine the service and absolute ceiling altitudes are labeled on this plot. The service ceiling is the altitude at which the aircraft's rate of climb is equal to 500 ft/min and the absolute ceiling is the altitude where the rate of climb is zero. The service ceiling is 37,500 ft. and the absolute ceiling is 42,000 ft.

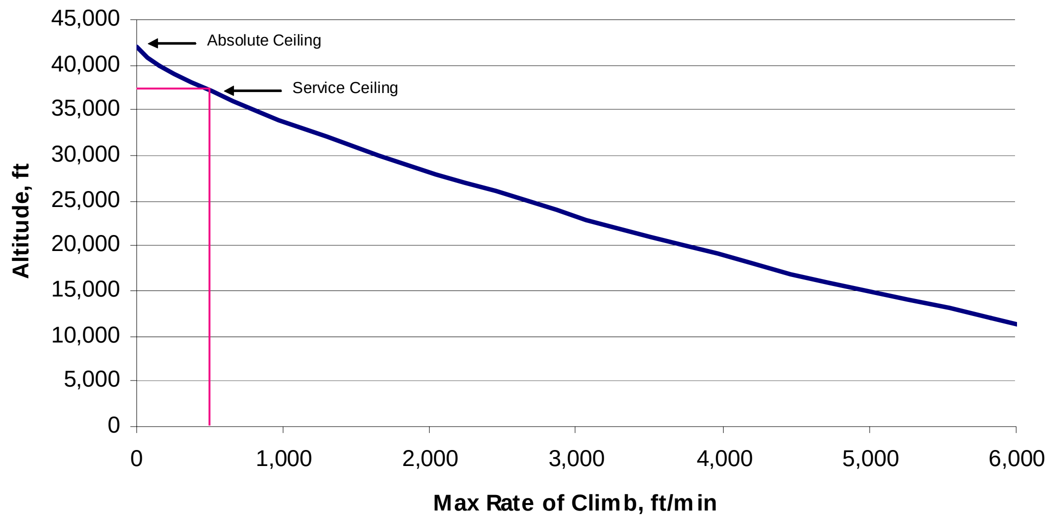

Figure 13.4: Rate of climb

In the first climb segment, the aircraft climbs at a rather steep angle of 21.1 degrees. Although the climb angle is high and the initial rate of climb is near 8,000 ft/min, this is a result of climbing at the maximum rate as stipulated by the RFP. The time to climb from sea level to the cruise altitude of 36,000 ft. is 16.1 minutes.

14. Cost

One of the most important aspects of the RFP is the requirement that pertains to the cost of the aircraft. Specifically, the acquisition and life cycle costs (LCC) should be minimized for production runs of 100, 200 and 400 aircraft. The cost of the Phoenix will be divided into 7 main components: Research, Development, Test and Evaluation Cost, Manufacturing Cost, Flyaway Cost, Operating Cost, Disposal Cost, Life Cycle Cost. The methods used to produce these cost estimates is outlined in Roskam's *Airplane Design: Part VIII.*[19] Cost estimations used in this section are based on the 2005 dollar value.

14.1 Research, Development, Test and Evaluation Cost (RDT&E)

The RDT&E cost covers most of the initial phases of the design of the aircraft. This includes conceptual and preliminary design, system integration and development. Six factors contribute to the total RDT&E cost: airframe engineering and design, development and testing, flight test airplanes, flight test operations, profit and financing. The breakdown of RDT&E costs are shown in Table 14.1 while the percentage of each factor contributes to the total RDT&E costs can be seen in Figure 14.1. The main variables affecting RDT&E costs are maximum velocity, takeoff gross weight, avionics cost, engine costs, labor rates, materials cost and the number of test airplanes. Six flight test planes and two static test planes were used for all cost estimations.

Category	Cost
Airframe Engineering and Design	$215.59
Development Support and Testing	$62.02
Flight Test Airplanes	$568.51
Flight Test Operations	$24.91
Profit	$113.12
Financing	$147.06
Total RDTE Cost	$1,131.21

Table 14.1: RDT&E Cost (in millions of 2005 USD)

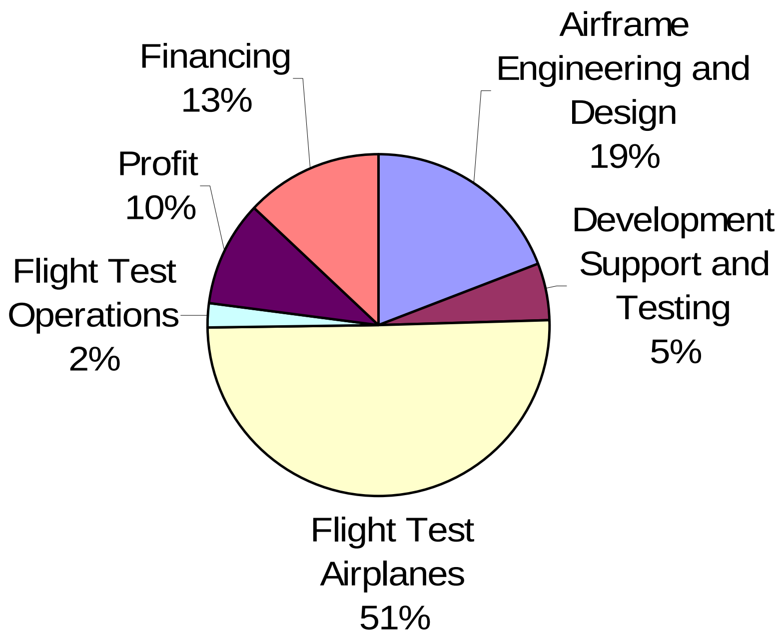

Figure 14.1: RDT&E Cost Breakdown by Percentage

14.2 Manufacturing Cost

The manufacturing cost covers the expenses incurred during the production of a certain number of aircraft. This cost is broken down into four sections: airframe engineering and design, airplane production, production flight test operations, and financing. Table 14.2 shows the summary of these elements and the total manufacturing cost for the production of 100, 200 and 400 aircraft.

Category	100 Planes	200 Planes	400 Planes
Airframe Engineering and Design	$149.04	$196.19	$250.63
Airplane Production	$1,638.93	$3,656.03	$6,169.19
Production Flight Test Operations	$20.00	$40.00	$80.00
Financing	$200.89	$432.47	$727.20
Total Manufacturing Cost	$2,008.86	$4,324.69	$7,272.02

Table 14.2: Manufacturing Cost (in millions of 2005 USD)

The key variables that affect the manufacturing costs are similar to those that contribute to the RDT&E cost with the addition of plane production rates and flight test hours.

The majority of the manufacturing cost is attributed to the actual production of the airplanes. This process includes five components: engines and avionics cost, manufacturing labor cost, manufacturing material cost, manufacturing tooling cost, and quality control cost.

14.3 Flyaway Cost

The flyaway cost, or acquisition cost, of an aircraft is based on the expenditures made and profits incurred in the manufacturing phase of aircraft production. Table 14.3 outlines the flyaway cost for Phoenix production runs of 100, 200 and 400 aircraft.

Category	100 Planes	200 Planes	400 Planes
Manufacturing Cost	$2,008.86	$4,324.47	$7,272.02
Manufacturing Profit	$200.89	$432.47	$727.20
Total Flyaway Cost	*$2,209.75*	*$4,756.94*	*$7,999.22*

Table 14.3: Flyaway Cost (millions of 2005 USD)

The price per unit can be easily obtained by dividing the total flyaway cost by the number planes being produced. Figure 14.2 shows the price of each aircraft at various production runs.

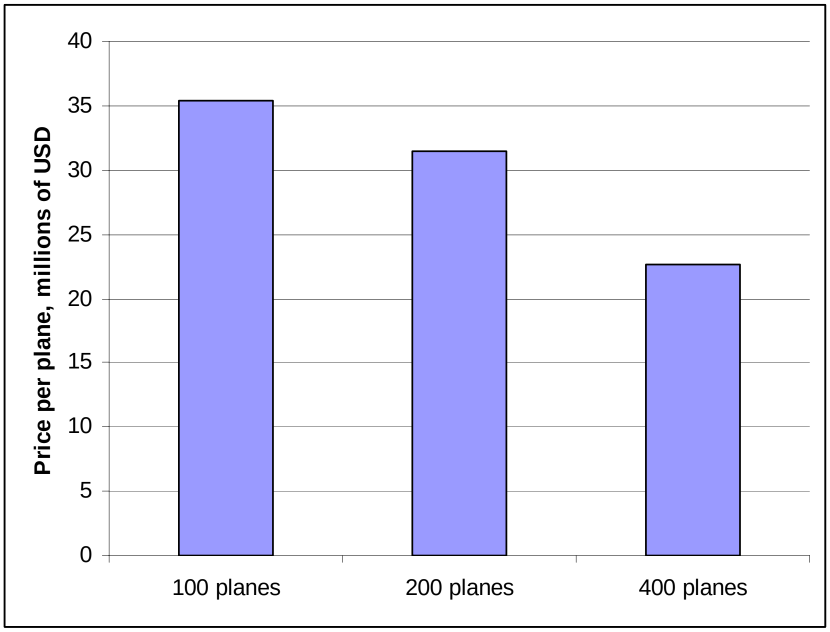

Figure 14.2: Unit cost per aircraft in 2005 USD

14.4 Operating Cost

The operating cost of a military aircraft can be the deciding factor on whether or not the design will be approved and monetary appropriations made. This is especially important for the Phoenix gunship, which is required to have a low cost due to current military budget constraints. The operating cost of military aircraft is different from that of a civilian aircraft in two ways. First, the plane does not depreciate since it is owned by tax paying citizens and not a private corporation. Second, financing cost estimates are not needed because all funds are allocated by Congress through an annual military budget.

Eight factors contribute to the total operating cost of a military aircraft: the cost of fuel, oil and lubricants, the cost of direct personnel, the cost of indirect personnel, the cost of maintenance materials, the cost of spares, the cost of depots and miscellaneous costs. The breakdown of these expenses for a production run of 200 planes is shown in Table 14.4.

Category	Cost
Oil/Petroleum/Lubricants	$1,965.03
Direct Personnel	$5,983.98
Indirect Personnel	$2,165.68
Mainenance Materials	$413.29
Spares	$2,475.47
Depots	$2,320.21
Miscellaneous	$154.82
Total Operating Cost	$15,478.48

Table 14.4: Operating Cost (millions of 2005 USD)

14.5 Disposal Cost

The cost of disposing of the airplane is approximately one percent of the life cycle cost (LCC). The disposal cost for Phoenix is $211 million in 2005 USD. This is based on the LCC for a production run for 200 aircraft.

14.6 Life Cycle Cost

The life cycle cost (LCC) is the total cost incurred during production of an aircraft program. The LCC is the sum of the RDT&E cost, Acquisition cost, Operating Cost, and Disposal Cost. The LCC for Phoenix production runs of 100, 200 and 400 aircraft is outlined in Figure 14.3.

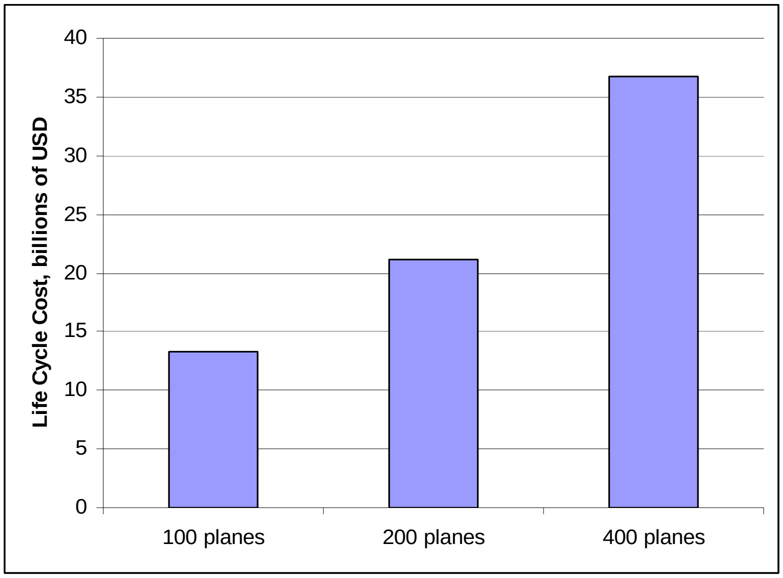

Figure 14.3: Life Cycle Cost in 2005 USD

14.7 Cost Comparison

The RFP states that the advanced gunship must be a cost effective aircraft in light of current budgetary constraints being placed on the military. By comparing the Phoenix to the AC-130U, the US Air Force's newest and most capable gunship, the argument can be made that Phoenix is an economical aircraft. The cost of one AC-130U Spectre gunship is approximately $190 million compared to only a little over $35 million (2005 USD) for one Phoenix gunship, assuming the worst possible production run of 100 planes.[23] Since the Phoenix gunship costs about a fifth of what the AC-130U costs while being able to destroy a greater range of targets with more effective weapons, it is clear that the Phoenix is a cost effective upgrade to current gunships.

References

1. AIAA Foundation RFP, 2004, avail. http://www.aiaa.org/documents/student/ugradteamairrfp.doc

2. Virginia Tech Design Software Website, 2005, avail. http://www.aoe.vt.edu/~mason/Mason_f/MRsoft.html

3. Marchman, J., AOE 3104 Aircraft Performance Notes, Virginia Tech, 2001

4. Raymer, Daniel P., Aircraft Design: A Conceptual Approach, 3rd Edition. AIAA Education Series, Reston, VA. 1999

5. Ball, Robert E., The Fundamentals of Aircraft Combat Survivability Analysis and Design, AIAA, 2003

6. AIAA Website, "Survivability Topics for the AIAA Foundation 2004-2005 Undergraduate Team Aircraft Design Competition", AIAA, 2004, avail. http://www.aiaa.org/tc/sur/Pages/Design_Comp_Frame%202004_05.html

7. US Marine Corps Website, "Hawk surface-to-air-missiles", 2004, avail. http://www.hqmc.usmc.mil/

8. Federation of American Scientists Website, "Man-Portable Air Defense systems (MANPADS) Proliferation: Understanding the Problem", avail. http://www.fas.org/asmp/campaigns/MANPADS/MANPADS.html

9. Eurofighter Website, "Eurofighter Typhoon, Nothing Stands in its Way", 2004, avail. www.eurofighter.com

10. Boeing Corporation Website, "Boeing 7E7 Dreamliner Will Provide New Solutions for Airlines, Passengers", 2004, avail. http://www.boeing.com/commercial/7e7/background.html

11. Middleton, Donald H., Composite Materials in Aircraft Structures, Longman Scientific & Technical, NY, 1990

12. Callister, William D. Jr., Materials Science and Engineering an Introduction", John Wiley & Sons Inc., NY, 2003

13. Global Security Website, "Large Aircraft Infrared Countermeasures (LAIRCM)", 2004, avail. www.globalsecurity.org/military/systems/aircraft/systems/laircm.htm

14. Honeywell Website, "Embedded GPS/INS (EGI)", 2004, avail. http://content.honeywell.com/dses/products/navigators/gn-h764g.htm

15. Goodrich Power Systems, "AC Generators", 2004, avail. www.power.goodrich.com/products/ac.shtml

16. SBS Technologies, "Configurable Advanced Mission Computer", 2004, avail. www.ferret.com.au/articles/4d/0c01ce4d.asp

17. Roskam, J., Airplane Design: Part VI Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics, DAR Corporation, 2004

18. Roskam, J., Airplane Design: Part VII Determination of Stability, Control, and Performance Characteristics, DAR Corporation, 2004

19. Roskam, J., Airplane Design: Part VIII Airplane Cost Estimation: Design, Development, Manufacturing, and Operating, DAR Corporation, 2004

20. Etkin et al., Dynamics of Flight: Stability and Control, John Wiley & Sons Inc., NY, 1996

21. Bertin, John J., Aerodynamics for Engineers 4th Edition, Prentice Hall, NJ, 2002

22. Eric, PhD, "V-n Diagrams (a.k.a flight envelope)", 2005, avail. http://www.aoe.vt.edu/~johnson/AOE3124/V-nDiagrams.pdf

23. AC-130H/U Spectre Gunship Fact Sheet, avail. http://www.globalspecialoperations.com/ac130.html

24. Shevell, R. S. et al. Aerodynamic Design Features of the DC-9, AIAA Paper # 65-738, 196

25. Airpower Journal Website, "Unmanned Aerial Vehicles", 1991, avail. http://www.airpower.maxwell.af.mil/airchronicles/apj/4spr91.html

26. Harris, Charles D. NASA Supercritical Airfoils. NASA TP 2969. 1990.