Proposed Solution for 2000/2001 AIAA Foundation
Undergraduate Team Aircraft Design Competition
May 9, 2001

TEAM VERTIGO

Adam Corliss	177917
Adam Jones	200946
Rachel Shuck	177932
Evan Perry	188818
T. Watson	191304
Dave Dartez	204726
Dave Owens	204725
Beverly Beasley	202245
Dave O’Brien	191303
Ben Marshall	192965

Executive Summary

This proposal provides an understanding of, and solution to, the problems inherent in the design of a Common Support Aircraft (CSA) for the U.S. Navy, in response to the AIAA Aircraft Design Team Undergraduate Request for Proposal for 2000-2001. First the purpose for the CSA as a replacement for four naval support aircraft due to retire service in coming years is explained. The requirements set forth by the AIAA RFP are then explained to show an understanding of the problem and the characteristics that must be inherent in, or provided by, the final design. Four initial concepts are presented, along with explanations of their unique approaches to solving the problem. Then, in conjunction with more detailed, weighted performance factors, a matrix type decision-making process is employed to narrow down the three concepts to the final design. The final design technical characteristics are then analyzed and defined in detail, providing explanations of the procedures used to accomplish this task throughout. We present a highly innovative and capable solution to the CSA problem.

The design proposed in this report involves a system of two interacting aircraft, nicknamed the Wombat and the Joey. The Wombat is a cargo/transport-type aircraft, while the Joey is a small UAV designed to be launched and recovered from the weapons bay of the Wombat. The Carrier-On-board Delivery (COD) mission is performed by a version of the Wombat with a pressurized cargo bay for passengers. The Anti-Submarine Warfare/Anti-Surface Warfare (ASW/ASUW) mission is performed by the Wombat with a version possessing a weapons bay and internal bomb racks for anti-ship missiles and torpedoes. The Wombat also allows for the bomb racks to be swapped out for two internally stored Joeys, and the deployment/retrieval system, to perform the Airborne Electronic Warning (AEW) and Electronic Surveillance (ES) missions. There are two variants of the Joey, an ES version and an AEW version, employing the use of advanced conformal radar, a technology which allows for radar elements to be placed along the skin of the aircraft, eliminating the need for a rotodome. A pair of Joeys may be deployed from the weapon bay of the Wombat to perform either the ES or AEW mission, while the Wombat acts as a control and relay station back to the carrier, providing an extensive over-the-horizon (OTH) capability. The Joeys then return to the Wombat for retrieval and return to the carrier.

A UAV was desired particularly for the AEW and ES missions because it has advantages over a manned platform. A UAV does not risk crew's lives when flying into hostile territory; therefore, allowing a UAV to perform longer and more effectively in a hostile environment. The Joey, and the sensitive on-board equipment, may be destroyed if there is a risk of it being captured by non-friendly nations by a self-destruct capability. Since the Joey is unmanned, no human can be captured, preventing situations like that which occurred in April 2001 between China and the crew of a Navy EP-3. The Navy and other military services are aggressively pursuing UAVs as the next platforms for electronic surveillance such as the Pioneer, VTUAV, and Global Hawk to name just a few. The Joey could also potentially become a multi-service platform.

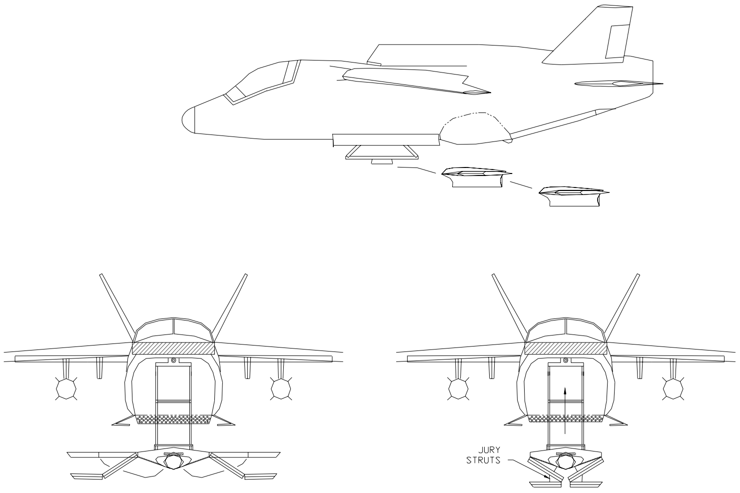
It was concluded however, that a UAV was not desirable for the COD and ASW/ASUW missions. A COD aircraft carrying passengers would require a pilot at the controls; no personnel would want to fly in something that didn't have a person in the cockpit. There are also concerns with the potentially dangerous maneuver of landing an unmanned vehicle on a crowded aircraft carrier deck. Moreover, there are restrictions associated with arms control

treaties against carrying and deploying weapons from UAVs, enhancing issues for performing the ASW/ASUW missions.

These pros and cons lead to the idea of the mother-daughter/Wombat-Joey aircraft configuration, providing unique benefits to mission operations. It is a highly flexible system in that it allows the aircraft to be reconfigured on ship to provide different capabilities for the required mission-at-hand. For example, if a Joey needs to be withdrawn for maintenance, another one can replace it, further; the Wombat is still capable of performing the COD and ASW/ASUW missions without it. Likewise, if a Wombat needs repairs, another Wombat can be reconfigured to carry the Joeys and perform the AEW/ES missions. Deployment and retrieval of the Joeys while in flight does not disrupt normal carrier operations, and overcomes the danger associated with carrier landings. In-flight deployment and retrieval extends the range of the Joey by not burning any fuel until deployment. More importantly, the use of dual Joeys provides an extended, redundant radar and ES coverage area. Reduced costs incurred from the common Wombat airframe are also a strong benefit.

This proposal presents a system that meets and exceeds all requirements set forth in the AIAA RFP. We add new capabilities to those called for in the RFP, providing the Navy, and possibly other services, with an advanced electronic surveillance and early warning capable UAV. UAVs are quickly becoming front line assets in the modern battle space. The fact that they do not endanger crewman's lives when carrying out missions in hostile airspace is reason enough to justify their further development and deployment.

This team's design provides for an advanced war fighting capability that keeps pace with cutting edge technologies, making our CSA, when fielded, relevant and effective well into the mid-21st century.



Example of Joey Retrieval

Table of Contents

List of Figures

List of Tables

Nomenclature

ADCAP	Advanced Capability
AEW	Airborne Early Warning
AGM	Advanced Guidance Missile
ALWT	Advanced Lightweight Torpedo
AOA	Angle of Attack
AR	Aspect Ratio
ASM	Air-to-Surface Missile
ASUW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
AWACS	Airborne Warning & Control System
BCA	Best Cruise Altitude
C_{Do}	Parasite Drag
C_D	Drag Coefficient
C_l	2-D Lift Coefficient
C_L	3-D Lift Coefficient
$C_{L\alpha}$	Lift curve Slope
c.g.	Center of Gravity
COD	Carrier On-Board Delivery
CSA	Common Support Aircraft
D	Drag Parameter
ECM	Electronic Counter Measures
ES	Electronic Surveillance
ESM	Electronic Support Measures
FLIR	Forward-Looking InfraRed
FOD	Foreign Object Damage
g	Acceleration due to gravity
GPS	Global Positioning System
IFF	Identify Friend-Foe
INS	Internal Navigation System
Joey	Name for UAV concept
JSF	Joint Strike Fighter
JSTARS	Joint Surveillance Target Attack Radar System
JTIDS	Joint Tactical Information Distribution Systems
L	Lift parameter
L/D	Lift to Drag Ratio
LHT	Lightweight Hybrid Torpedo
M	Mach Number
Mac	mean aerodynamic chord
MAD	Magnetic Anomaly Detector
n	Load Factor
NASA	National Aeronautical and Space Administration
NFO	Naval Flight Officer
NLF	Natural Laminar Flow
nm	Nautical Miles
OTH	Over-the-Horizon
P	Pressure
psf	Pounds per square foot
R&D	Research and Development
ROC	Rate of Climb
RFP	Request for Proposal
S	Wing Reference Area
SA	Standard Atmosphere
SEROC	Single-Engine Rate of Climb
SFC	Specific Fuel Consumption
SR	Specific Range
STOL	Short Takeoff and Landing
T	Thrust
T	Temperature
t	Time
t/c	Thickness to Chord Ratio
TOGW	Takeoff Gross Weight
TSFC	Thrust Specific Fuel Consumption
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
VSTOL	Vertical or Short Takeoff and Landing
W	Weight
Wombat	Name for compound wing concept
WOD	Wind Over Deck

Greek Symbols

α	Angle of Attack
α_L	Thrust Lapse Ratio
β	Weight Fraction
α_{0L}	Zero Lift Angle of Attack
Δx	Change in Parameter x
Λ_{LE}	Leading Edge Sweep
ρ	Density
λ	Wing Taper Ratio

Subscripts

f	Force
L	Landing
LO	Liftoff
MAX	Maximum
MIN	Minimum
p	Powered
SL	Sea Level
TD	Touchdown
TO	Takeoff

CHAPTER 1 – INTRODUCTION AND CONCEPTS

1.1 Introduction

With an aging fleet of aircraft, the United States Navy is in need of an affordable multi-use family of aircraft to replace certain mission specific platforms. These platforms include carrier-based aircraft that accomplish the roles of airborne early warning, anti-submarine warfare and anti-ship warfare, electronic surveillance, and carrier on-board delivery. These missions are critical to the safety and readiness of the fleet. The existing aircraft do fulfill their missions and are carrier suitable; however, all four aircraft are reaching the end of their operational lives. All of the current aircraft were developed in the 1960s and 1970s, so their technology is limited and upgrades have been maximized on these platforms. This is a detriment to a competitive naval fleet.[1.1] The purpose of the 2000/2001 AIAA Undergraduate Aircraft Design Competition is to combine these platforms into a small family of aircraft, capable of fulfilling each mission. We are pleased to propose a solution for this problem.

1.2 AIAA RFP

The 2000/2001 AIAA Undergraduate Aircraft Design Competition requested a proposal[1.2] for the United States Navy Common Support Aircraft (CSA). This program is desired to perform the missions of the E-2C Hawkeye, S-3B Viking, ES-3A Shadow, and C-2A Greyhound which currently fulfill the roles of AEW, ASW/ASUW, ES, and COD, respectively. However these aircraft are expected to reach the end of their service lives within the next 15 years. The CSA program is intended to fulfill all the missions with an affordable carrier based family of aircraft with initial operating capability of 2013.

1.2.1 Airborne Early Warning (AEW)

The AEW version of the CSA will need to carry 12,000 pounds of avionics, sensors, and radar. It will have a crew size of four, pilot, co-pilot, and two mission specialists/operators. Its mission will be as follows (Figure 1.1):

1. Warm up, taxi, and takeoff fuel allowance equal to the fuel consumed during 5 minutes of operation at maximum take off power
2. Climb at maximum climb power and best climb speed from sea level to cruise altitude (not a cruise climb)
3. Cruise at best cruise altitude and speed for 250 nm
4. Loiter 4.5 hours at 35,000 feet at best endurance speed
5. Return cruise at best cruise altitude and speed for 250 nm
6. Descend to sea level with no distance credit for descent
7. Loiter at sea level for 20 minutes at best endurance speed
8. Keep 5% of total mission fuel as reserve fuel

[1.1] www.fas.org

[1.2] 2000/2001 AIAA Foundation Undergraduate Team Aircraft Design Competition Request for Proposal

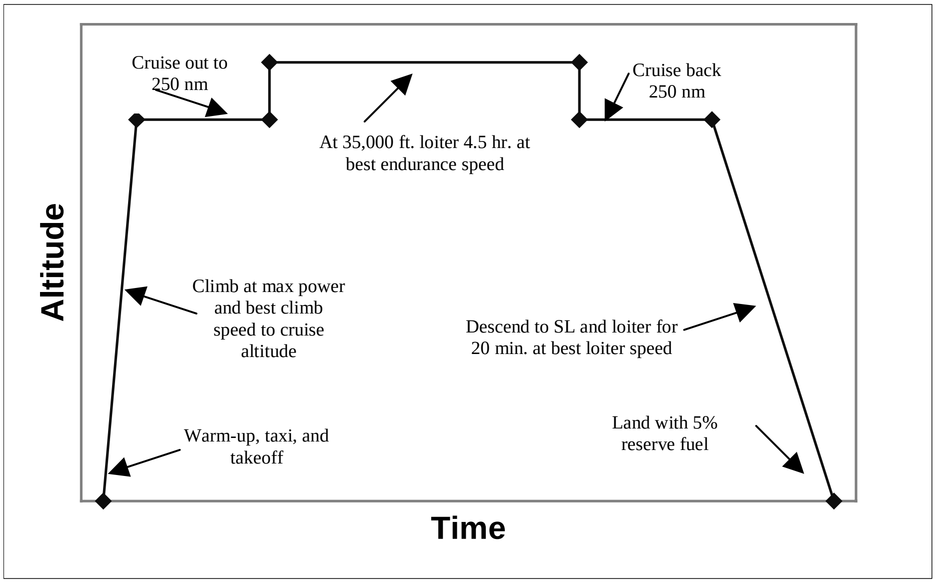


Figure 1.1 – RFP AEW Design Mission Profile

1.2.2 Anti-Submarine/Anti-Surface Warfare (ASW/ASUW)

The ASW/ASUW version of the CSA will need to carry 5,000 pounds of avionics, 68 A-size sonobuoys, two advanced torpedoes, and two advanced anti-ship missiles. It will have a crew of four; pilot, co-pilot, and two mission specialists/operators. Figure 1.2 sketches the mission with altitude as a function of time.

1. Warm up, taxi, and takeoff fuel allowance equal to the fuel consumed during 5 minutes of operation at maximum take off power
2. Climb at maximum climb power and best climb speed from sea level to cruise altitude (not a cruise climb)
3. Cruise at best cruise altitude and speed for 245 nm
4. Loiter 4.5 hours at 25,000 feet at best endurance speed
5. Launch anti-ship missiles weighing 2,200 pounds
6. Return cruise at best cruise altitude and speed for 245 nm
7. Descend to sea level with no distance credit for descent
8. Loiter at sea level for 20 minutes at best endurance speed
9. Keep 5% of total mission fuel as reserve fuel

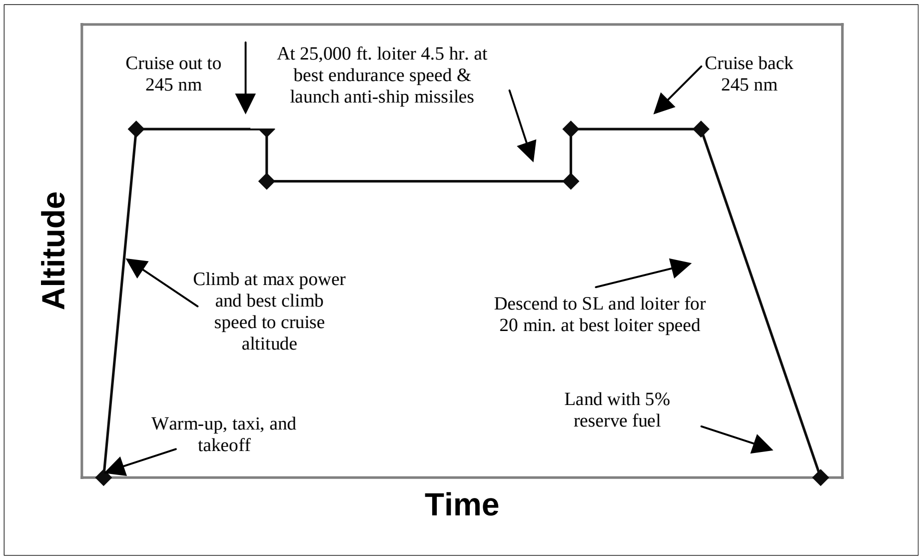


Figure 1.2 – RFP ASW/ASUW Design Mission Profile

1.2.3 Electronic Surveillance (ES)

The ES version of the CSA will need to carry 9,800 pounds of sensors and avionics. It will have a crew of four; pilot, co-pilot, and two mission specialists/operators. Figure 1.3 sketches the mission with altitude as a function of time.

1. Warm up, taxi, and takeoff fuel allowance equal to the fuel consumed during 5 minutes of operation at maximum take off power
2. Climb at maximum climb power and best climb speed from sea level to cruise altitude (not a cruise climb)
3. Cruise at best cruise altitude and speed for 520 nm
4. Loiter 2.5 hours at 40,000 feet at best endurance speed
5. Return cruise at best cruise altitude and speed for 520 nm
6. Descend to sea level with no distance credit for descent
7. Loiter at sea level for 20 minutes at best endurance speed
8. Keep 5% of total mission fuel as reserve fuel

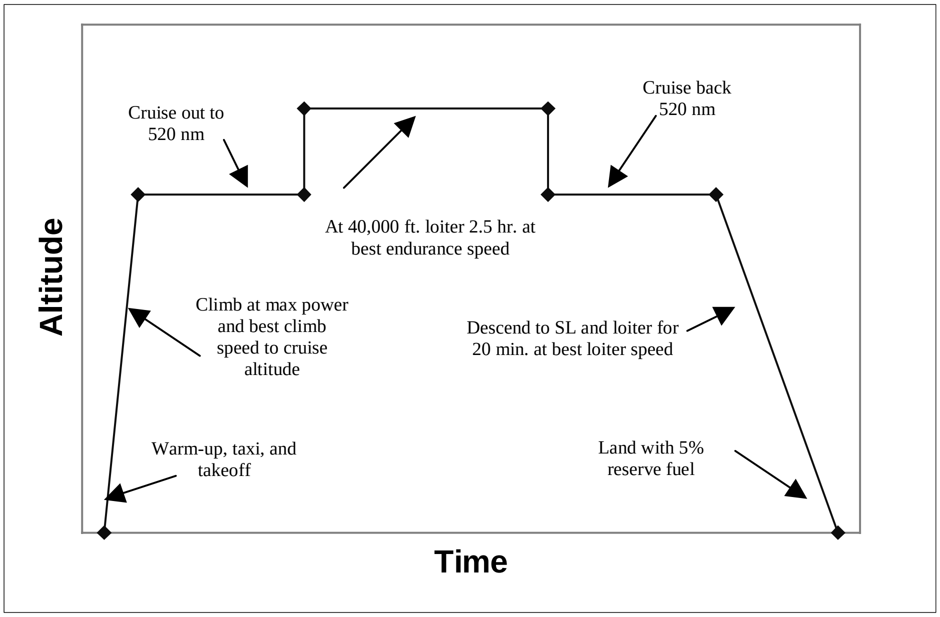


Figure 1.3 – RFP ES Design Mission Profile

1.2.4 Carrier On-board Delivery (COD)

The COD version of the CSA will need to carry 26 passengers or 10,000 pounds of cargo. It will have a crew of two, a pilot and co-pilot. It will also carry 2,000 pounds of avionics. It will be capable of both refueling and receiving fuel. Figure 1.4 sketches the mission with altitude as a function of time.

1. Warm up, taxi, and takeoff fuel allowance equal to the fuel consumed during 5 minutes of operation at maximum take off power
2. Climb at maximum climb power and best climb speed from sea level to cruise altitude (not a cruise climb)
3. Cruise at best cruise altitude and speed for 1,600 nm
4. Descend to sea level with no distance credit for descent
5. Loiter at sea level for 20 minutes at best endurance speed
6. Keep 5% of total mission fuel as reserve fuel

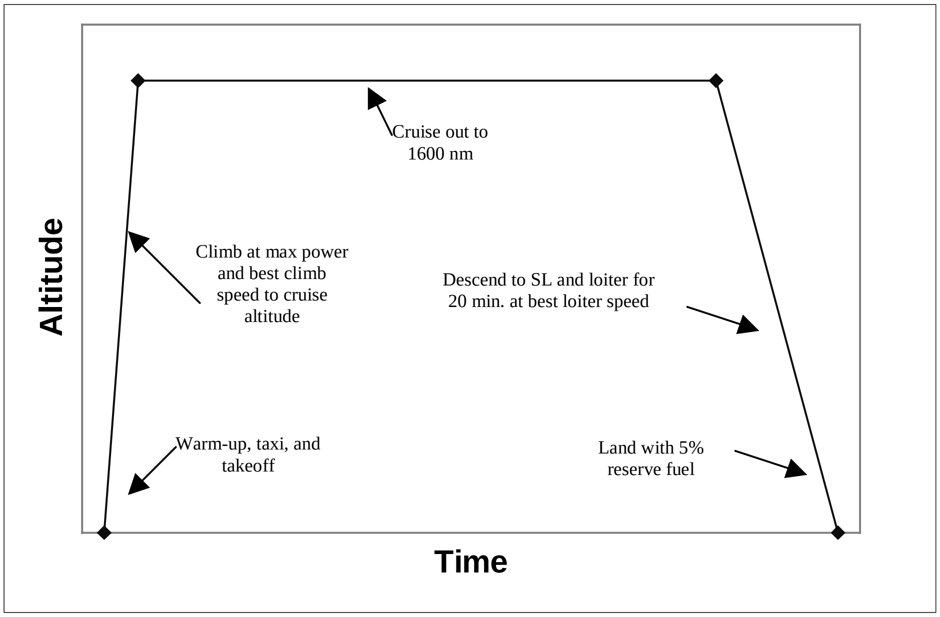


Figure 1.4 – RFP COD Design Mission Profile

1.2.5 Point Performance and Carrier Suitability Requirements

Along with mission requirements, each aircraft variant must meet the following performance and carrier requirements:

1. Launch Wind Over Deck (WOD) not greater than zero knots. (C-13-2) catapult.
2. Approach WOD not greater than 5 knots. (Mark 7 Mod 3) arresting gear.
3. Launch single-engine rate of climb (SEROC) not less than 200 ft/min.
4. Approach SEROC not less than 500 ft/min.
5. Unfolded wingspan not greater than 80 feet (Navigation mast on starboard side of catapult 1 limits unfolded wingspan.)
6. Folded wingspan not greater than 76 feet (hangar bay door clearance).
7. Overall length not greater than 60 feet (jet blast deflector clearance).
8. Overall height not greater than 18.5 feet (aft hangar bay height).
9. Minimize spot factor by minimizing total planform area for aircraft in stowed configuration (e.g. wings folded).
10. Maximum take-off gross weight not greater than 90,000 lb. (elevator deck strength limits and support equipment capability).
11. Dash speed at loiter altitude not less than 425 kts.

1.3 Initial Concepts

Ten different concepts were produced during preliminary design and initial plus/minus charts reduced these ten concepts to four possible candidates: conventional, boxed-wing, compound wing, and compound wing with UAV. The original ten designs played a significant role in the selection of the final concept by integrating the best ideas from a number of concepts into the final design. The final concept that this team decided upon was a compound wing mother ship with deployable UAVs. Section 1.3 presents the initial concepts and the procedure that was followed to narrow the concepts down to the final.

1.3.1 Conventional Aircraft

The conventional concept, Figure 1.5, utilizes a single airframe for all missions, with two different internal configurations. One design configuration will perform the COD mission, while the other performs the AEW, ASW/ASUW, and ES missions. The AEW version uses conformal radar in place of a rotodome. The engines are identical for each configuration: two wing-mounted high-bypass turbofan engines. These engines will be upgrade versions of the General Electric TF-34 turbofans, currently installed on the S-3Bs. Pitch is controlled by elevators on the horizontal tail, yaw is controlled by a rudder on the vertical tail, and lateral control by ailerons and spoilers on the outboard wing panel. The fuselage length is 49.5 feet with a maximum width of 9 feet. The wings have an unfolded span of 65.3 feet, and a folded span of 35.5 feet. Leading edge sweep is 16º, and the wing aspect ratio is 6.9. The vertical tail also folds for hangar stowage.

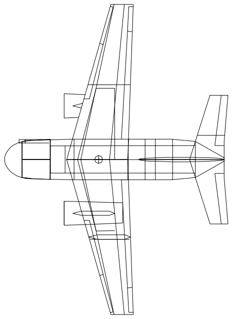


Figure 1.5 – Conventional Concept

A major advantage of this design is its cost. Since it is a conventional design, the research and development costs would be greatly reduced. Two fuselages with mission-specific modifications would perform all the missions, fulfilling the family concept requirement. For the COD mission the cargo would be loaded through a lowered ramp in the aft end, as is done in the C-2. The wing folds are conventional, which minimizes the time and difficulty associated with folding the wings. The biggest disadvantage to this concept is the difficulty associated with obtaining full 360° radar coverage using conformal radar. Conformal radar is discussed in detail in Chapter 8. It may become necessary to add additional radar antenna external to the fuselage to obtain the full viewing area.

1.3.2 Boxed Wing

The boxed wing design, Figure 1.6, was a result of the idea that the Airborne Early Warning mission is the design driver of the CSA project. While a conventional rotodome could have been used, as seen in the E-2C Hawkeye, it was decided that the use of the more unconventional and technologically advanced conformal radar system would be more beneficial. The wing tips of the CSA boxed-wing design utilize the blended winglets concept, where the wing-tips sweep up and back from the main wing and forward and down from the horizontal stabilizer. Blended wing tips of the main wing and the horizontal stabilizer join to form the box like that seen in Lockheed Martin's concept to meet the United States Air Force's requirement for an upgraded Strategic Mobility fleet, which will provide heavy cargo transportation and air-to-air refueling capabilities.[1.3] These functions are currently provided by the C-141B and the KC-135. With this concept, multiple refueling booms can be deployed from structurally damped outboard wing installations. It also provides a much greater flight range due to increased aerodynamic efficiency.

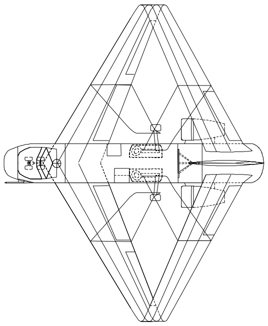


Figure 1.6 – Boxed Wing Concept

The boxed-wing design also has to meet the carrier specifications and requirements. To meet these requirements, this aircraft has a low mounted main wing, swept at 32°, with a span of 70 feet, which is under the maximum dimension of 80 feet. The wing tip blends upward, joining the rear stabilizer/wing, with the leading edge forward-swept at 23° and high mounted near the rear of the 60-foot long fuselage. There are two types of fuselage, each with a mission dependent diameter of 9 or 10.9 feet. Height of the two fuselage variations are 24 and 25.9 feet. The roles of AEW, ES, and ASW/ASUW utilize the same fuselage, empennage, and wing sections. The COD variant requires the larger 10.9-foot fuselage to carry the cargo volume required by the RFP. This variant also employs vertical extensions at max span in the blended wing tips to accommodate the larger fuselage height. Cargo, passengers, and mid-air refueling equipment are located in the rear aircraft fuselage.

Both wings and the vertical tail fold due to carrier hangar deck clearance requirements. The tail is folded to the starboard side, reducing the height to the required maximum of 18 feet. The wings unlock in the center of the blended tip, both folding upward and inward, reducing the wingspan to the required 36 feet. Turbofan engines are mounted on each side of the fuselage at centerline height, on the aft section of the aircraft. Fuel is stored in the wings, inboard of the wing fold.

1.3.3 Compound Wing

The compound wing design, discussed in detail in Chapter 2, represents a more innovative solution to the problem than the conventional concept. Like other designs, this concept utilizes conformal radar. It also has two variants: a COD/ES/AEW version and an ASW/ASUW version.

[1.3] Dane, Abe.,"Diamond Eyes," *Popular Mechanics* [online], URL: http://popularmechanics.mondosearch.com/cgi-bin/MsmGo.exe?grab_id=36894690&host_id=1&page_id=1031&query=conformal+radar [cited 3 May 2001]

The fuselage is the same for both versions and has a length of 59 feet and maximum width of 11 feet. The wings have a leading edge sweep of 30º, an unfolded span of 75 feet with an aspect ratio of 8.0, and a folded span of 39 feet. Conformal radar is integrated into the leading and trailing edges of the inboard section of the wings, and the ailerons are located on the outboard section. Pitch is controlled by an all-flying horizontal tail, and yaw is controlled by a butterfly vertical tail with rudders.

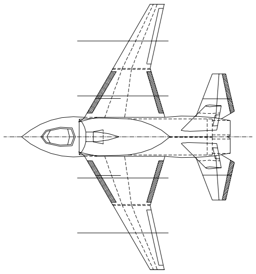


Figure 1.7 – Compound Wing Concept

1.3.4 Compound Wing with UAV

The fourth concept that was envisioned used the compound wing aircraft, discussed in section 1.3.3 and paired it with internally carried UAV drones. The motivation for this concept originated from the desire to truly meet the vision of a CSA. This particular design allows a high commonality for the family concept while still fulfilling all the required missions.

The UAV will fulfill the AEW and ES missions. Currently the E-2C is used to monitor airspace and provide the carrier with an over-the-horizon capability. With advances in radar technologies, a single UAV can be designed and achieve comparable radar coverage as the E-2C. The UAV will be able to perform the AEW and ES missions more efficiently than the E-2C and ES-3A without placing their crews in harms way. It would essentially be a flying radar with an engine.

The UAV is a pure flying wing design with an unfolded wingspan of 24 feet. Since this aircraft must fit inside the mother ship platform, the folded UAV was sized to fit within the dimensions of a cargo pallet. To accomplish this the wings fold twice to obtain a folded width of 8 feet. Since the UAV is a pure flying wing, it does not possess a vertical tail allowing the UAV an unfolded height of 2.5 feet. The wings fold below the fuselage to provide the folded height to be 4.2 feet tall, which is well within the pallet height of 7 feet. The length of the UAV is 10 feet in its unfolded configuration and 8 feet long once folded.

The radar components used in each UAV are expected to weigh 800-1,000 pounds as discussed in Chapter 8. Using this information, the UAV launch gross weight was estimated to be 5,120 pounds if the UAV flies back to the carrier and 4,700 pounds if the UAV is retrieved by the mother ship. The fuel weight for each of the above cases is 1,500 pounds for the return to the mother ship. Although there is an insufficient amount of data and methods for estimating the empty weight fraction of a UAV, other UAVs were used to check the values estimated by the sizing code discussed in the next section.

CHAPTER 2 – FINAL CONFIGURATION DESCRIPTION

2.1 Preferred Concept Selection

2.1.1 Design Matrix

A design matrix as a quantitative, logical method to choose a final concept. Several factors were chosen and weighted according to importance to the overall design in order to create the matrix. A score was assigned to each of the design concepts according to how well that particular design fulfilled the design initiative, with a value of one being the lowest and ten being the highest. This design matrix was created with ten design initiatives, and the four concepts were evaluated accordingly. The design matrix is shown in Table 2.1.

Table 2.1 – Concept Design Matrix

Initiatives	Weighting Factor (%)	Compound Wing	Compound w/ UAV	Boxed Wing	Conventional
Cost	10	8	7	6	9
Marketability	5	7	8	5	7
Safety	10	7	8	7	7
Maintainability	15	6	7	4	9
TOGW	10	7	6	6	7
Handling Qualities	10	8	8	7	7
Manufacturing	10	8	7	5	8
Advanced Technology	10	7	10	8	6
Spot Factor	5	7	8	6	7
Mission Diversity	15	8	10	4	4
SCORE (possible 1000)		730	795	565	705

Cost, the first initiative evaluated, was given a weighting factor of ten percent. The cost initiative included costs of R&D, manufacturing, operating, and maintenance. The compound wing and conventional wing were assigned relatively high scores based on their ease of maintenance and the likely low R&D costs, while the unconventional UAV and boxed-wing designs scored lower. With two UAVs and a mother ship to develop, and the fact that it incorporates new technology, R&D costs would be high. The boxed-wing has a huge cost in R&D due to the relatively unknown characteristics of its performance, and high maintenance costs in the upkeep of the joint system at the wing fold.

The second initiative evaluated was the aircraft's marketability, weighted with a value of five percent. This low value of importance was chosen because the need for a common aircraft outweighs any public-relations considerations. The boxed-wing, because of its unusual characteristics, most likely would not be very marketable, and was therefore given a low score. The compound wing and conventional aircraft were given a fair score for their moderate potential,. The compound wing with UAV was given a high value because of its highly innovative approach and the conventional aircraft with the UAV approach was downgraded due to the possible detrimental effect of engine exhaust during UAV recovery.

At a weighted value of ten percent, safety was the third initiative evaluated. The military imposes stringent safety requirements that all its aircraft must meet, and the Navy adds to these requirements. All the aircraft will meet the safety regulations and were therefore given high scores, but the compound wing with UAV design was given a higher score for its ability to eliminate the human risk factor by incorporating the UAV into the AEW and ES missions.

Maintainability, the fourth initiative, was weighted heavily due to the effect on aircrews and carrier operations. At a value of 15%, this is one of the highest rated initiatives. Each aircraft's ease of maintenance, downtime, complexity of joints, and ease of access contribute to the scores each design received. The compound wing was given a lower rating, because of poor engine access. Engines would have to be translated aft to clear the fuselage before lowering them to deck level, compromising aircraft placement and spotting factor in the hangar bay. The compound wing with the UAV has the same problem, coupled with two additional engines to maintain. Maintenance on the boxed-wing would be difficult as a result of four large wing folds, and its wing geometry cause high loads at the joints. The conventional aircraft was given a high rating for its basic design and its relative ease of maintenance.

TOGW was weighted at a value of ten percent because of its carrier suitability restrictions. With a maximum allowable TOGW of 90,000 pounds., all aircraft rated well because of their low initial weight values. The conventional and compound wing designs rated higher than the compound with UAV and the boxed-wing because of additional weight due to the UAVs and the complex wing-fold system, respectively.

Handling qualities, the sixth initiative evaluated, was rated at a value of ten percent. The aircraft have to have good handling characteristics under all conditions, including carrier-takeoff and landing. The compound wing, conventional wing, and boxed-wing were given good scores, with their handling qualities assumed acceptable. Few performance characteristics are known for boxed wings, so this assumption is solely based on theoretical concepts, and Lockheed Martin's continued interest in this concept. A concern with the compound wing with UAV is the launching and recovering of the UAVs from the mother ship.

Manufacturing, weighing ten percent, was the seventh initiative evaluated. Cost and R&D are the primary rationale behind the relatively high weight of manufacturing. Because of their ease of manufacture, the conventional wing and the compound wing were given high scores for this initiative. With two UAVs to manufacture, the compound wing with UAV design was rated slightly lower than its counterpart, the compound wing. The boxed-wing scored low in this category, with expected high manufacturing and R&D costs because of the new technology involved and the complex wing structure utilized.

The eighth initiative evaluated in the design matrix was advanced technology, weighted at ten percent. The conventional aircraft was given a moderate value because of its use of conformal radar. The compound wing received a slightly higher score for incorporating the conformal radar as well as the advanced wing design. . The boxed-wing was given an even higher score for using advanced boxed-wing structure placement, beneficial aerodynamic characteristics, and achieving optimal conformal radar placement. The compound wing with UAV received perfect score of ten because of its use of UAVs as well as conformal radar in two aircraft platforms enhancing radar and signal coverage.

Spotting factor, a serious concern in carrier operations and the ninth initiative evaluated, was weighted at a value of five percent. The compound wing and conventional concepts were each given a moderate value of seven on this initiative for exhibiting a moderate spot factor. The compound wing with UAV was given a slightly higher score of eight, because it combines three aircraft in the place of one, decreasing the overall spot factor. The boxed-wing score was rated lower, 6, because of concerns with the unproven wing fold scheme, which might not prove feasible.

The aircraft's mission diversity, its ability to perform across all mission profiles, is the tenth and final initiative evaluated in the design matrix, weighing 15%. The compound wing concept received a moderately high score because of its ability to utilize two highly similar airframes across all missions. The boxed-wing and the conventional aircraft received poor scores, because these aircraft utilize two fuselages in order to complete all necessary missions. The compound wing with UAV received the highest score again since it uses one fuselage for all missions, and incorporates UAVs to achieve enhanced mission capabilities on the ES and AEW mission profiles.

With a total matrix score of 795, the compound wing with UAV, hereafter referred to as Wombat and Joey, was selected as the preferred concept.

2.2 Concept Layout

Different options were explored for the configuration of the Wombat and its payload. The Wombat is able to carry two Joeys, so there is the option of having the UAVs configured for either AEW or ES. This allows for a more versatile aircraft family. For example, the Wombat could carry one of each type Joey and perform AEW and ES simultaneously, or carry two of one type of Joey for extended coverage and added capability in one particular mission area. Ideally, a single Joey capable of both missions would be able to switch between them literally on the fly, but interference between systems and the combined weight do not leave this as a feasible option at this point.

2.2.1 Compound Wing – The Wombat

The compound wing configuration including major components and dimensions is shown in Figure 2.1. The overall length of the aircraft is 59.52 feet, with a wingspan of 75.0 feet, well within the maximum CVN-68 class Aircraft Carrier span constraint of 80 feet. The maximum fuselage width is 11.79 feet (141.5 inches), which includes the main landing gear stowage space and is constructed using four different curvatures. Maximum height of the compound wing with V-Tail unfolded is 19.21 feet. Externally, the structure is the same for all four missions. In place of a conventional chin inlet, overhead engine intakes are positioned to avoid foreign object damage and steam ingestion from the catapult launching system.

The wing planform of the aircraft is a compound type (thus its name) with a leading edge sweep of 25.0° and full span anhedral angle of 4.22°. Leading edge sweep allows for better transonic performance characteristics. The larger root chord provides additional lift, and delays stall at high angles-of-attack. Also included on the wing structure is a fold system placed 14.68 feet from the centerline, which consists of a Grumman type fold and twist combination about a skewed hinge. When the folding process is completed the wings are secured to the horizontal tail. This wing fold system allows for a folded span of 30.49 feet, without exceeding the overhead height during fold of 18.5 feet, providing sufficient carrier clearance. The inboard portion of the wing includes trailing edge Fowler flaps for additional lift during take-off and landing or as necessary. Also located on the inboard section

CSA WOMBAT

GENERAL ARRANGEMENT
DRAWN BY: ADAM R. JONES
DATE: 4/24/01
MISSION: ASW, ASUW, COD, ES
SPECS: UNITS ARE IN FEET

M	WING	VTAIL	HTAIL
S, AREA	750.00	119.20	198.00
AR	7.50	2.40	6.52
T. RATIO	0.19	0.41	0.34
SPAN	75.00	8.30(T)	36.00
ROOT	18.60	9.98	11.00
MAC	11.81	7.54	7.32
℄ TO ¼ c̄	14.19	9.29	10.50
TIP CHRD	3.50	4.38	3.75
THICK	18(R)12(T)%	9.5%	11.0%
LESWEEP	25.0°(T)	40.0°(T)	21.0°(T)

WING INCIDENCE: +2.0°
MAX FOLD HGT. WING: 24.50
TURNOVER ANGLE: 54.00°(T)
SCALE:
1IN:15.2FT
UNITS ARE IN FEET
T = TRUE
0 10 20 30

① MAIN GEAR TIRE SIZE 36" X 11" (2)
NOSE GEAR TIRE SIZE 22" X 5.5" (2)

② PYLON POSITIONS FOR EXTERNAL FUEL TANKS OVERLOAD CARRIAGE AND/OR HARDPOINTS. (TYP)

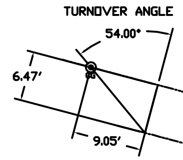
③ DOOR LOCATED ON STARBOARD SIDE FOR CREW STATION AND/OR FOR STOWABLE CARGO NOT CARRIED IN PALLETS

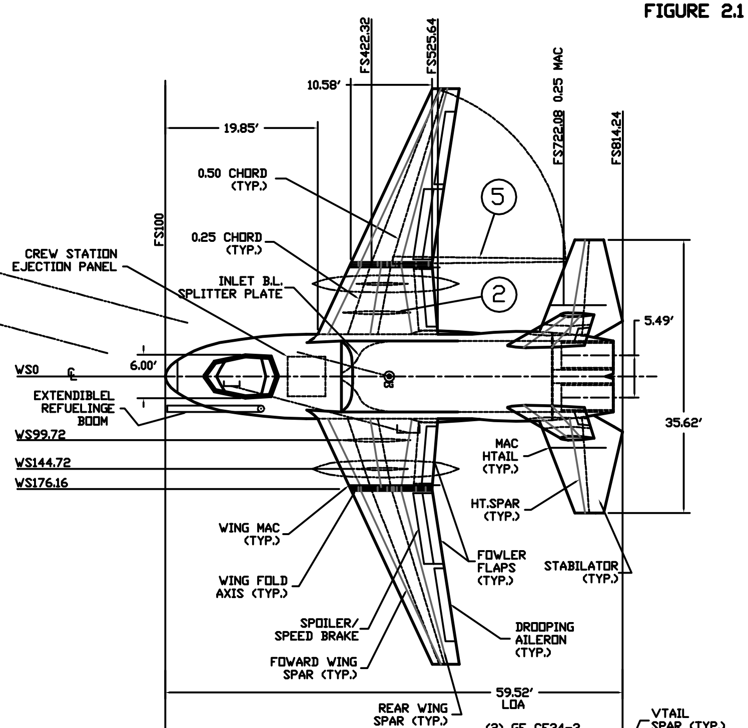
④ COD, ASW, ASUW, AND ES USE THE SAME EXTERNAL FUSELAGE STRUCTURE. FOR DIFFERENCES IN THESE VERSIONS REFER TO THE INBOARD PROFILE

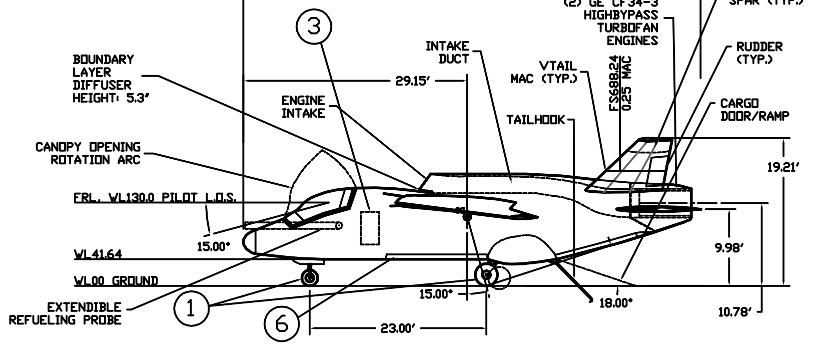
⑤ WING FOLD (TYP.): STANDARD FOLD AND TWIST COMBINATION ABOUT SKEWED HINGE. WINGS SECURE ONTO THE HORIZONTAL TAIL.

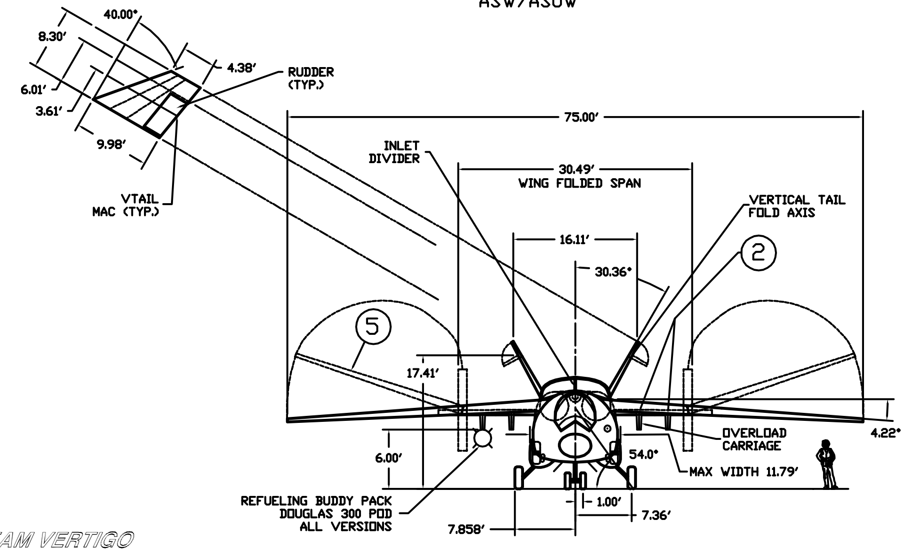
⑥ WEAPON BAY DOOR: FOR AEW AND ASW/ASUW

FIGURE 2.1









TEAM VERTIGO

of each wing are two pylon locations used for Douglas 300 gallon auxiliary fuel tank refueling pods or overload weapons carriage. Located on the outboard section of the wing are trailing edge Fowler flaps, drooping ailerons and spoilers/lift dumpers ahead of the flaps. These devices are used for additional lift and roll control, respectively.

Yaw control for the compound wing is supplied by a twin, splayed tail with an angle from the vertical of 30.36° and a leading edge sweep of 40.0°. Each vertical tail has a true span of 8.30 feet with a taper ratio of 0.34. Each rudder has an area of 13.6 ft^2. A tip fold is integrated into the design to meet carrier stowage requirements of 18.5 feet, with a height of 17.41 feet. The horizontal tail is an all-flying tail for pitch control. It has a span of 35.62 feet and a total area of 198 ft^2.

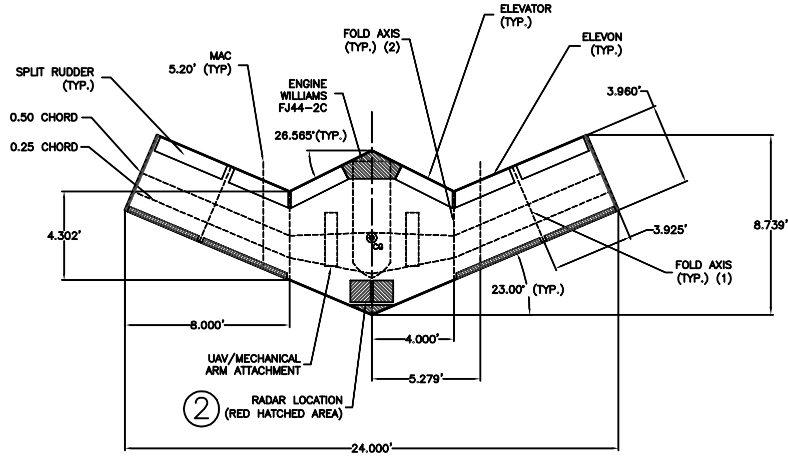
Three inboard configurations are shown in Figure 8.1 for the COD, AEW/ES, a ASW/ASUW versions. All versions have a rear cargo ramp and a side exit. The communications/navigation avionics installation, radome, refueling probe, and crew stations will remain common for all three versions. All variants are capable of carrying 17,900 pounds of fuel, or 355 ft^3. The COD version is capable of seating 26 passengers and baggage or carrying two 463L cargo pallets. The AEW/ES version carries two UAVs on a mechanical arm extension launch and retrieval system, described in Chapter 8. This aircraft has a large weapons bay for deployment and retrieval of the UAVs and weapons carriage. With the floor attached over the extension bay, the ASW version is capable of carrying two Mk-54 torpedoes and two AGM-84 Harpoons along with 68 sonobuoys. An extendible MAD boom is located in the rear of the fuselage between both engines. The rear crew station can carry either two or three crewmembers, as the mission requires, such as Joey operators or fire control personnel.

2.2.2 UAV – The Joey

The Joey, shown in Figure 2.2, is a small all-flying wing, used for electronic surveillance and airborne early warning missions. The wing span is 24.0 feet with a leading edge angle of 23.0° and overall length of 8.739 feet. Control surfaces for pitch, yaw, and roll cover 47.17 ft^2. The aircraft employs two wing folds in order for it to be carried to the mission area within the Wombat, and are unfolded outside the aircraft prior to release. These folds are located 4 feet from the centerline and 3.925 feet from and parallel to the raked wingtip. The wing double folds enabling it to fit within the size constraints of a 463L pallet. Jury struts support dynamic loads during ground and in-flight transport.

Conformal radar panels are placed on the skin of the aircraft on the bottom and top surfaces as well as the leading and trailing edges to ensure full 360° coverage of the mission area. The engine is located on the centerline on the bottom of the aircraft. This helps prevent wake ingestion from the compound wing during deployment and retrieval. Six tanks, as shown in Figure 2.4, provide 2,100 pounds (42.0 ft^3) of fuel storage. Batteries and avionics systems are located in the nose of the aircraft forward of the engine. A retrieval attachment is located on the forward surface of the upper wing.

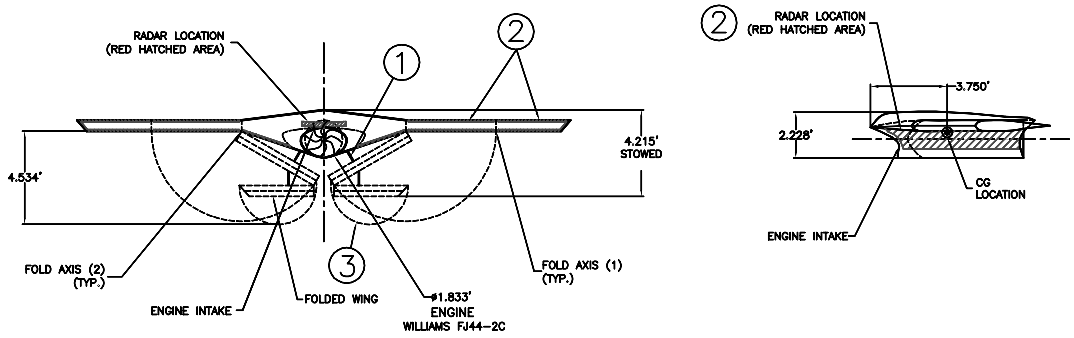
FIGURE 2.2

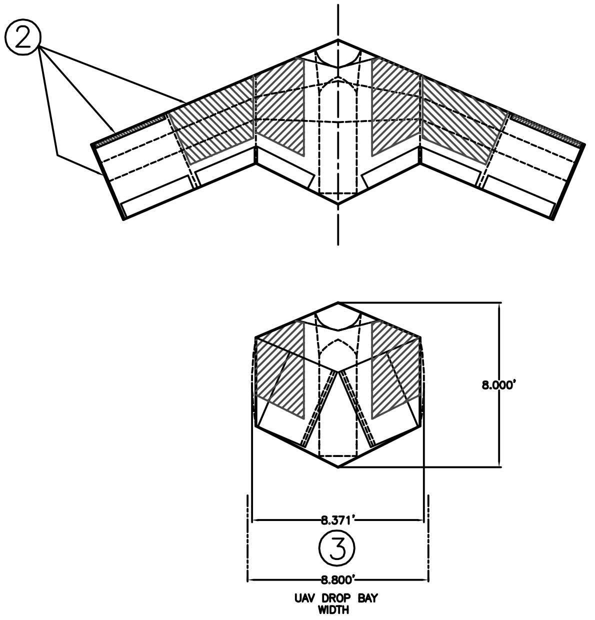


	WING
JOEY-AEW/ES UAV	
GENERAL ARRANGEMENT	
DRAWN BY: ADAM R. JONES	
DATE: 4/24/01	
S, AREA	111.40 (SQ. FT)
AR	5.20
T. RATIO INB./OUTB.	0.495/1.00
SPAN	24.00 (FT)
ROOT	8.00 (FT)
MAC	5.20 (FT)
℄ TO ¼ $\bar{c}$	5.279 (FT)
TIP CHRD	3.96 (FT)
t/$\bar{c}$ OUTB. PAN.	13.58%
LESWEEP	23.00°

SCALE: 0 5 10

UNITS ARE IN FEET





NOTE:

UAV IS STOWED AND FLIES AS SHOWN.

① JURY STRUTS TO TIE FOLDING WING PANELS TOGETHER (OR TO FUSELAGE) TO AVOID DAMAGE TO JOINTS, ACTUATORS UNDER CATAPULT AND ARRESTMENT LOADS. STRUTS ARE AUTOMATED TO ENGAGE AND RELEASE.

② MAJORITY OF THE RADAR COMPONENTS ARE LOCATED ON THE BOTTOM SURFACE OF THE UAV AND ARE COOLED BY FUEL LOCATED IN THE WING AND FUSELAGE. RADAR IS REPRESENTED BY RED HATCHED AREAS.

③ UAV EXTENDED AND RETRACTED WITH THIS GEOMETRY AND DIMENSION WINGS FOLD/UNFOLD SIMULTANEOUSLY

TEAM VERTIGO

2.2.3 Airborne Early Warning (AEW)

The Joeys would be deployed from the Wombat and fly in mission dependent formations. The benefits that a UAV provides, such as a more efficient and complete coverage range, simple radar integration, unmanned capability and possible joint service justify its inclusion in the CSA project. The radar integration is simple since the entire body of the UAV will house the conformal radar panels. The high wetted area of the Joey, where the panels will be located, provides complete coverage around the body, minimizing blind spots. If upgrade or repair is needed, the Joey's comparatively small spot factor ensures ease of maintenance. Joeys can also be stored hanging from the overheads to relieve deck space on the hangar decks.

Also, other CSA missions could be carried out by the Wombat while the Joey is being serviced or the Joey can be replaced. Another benefit mentioned previously is the unmanned capability. Airborne early warning is usually carried out while flying in or around hostile territory, endangering crewmen's lives. The addition of the Joey to the design allows for more aggressive information gathering techniques by flying it into these areas while the Wombat stays at a safe standoff distance.

2.2.4 Anti-Submarine Anti-Surface Warfare (ASW/ASUW)

The avionics are incorporated into the aircraft at the crew station displays and controls and in the fuselage. The sonobuoys, torpedoes, and ASMs are all carried internally as depicted in the Wombat inboard profile, Figure 8.1. Ejector racks are required to get the missiles out of the aircraft when flying at Mach 0.6-0.7. They are ejected along vertically mounted guide racks through double hinged weapon bay doors. The internal design weapon carriage leaves the wing pylons for overload weapons carriage, fuel tanks or electronics equipment pods and new capabilities.

2.2.5 Electronic Surveillance (ES)

The ES mission performs in much the same manner as the AEW mission. The UAV carries the electronic surveillance equipment and performs the ES mission. It is deployed from the mother ship and flown to the desired coverage area, following a prescribed mission profile. This method possesses many advantages over a conventional ES dedicated aircraft. The Joey is deployed forward of the aircraft carrier, and can survey a greater area because it is carried for part of the mission by the mother ship. This results in a larger and more efficient coverage range. Because the object of ES is to intercept enemy signals, the closer to the enemy the Joey can get, the more effective it is. Eliminating the human risk factor, the Joey can fly deeper into hostile territory and is therefore very useful for the ES mission. In today's popular expectation of casualty-free warfare, UAVs are playing a more and more important role in the modern battle space precisely for the reason that they do not risk pilot's and crewmen's lives and would not cause as much adverse publicity if downed. A stealth capability inherent in this UAV's design, an eventual design goal, should extend the survivability of the Joey in hostile territory.

This avionics package requirement poses a minor problem in our UAV design, because there is no capability to carry the weight of existing surveillance systems. Like the radar system however, we believe that with modern electronics this weight may be significantly reduced to an acceptable amount. It has also been assumed that power generation and supply to the electronic sensors will also be significantly advanced in the next ten years.

2.2.6 Carrier On-Board Delivery (COD)

The final Wombat concept performs the COD mission with the mothership only. With the cargo bay empty (i.e. no Joeys, no weapons) there is roughly 1,200 ft^3 of available cargo volume, with 26 feet of length. This accommodates two 463L type cargo pallets, or 26 aft facing passenger seats, or other cargo configurations such as engines for the F/A 18 E/F or JSF.

This configuration allows for 2000 pounds of avionics to be installed in the nose section, crew stations, and other areas of the aircraft. With the 1,200 ft^3 of cargo volume the Wombat easily meets the 12 lb/ft^3 requirement, and a possible maximum of 20,000 pounds payload may be achieved, allowing much higher cargo weight for reduced range missions. The various mission configurations can be seen in the inboard profile of the aircraft, Figure 8.1. The higher payload weight was necessary to carry the two Joeys, together weighing 12,000 pounds. This was the driving factor to design a new mother ship, rather than configure a cargo aircraft to deliver the Joeys. The weight of the Joeys drove the design of the COD aircraft to have the proper payload capacity.

2.3 Wombat and Joey Sizing and Methodology

After the final concept was chosen the next step was defining the initial sizing of the aircraft, providing a starting point for more advanced analysis. The most important characteristics to come out of the sizing analysis revealed were the aircraft empty weights, the fuel, and the takeoff gross weights. Values for these characteristics were needed to begin performance, aerodynamic, internal layout, and structural analyses. This section explains the procedures used to determine the sizing characteristics and the results.

The code used to determine the initial sizing of the design concept is a modified version of acsize.QB, a code implementing Nicolai's aircraft sizing method.[2.1] Assuming an initial TOGW, the required empty weight is computed using the following equation to begins an iterative process,

$$W_{Empty\,\mathrm{Re}\,q'd} = KS \cdot A \cdot TOGW^{B}$$

where *KS* is a structural technology factor between zero and 1 with 1 representing conventional aircraft materials, and A and B are weight correlation factors dependent on the aircraft family. Next the available empty weight is computed. The process is repeated until

$$W_{Empty\,\mathrm{Re}\,q'd} - W_{EmptyAvail} < \varepsilon$$

where ε is the allowed difference between the two weights. Since the program is mission oriented, specific fuel weight fractions of the mission can be computed depending on the cruise distance or loiter time. The weight fractions for range segments of the mission utilize the Brequet equation.

$$\frac{W_{i+1}}{W_i} = e^{-\frac{R \cdot sfc}{V \cdot (L/D)}}$$

In this equation, the *R* represents the range of the mission, *sfc* is the specific fuel consumption of the mission leg, *V* is the velocity, and *L/D* is the lift-to-drag ratio.

[2.1] http://www.aoe.vt.edu/faculty/Mason_f/acsize.QB

The weight fraction for loiter segments of the mission are computed by the equation.

$$\frac{W_{i+1}}{W_i} = e^{-\frac{E*sfc}{L/D}}$$

For this equation the *E* in the exponent represents loiter duration of the aircraft's mission.

For a specific aircraft geometry, payload, and mission, outputs for the program include: outbound cruise weight fraction, return weight fraction, loiter weight fraction, overall landing to takeoff weight fraction, fuel weight, empty weight, and takeoff gross weight.

Sensitivity of the inputs in acsize.QB were examined by changing the input parameters. Variables are kept constant except the parameter in question. Increasing the mission radius by 100 nautical miles increased the TOGW by approximately 3.6%. Increasing the specific fuel consumption (*sfc*) by 0.1 caused an approximate 4.3% increase in the TOGW. A less aggressive structural technology factor (*K*), with a decrease of 0.05, increased the TOGW by approximately 6.8%. A 0.005 increase in the zero lift drag (C_{Do}) caused an approximate 4.2% increase in TOGW. Raising the aspect ratio (*AR*) by one unit decreased the TOGW by approximately 2.5 %. The *L/D* and C_L are not inputs, and are computed given the C_{Do} and *AR* by the equations,

$$\frac{L}{D} \approx \frac{0.5}{(C_{D0}k)^{1/2}}$$

$$C_L \approx 0.5(C_{D_0} \cdot k)^{1/2}$$

where *k* is equal to $\frac{1}{\pi * AR * e}$. This means that *L/D* decreased with increasing C_{Do} and decreasing *AR*. C_L increased as a product of C_{Do} and *AR*. The effects of these parameters on TOGW are seen through the independent effects of the *AR* and C_{Do}.

Using acsize.QB, the TOGW was estimated. The Joey's launch weight was estimated first, so that the required fixed weight of the Wombat could be determined. The fixed weight for the Joey includes the avionics and radar systems required for the AEW and ES missions. The fixed weight of this equipment is approximately 2,500 pounds. Since the Joey is deployed and recovered by the mother ship the loiter-time is the only fuel weight fraction that the aircraft requires. The aerodynamic data used in the computation of the TOGW of the Joey included an aspect ratio of 5.2, a parasite drag of 0.02, and an Oswald efficiency factor of 0.9. Since the Joey will not be required to land on the carrier an aggressive structural technology factor of 0.8 was assumed, meaning most of the load-bearing structure is lightweight composite material. Flight condition inputs for the Joey include a loiter Mach number of 0.5, which correlates to a dynamic pressure of 55.9 lb/ft^2 at 35,000 feet. This lower speed was assumed because the Joey will only loiter as it performs the AEW and ES missions. Weight constants in both the Joey and the Womabt needed for the required empty weight are 0.911 and 0.947 for *A* and *B* respectively as found in Raymer's Aircraft Design textbook. After all these inputs were made, the UAV TOGW produced by the program was 6,750 pounds.

Since the TOGW depends on the specific missions the Wombat is to perform, the following table of mother ship TOGW was made.

Table 2.2 – Mission Weights

Mission	AEW	ES	ASW	COD
TOGW (pounds)	57,258	56,257	49,817	44,403

For the AEW and ES missions, the Joey was carried within Wombat for a portion of the mission. This explains the much higher TOGW for these two missions. Since the AEW mission requires the highest TOGW, this mission became the structural design driver instead of the COD. The inputs for this mission include a fixed weight of 17,000 pounds, approximated by the combined weight of the crew, Joeys, and the Joey deployment and retrieval device. The geometric and aerodynamic characteristics of the mother ship are common for all missions; an aspect ratio of 7.5, parasite drag of 0.03, and an Oswald efficiency factor of 0.85. The structural technology factor for the Wombat is 0.9 since the aircraft must be structurally reinforced to withstand carrier landings, the large Joey deployment bay, and the cargo door/ ramp, but also employs the use of composites where possible. Flight condition inputs for the Wombat include a cruise Mach number of 0.67, which correlates to a dynamic pressure of 171 lb/ft^2 at 35,000 feet. The empty weight of the AEW aircraft computed by the program is 26,267 pounds. This weight represents the empty weight for the mother ship for all four missions. The required fuel weight for the AEW mission is approximately 14,000 pounds.

2.3.1 Sizing Carpet Plots

Another computer program was used to produced data for the carpet plots for analysis of aircraft sizing. This program not only produced the appropriate data, but verified the sizing data obtained using the previously described program, acsize.QB. A modified version of the TOGW estimation method outlined in Chapter 6 of Aircraft Design by Daniel Raymer[2.2] was the program's base algorithm.

This method uses a detailed approximation of the empty weight ratio based on historic trends. The weight fraction is calculated using the following approximation.

$$W_e / W_0 = K_{st}[0.07 + 1.71 W_0^{-0.10} AR^{0.10} (T / W_0)^{0.06} (W_0 / S)^{-0.10} M_{\max}{}^{0.05}]$$

The coefficients used were for a military cargo/bomber type aircraft and a structural factor (K_{st}) can also be applied to account for material advances. The variables used in this approximation are the empty weight (W_0), aspect ratio (AR), thrust to weight ratio (T/W), wing loading (W/S), and maximum Mach number (M_{max}). With a specific thrust value (T) and wing area (S) known, a value for the empty weight can be assumed in the formula, providing a baseline value. Moreover, specific T/W and W/S ratios can also be applied to create a sizing matrix for a carpet plot.

The program works by estimating an empty weight and then iterating until a solution converges. A fuel fraction for each mission segment is predetermined and then the amount of fuel consumed per segment is calculated during each iteration. Before the next segment is calculated, the fuel from the previous segment is subtracted from the total weight. Accounting for the fuel used in each mission segment allows for a more detailed approximation of

---

[2.2] Raymer, Daniel P., *Aircraft Design: A Conceptual Approach*, AIAA, Washington, D.C.,1992.

the TOGW. Payload releases and retrievals are computed in between mission segments by simply adding or subtracting from the appropriate segment weight.

Using this program for the Joey with the input parameters used in the other sizing programs, a TOGW of 6,163 pounds was estimated for the Joey, close to the value of 6,750 pounds obtained using the other sizing program. The empty weight was determined to be 3,225 pounds and the fuel weight was calculated to be 938 pounds. The Joey's sizing constraints are due to the requirements of fitting inside the Wombat cargo bay. Sizing for the Joey showed that the T/W ratio could be reduced. However, this did not take into account the necessary recovery of the Joey in the Wombat. The Joey requires a large amount of thrust to ensure that it can dock with the mother ship in-flight and not cause stall of either platform. One value that is important to the design is wing loading for optimum loiter. This value is determined from the formula.

$$W / S = q\sqrt{\pi AR \cdot eC_{D0}}$$

Using a loiter speed of 0.5 Mach at 35,000 ft., the optimum W/S was determined to be 47.9 lb/ft^2, which is close to the Joey's actual W/S of 47.4 lb/ft^2.

The same procedure was applied to mother ship with the only changes being differences in input parameters. The results from the program yielded a TOGW of 58,321 pounds for the AEW mission, near the 57,258 pounds obtained using the other sizing program. The fuel weight was determined to be 14,792 pounds and the empty weight of the aircraft was computed to be 25,729 pounds. A large portion of the difference between TOGW and the empty weight is accounted for by the weight of the two UAVs being part of the takeoff cargo. Unlike the Joey, the Wombat's size is modified based on analysis seeking the lowest TOGW.

Next, a sizing matrix was created for the AEW mission using this program to study the impact of constraints. As previously mentioned, the T/W and W/S ratios could be varied because they were no longer dependent on the empty weight estimation. The TOGW sizing matrix for the Wombat is shown below (all values in pounds).

Table 2.3 – Carpet Plot Data

	W/S = 50 lb/ft^2	W/S = 60 lb/ft^2	W/S = 70 lb/ft^2	W/S = 80 lb/ft^2	W/S = 90 lb/ft^2	W/S = 100 lb/ft^2
T/W = .45	63,762	62,170	60,897	59,844	58,951	58,180
T/W = .40	63,133	61,578	60,334	59,304	58,431	57,677
T/W = .35	62,439	60,924	59,711	58,707	57,856	57,120
T/W = .30	61,659	60,189	59,011	58,036	57,208	56,493
T/W = .25	60,767	59,347	58,209	57,266	56,466	55,773

Using the sizing matrix, the carpet plot shown in Figure 2.5 was created.

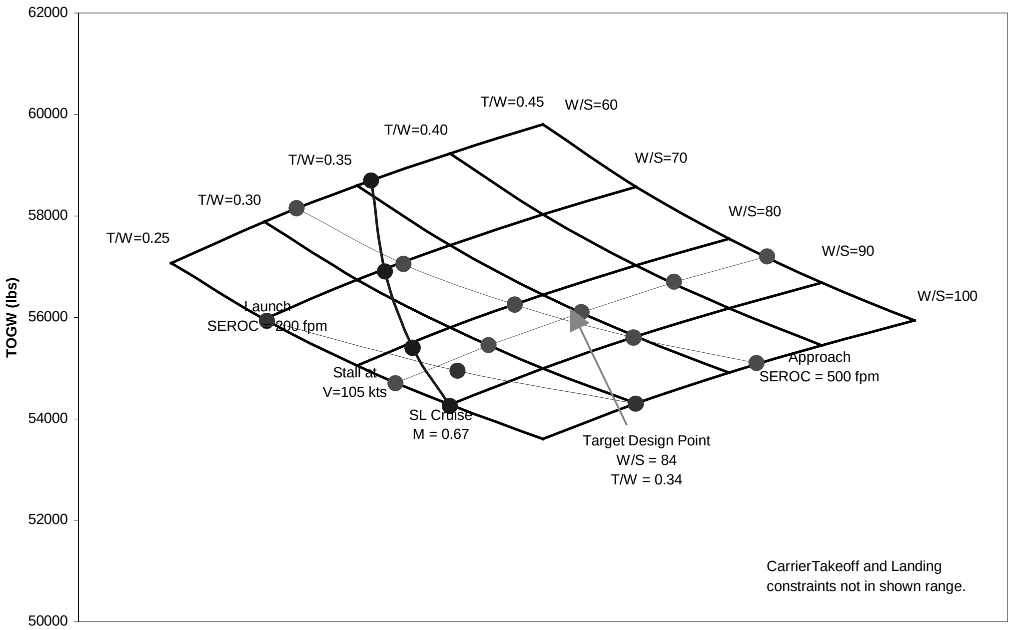


Figure 2.3 – Optimum Sizing Carpet Plot

The carpet plot shows a large amount of data in an organized manner. The carpet plot was created by plotting one T/W curve on a plot of TOGW versus W/S and then staggering the next T/W by shifting the W/S axis. Applying this method for all five T/W lines yields the initial design space mesh. Various constraints were then applied to determine the design point.

The result was an optimum wing loading of 81.6 lb/ft^2. The other constraints applied were a single engine-out climb gradient, maximum stall speed of 110 knots, catapult takeoff, arrested landing, and cruising. The cruise and catapult takeoff conditions did not fall in the given design space; however, the other conditions did appear and are plotted on the carpet plot, Figure 2.3. The climb gradient was set at 3% and a takeoff speed of 175 knots was used to allow for the catapult to be operated at lower power. The cruise conditions required a T/W ratio of roughly 0.15 and the catapult takeoff yielded a wing loading constraint of 175 lb/ft^2. Applying these constraints, an optimum design point was found at a T/W of roughly 0.34 and W/S of 84 lb/ft^2.

In summary, the final sizing data obtained using the two programs resulted in the following table.

Table 2.4 – Initial Sizing Summary

	Program #1 – based on Nicolai's Method	Program #2 – based on Raymer's Method	Estimates Employed in Calculations
TOGW (Joey)	6,750 pounds	6,163 pounds	6757 pounds
TOGW (Wombat - AEW)	57,258 pounds	58,321 pounds	58324 pounds
Empty Weight (Joey)	3,083 pounds	3,225 pounds	4642 pounds
Empty Weight (Wombat)	26,268 pounds	25,729 pounds	25791 pounds
Fuel Weight (Joey)	1,168 pounds	938 pounds	2115 pounds
Fuel Weight (Wombat)	14,000 pounds	14,792 pounds	17746 pounds

The comparison table shows the definite correlation between the values obtained from the two different sizing programs. This is a good indication of the validity of the final sizing analysis. This data provides the initial starting values for use in the next steps of the design process.

2.4 Weights and Balances

Weight estimates for every major component for the Wombat, excluding Joey's, were done using empirical formulas outlined by Raymer's Method in Chapter 15. It can be seen from the weight statement, Table 2.5, that the structures, propulsion systems, and fixed systems for every mission the Wombat will perform are 100% common. This is made possible because the Joeys, not the Wombat, perform all radar operations. The AEW requires the most fuel; however, each Wombat has the same fuel tank configuration and capacity. Therefore, the difference in the fuel weight represented in the weight statement is due to fuel requirements alone. Major differences in each configuration come from the actual payload to perform the different missions. Table 2.6 shows the center of gravity locations for the various systems. and Figure 2.4 graphically shows the center of gravity locations for each major system group. Figures 2.5 through 2.7 show center of gravity travel for various missions.

Table 2.5 – Weight Statement

Component	AEW (lbs)	ES(lbs)	ASW/ ASUW (lbs)	COD (lbs)
Wing (includes high lift devices)	4453	4453	4453	4453
Fuselage	6672	6672	6672	6672
Horizontal Tail	538	538	538	538
Vertical Tail	663	663	663	663
Nacelle (overhead intake system)	660	660	660	660
Nose Gear	625	625	625	625
Main Gear	1367	1367	1367	1367
Arresting Gear	166	166	166	166
Stucture Subtotal (pounds.)	**15144**	**15144**	**15144**	**15144**
Engines (installed/ accessory pack included)	5351	5351	5351	5351
Fuel System	538	538	538	538
Engine Controls	45	45	45	45
Refueling Probe	240	240	240	240
Starter	102	102	102	102
APU	350	350	350	350
Powerplant Subtotal	**6626**	**6626**	**6626**	**6626**
Flight Controls	326	326	326	326
Electrical System	1017	1017	1017	1017
Environmental Control System	950	950	950	950
Lavatory/Galley	300	300	300	300
Radome	130	130	130	130
Avionics	1078	1078	1078	1078
Instruments	220	220	220	220
Fixed Equipment	**4021**	**4021**	**4021**	**4021**
Total Empty Weight (Structures, Powerplant and Equipment)	**25791**	**25791**	**25791**	**25791**
Wing Box Fuel	7616	7616	6548	4228
In-Board Wing Fuel	6502	6502	6502	6502
Fuselage Fuel	3628	2168	0	0
Fuel Subtotal	**17746**	**16286**	**13050**	**10730**
Joey 1	4964	4964	0	0
Joey 2	4964	4964	0	0
Joey Launch and Retrieval System	2289	2289	0	0
Design Cargo	0	0	0	12000

Armament (2 Harpoon missiles, 2 Mk-54, 68 Sonobuoys)	0	0	5200	0
ASW/ASUW Avionics (includes MAD)	0	0	5000	0
Joey Relay Station	250	250	0	0
Cabin Pressurization System	0	0	0	850
Pilot Ejection Seats	800	800	800	800
Flight Officer Ejection Seats	800	800	800	0
Crew	720	720	720	360
Payload Subtotal	**14787**	**13387**	**12520**	**14010**
TOGW	**58324**	**55464**	**51361**	**50531**

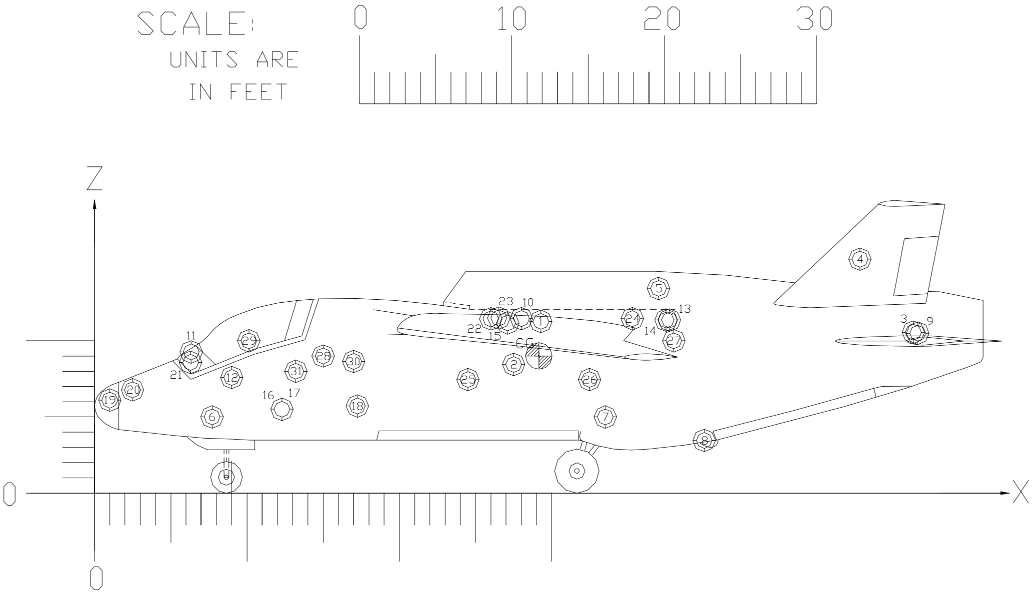


Figure 2.4 - Component CG Locations

Table 2.6 AEW Component CG Location

Component #	AEW Version	x-position from the nose (ft)	z-position from the ground (ft)
1	Wing (includes high lift devices)	29.1	11.2
2	Fuselage	27.5	8.5
3	Horizontal Tail	53.8	10.8
4	Vertical Tail	50.2	16.5
5	Nacelle (overhead intake system)	37	13.5
6	Nose Gear	6.3	5
7	Main Gear	32.5	5
8	Arresting Gear	40	3.2
9	Engines	54	10.5
10	Fuel System	27.9	11.5
11	Engine Controls	6.2	9.4
12	Refueling Probe	9	7.6
13	Starter	37.8	11.4
14	APU	37.5	11.4
15	Flight Controls	27.1	11.2
16	Electrical System	12.2	5.5
17	Environmental Control System	12.2	5.5
18	Lavatory/Galley	17.3	5.8
19	Radome	1	6.1
20	Avionics	2.5	7.3
21	Instruments	6.3	9.4
22	Wing Box Fuel	25.9	11.5
23	In-Board Wing Fuel	26.5	11.5
24	Fuselage Fuel	35.2	11.5
25	Joey 1	24.5	7.5
26	Joey 2	32.5	7.5
27	Joey Launch and Retreival System	28	10
28	Joey Relay Station	15	9
29	Pilot Ejection Seats	9.5	10
30	Flight Officer Ejection Seats	17	8.8
31	Crew	13.3	7.9

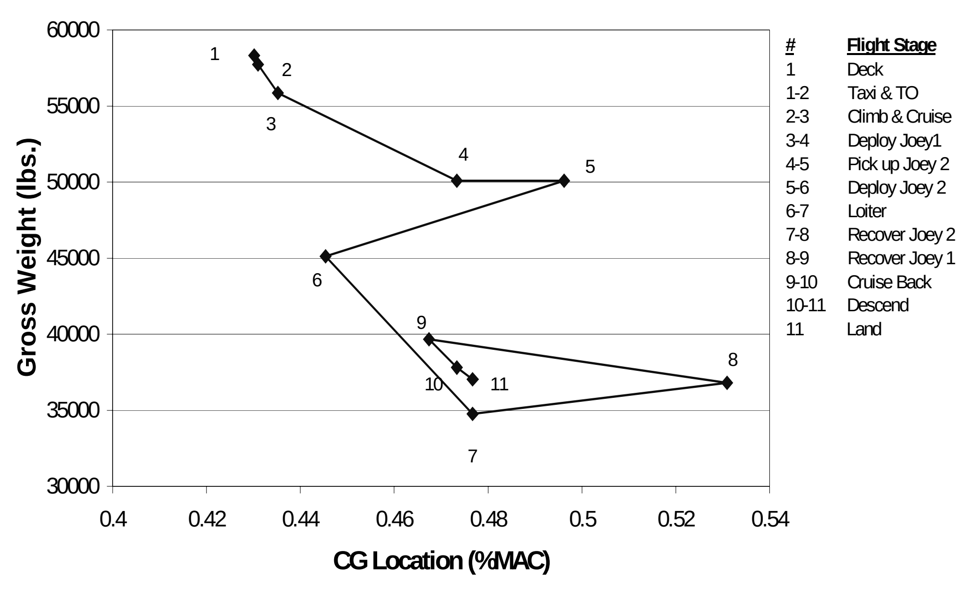


Figure 2.5 – AEW CG Travel

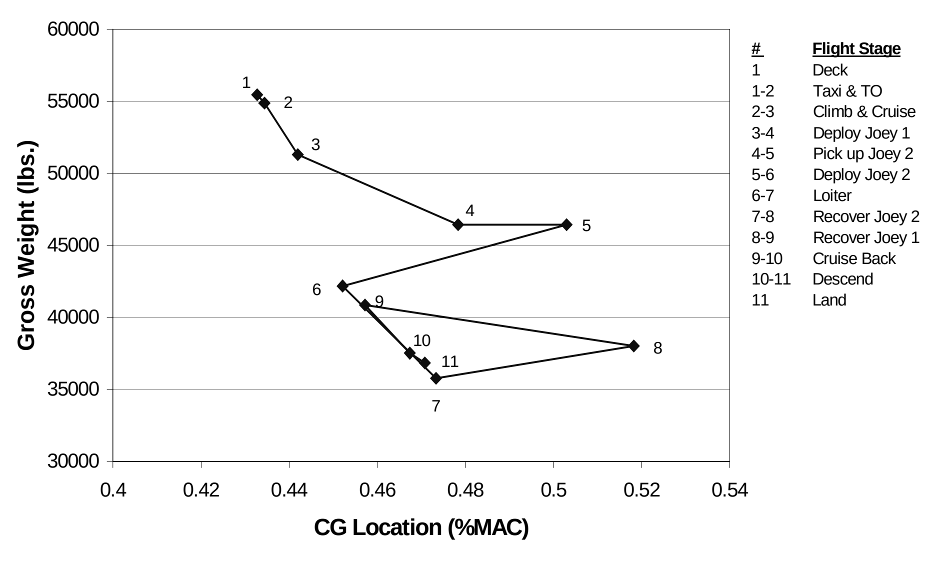


Figure 2.6 – ES CG Travel

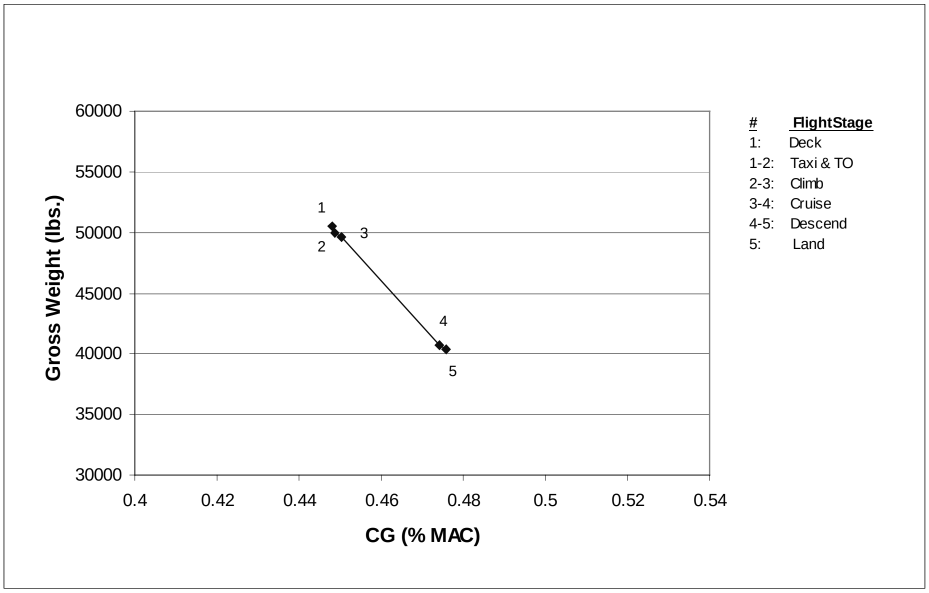


Figure 2.7 – COD CG Travel

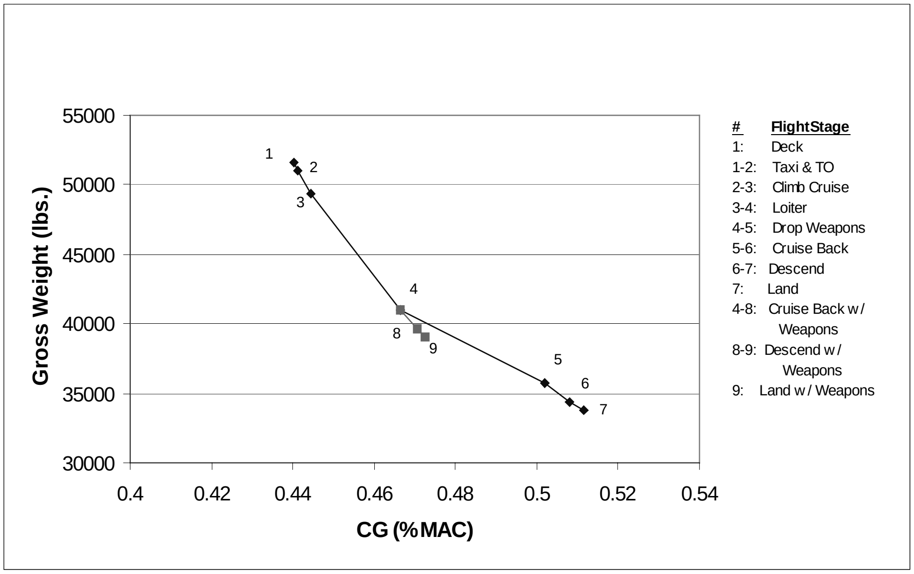


Figure 2.8 – ASW/ASUW CG Travel

CHAPTER 3 – PROPULSION

3.1 Engine Requirements and Considerations - Wombat

Engine placement for the design of the Wombat and the Joey are key elements to the design for the AEW/ES missions. Since Joeys are launched and recovered in flight, the intake for each aircraft must be as far apart from each other as possible to reduce the disturbances in the flow. The release and retrieval of the Joey below the Wombat decided placement of the Joey's chin type intake and engine deck. The advantage to this inlet is that it will be able to utilize the free stream air for engine start when it is being launched and recovered. The UAV launching constraint concomitantly limited the placement for the Wombat's intake and engines. Since wing-mounted podded engines could possibly interfere with the flow for the Joey, an overhead inlet was chosen for the Wombat. This is especially true during retrieval where the Joey comes from behind for capture. With the overhead inlet on the Wombat and the chin inlet on the Joey, no flow interference between intake and exhaust flows are expected.

The operating envelope for the Wombat is between Mach 0.4 to 0.8. Within this envelope, the most efficient propulsion system with respect to thrust-to-weight compared to fuel consumption is a high bypass turbofan engine. Other design considerations for the Wombat include the internal configuration of the twin engines, which limit the engine diameter, as well as the aft location of the engines, which limit the engine weight. The target design thrust-to-weight ratio for the Wombat is approximately 0.34 as seen in Figure 2.3. With an initial design take-off-gross weight of approximately 58,000 pounds, the required static thrust of the total propulsion system for both engines is 19,720 pounds.

Many existing commercial turbofan engines were studied in the selection process for the propulsion system. This yielded a design engine matrix where engine specifications could be compared, as shown in Table 3.1.

Table 3.1 – Engine Options

Company/ Engine Model	Thrust (pounds)	SFC (lb/hr/lb)	BPR	Length (in)	Diameter (in)	Weight (pounds)	Year in Service
GE/ TF34-GE100	9067	0.37	6.42	100	50	1440	1975
GE/ CF34-3	9220	0.35	6.2	103	44	1670	1996
GE/ CF-34-8	13600	0.35	5	128	46.2	2460	2000
RR/ Spey 168-807	11030	0.66	0.78	96.7	32.5	2417	1969
RR/ Tay 611	13850	0.43	3.04	102	60.6	3400	1988
RR/ BR710	14845	0.39	4	88	54	3564	1996

The engine selected from this matrix for propulsion is a variant of the General Electric CF34-3 turbofan engine. Figure 3.1 shows the current configuration of the CF34-3 engine. This engine meets the size constraints for the fuselage envelope and a low weight in order to prevent a large moment, which would drive the center of gravity aft. Since its static thrust does not meet the required thrust outlined by the Figure 2.3, a variant of the CF34-3 will have to be developed. For design purposes the geometric specifications of the engine would be held constant and weight would be added to account for the added thrust. Using the existing thrust-to-weight ratio of 5.52 for the CF34-3, the new engine design would have static thrust of approximately 11,000 pounds and a weight of 1950 pounds. The 1,000 pounds of excess thrust was added due to expected losses the engine will encounter after installation.

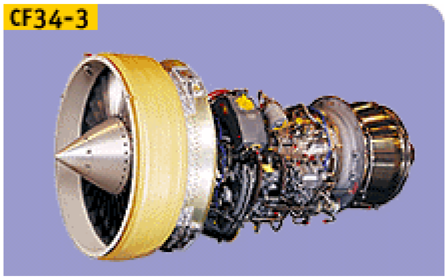


Figure 3.1 – General Electric CF34-3 Turbofan Engine[3.1]

3.2 Engine Performance -Wombat

Aircraft engines perform differently at different Mach numbers, altitudes, and operating conditions. Data such as turbine inlet temperature and fan pressure ratio for the CF34-3 were not available to construct exact engine performance analysis. For design purposes empirical formulas were utilized in Chapter 7 to construct the performance charts of thrust versus specific fuel consumption and thrust versus Mach number. Efficiencies of engine components were assumed to be 0.98 for the intake inlet, 0.96 for the S-duct, and 0.97 for the nozzle. These efficiencies yield an overall efficiency of 0.91 corresponding to approximately 1,000 pounds of thrust lost for each engine. Using these assumptions, Figure 3.2 was used to investigate the performance characteristics of the engine at various Mach numbers and altitudes. This plot is useful in estimating the performance of the engine for fuel and thrust considerations over the entire flight envelope.

[3.1] http://www.geae.com/military/serv_models_tf34.html

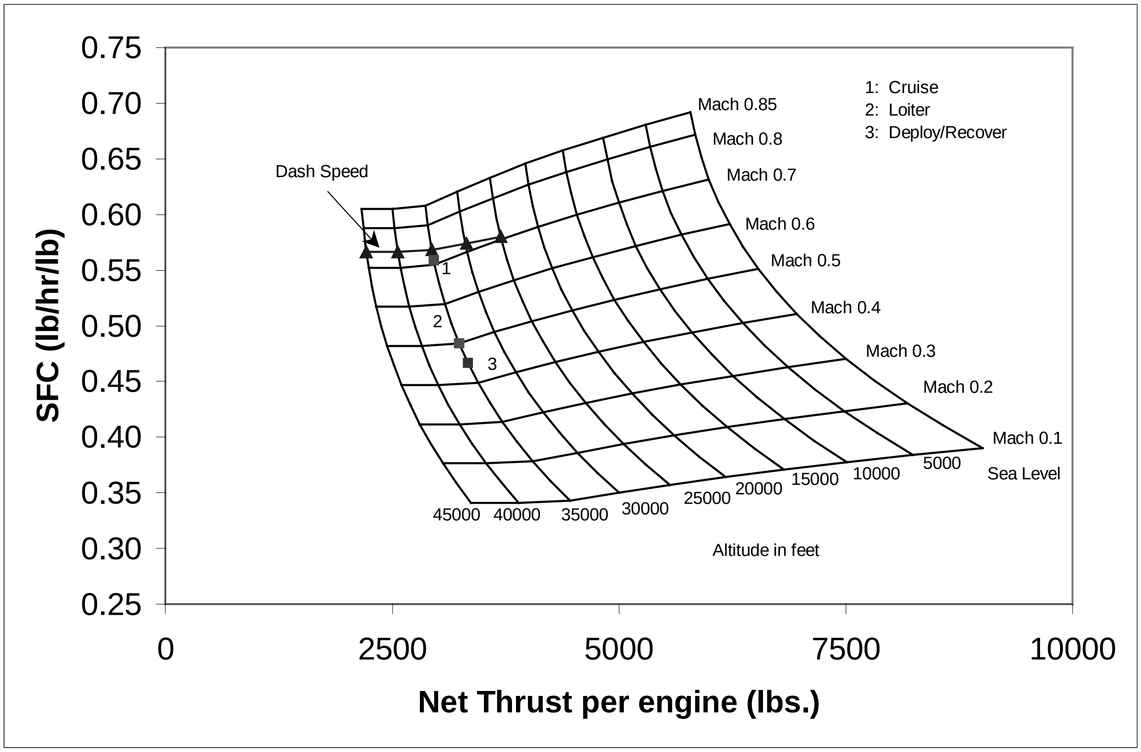


Figure 3.2 – CF34-3 Variant Thrust versus Specific Fuel Consumption

3.3 Nacelle Design - Wombat

As seen in Figure 3.3, the inlet for the Wombat will be an overhead pitot inlet for the rear buried turbofan engines. Pitot inlets are widely used for subsonic aircraft due to the efficient total pressure recovery. Advantages to the overhead inlet included reduced FOD and the reduction of area required in the forward section of the fuselage. The required capture area of the inlet was estimated by Raymer's method outlined in Chapter 10 of his textbook. A graph of capture area divided by engine mass flow versus Mach Number (Raymer Figure 10.16) yielded a value of 0.025 ft^2 / (lb per s) for Mach numbers less than 1. Using Raymer's estimation[3.2] for engine mass flow:

$$\dot{m} = 2.6d^2$$

where *d* is the engine front-face diameter in feet. The estimated mass flow for the GE34-3 variant turbofan engine becomes 224 lb/sec. Therefore the required inlet capture area for each engine on the Wombat is approximately 5.6 ft^2. The inlet system will include an inlet divider leading to two separate S-ducts, one for each engine, that will be designed to slow the airflow to approximately Mach 0.4.

[3.2] http://www.geae.com/military/serv_models_tf34.html

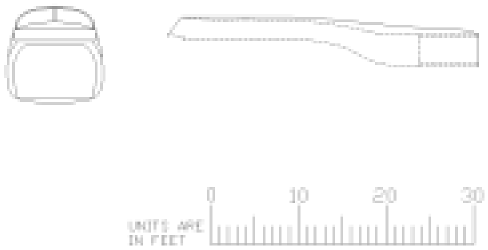


Figure 3.3 – Wombat Inlet Concept

A disadvantage to the overhead inlet includes the potential loss of free stream airflow at high angles of attack; however a well-faired fuselage, and a well-designed boundary layer diverter solve this problem. The boundary layer diverter utilized on this design concept will be a channel type diverter. To assure flow into the inlet the step distance from fuselage to inlet lip will be two percent of the total length measured from the nose of the aircraft to the inlet face. This distance is approximately 22.1 feet yielding a boundary layer diverter height of 5.3 inches.

3.4 Engine Requirements and Considerations - Joey

From thrust vs. drag calculation, the design thrust required for the Joey is 2,100 pounds. Once again a high bypass turbofan offers the best performance efficiency for the operating envelope. The engine on this aircraft will be the Williams FJ44-2C turbofan engine, shown in Figure 3.4. This engine offers sea level static thrust of 2,400 pounds, and is well within the geometric constraints for fitting within the Joey airframe, having a length of only 40.2 inches and diameter of 23.7 inches. The Williams engine has a bypass ratio 3.28:1 and a pressure ratio 12.8:1. The uninstalled engine weight is 448 pounds. Performance curves shown in Figure 3.5 were also constructed for the Joey engine to identify the fuel consumption through the mission envelope. The engine is currently in mass production, which would drive the overall cost of the Joeys down.

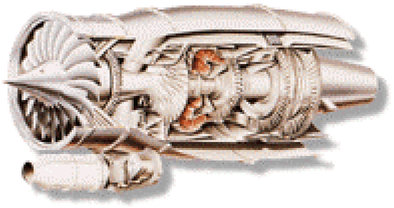


Figure 3.4 – Williams FJ44-2C[3.3]

[3.3] http://www.rollsroyce.com/civil/products/turbofans/fj44/Default.htm

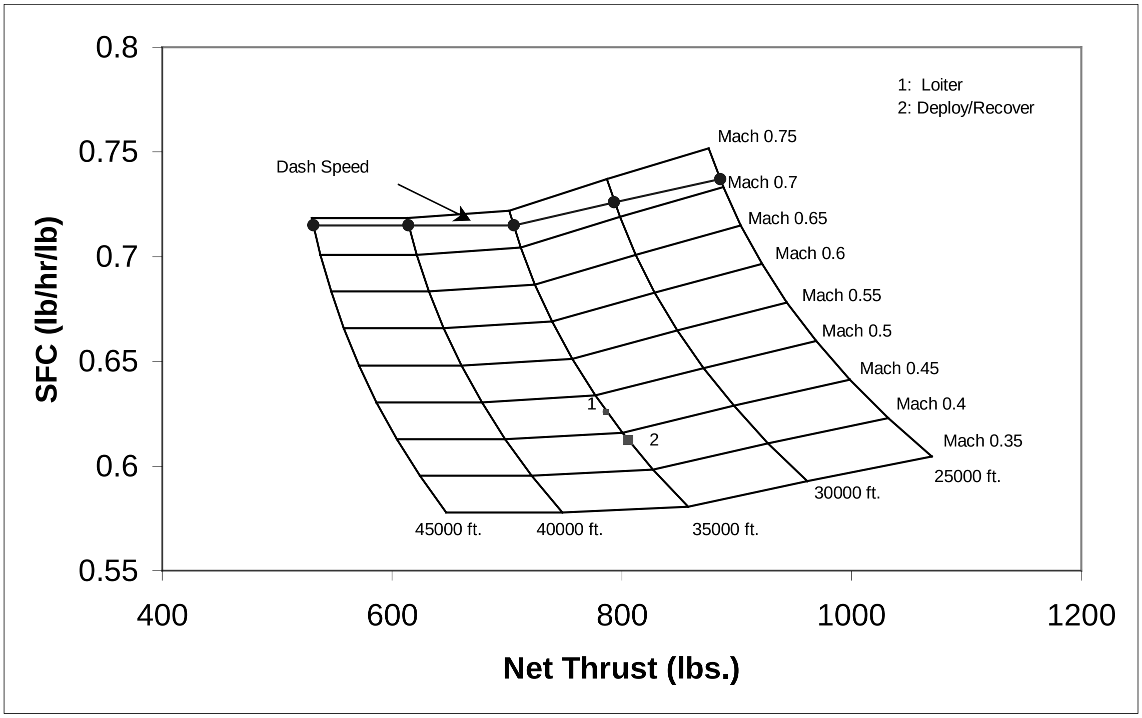


Figure 3.5 – FJ44-2C Thrust versus Specific Fuel Consumption

3.5 Nacelle Design - Joey

The inlet on the Joey will be a pitot chin inlet utilizing the free stream airflow. The disadvantage to this inlet type is susceptibe to runway FOD, which will never be encountered since the Joey is launched and recovered by the mother ship. An advantage to this inlet type is that it will be able to use free stream air for engine start when it is lowered for launch. Raymer’s method can be used to estimate the mass flow of the UAV engine. Using this method, the mass flow of the FJ44-2C is estimated at 64.9 pounds per second. When compared to Raymer’s statistically generated capture area divided by mass flow plot, the required capture area of the inlet becomes 1.62 ft^2 correlating to a diameter of 1.44 feet.

3.6 Engine Maintenance and Removal

Naval aircraft engines are exposed to heavily corrosive salt air and water and therefore must be constructed of environmentally resistant materials. The two engines selected in this design are already military proven and capable of the Navy’s needs. Naval engines must be available for routine repairs, or complete engine removal. Ability of the Joeys to be removed from the Wombat eases space constraints because their engine maintenance will be performed outside of the mother ship. Wombat engine removal will be similar to that of the DC-10, center engine. Each engine will be lowered after it is first translated aft to clear the rear cargo door as shown in Figure 2.2, the ASW/ASUW variant. Lower cowling doors will facilitate this procedure as shown in section G-G, Figure 2.2. Minor maintenance and inspections can be performed through the outward and upward opening engine cowl doors.

CHAPTER 4 – AERODYNAMICS

4.1 Aerodynamic Benefits

In pursuit of an effective design, and the desire to improve performance, unique aerodynamic configurations were examined for the CSA project. Using a combined system of a compound wing mothership with multiple UAVs is a highly atypical family of aircraft, which will be shown to have superior aerodynamic and system properties.

The Wombat's wing has a low taper ratio due to the large root chord. This much larger root chord adds a significant increase in area that provides additional lift. The added area also delays stall at high angles of attack and during landing, when trailing-edge flaps are employed.

The Joey design is a pure, tailless flying wing. Having an entire surface that acts as a lifting body is the optimum in aerodynamic design, and a flying wing closely approximates this optimum. With the unmanned and mother-ship retrieval capabilities, the Joey does not have to incorporate landing gear or high-lift systems into its design.

4.2 Planform – Wombat

Figure 4.1 shows the layout of the Wombat wing with principal dimensions cited in the table. The length of the fuselage is 59 feet with a maximum width of 11.01 feet. The span of the Wombat is 75 feet unfolded, with a folded wingspan of 39 feet to meet aircraft storage requirements aboard a carrier. The taper ratio of this wing design is 0.188 with root and tip chord lengths of 18.6 and 3.5 feet respectively. The mean aerodynamic chord, *mac*, used together with the wing area to non-dimensionalize the pitching moment, was calculated as 11.81 feet and is located 13.94 feet from the aircraft centerline. Sweep angles were defined at the leading edge, ¼ chord and ½ chord locations. A value of 30.0˚ was used as the initial leading edge sweep, providing $\Lambda_{1/4} = 25.84^\circ$ and $\Lambda_{1/2} = 21.71^\circ$. The wing was redesigned to obtain more lift from the body by reducing the sweep angles. The redesigned wing has the following angles: $\Lambda_{LE} = 25.0^\circ$, $\Lambda_{1/4} = 19.52^\circ$ and $\Lambda_{1/2} = 13.78^\circ$.

$S = 750\ ft^2$
b = 75 ft.
AR = 7.5
$\hat{c} = 10.0$ ft.
mac = 11.81 ft.
y = 13.94 ft.

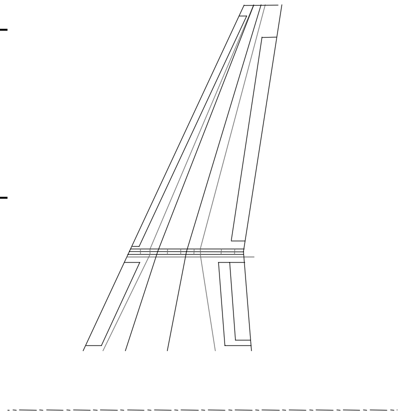


Figure 4.1 – Configuration of the Wombat Wing

To enable level flight in cruise as necessary for the COD variant, the wing was mounted at an incidence angle of +2.0°, corresponding to a lift coefficient of 0.44 in cruise. This design incorporated anhedral into the mounted orientation of the wing. A value of 4.22° was calculated as the anhedral angle. A twin, splayed tail was used on the Wombat, in which the two tails are mounted at 30.36° with respect to the vertical, with their tips 16.11 feet apart. The tips of these tails also fold to conform to carrier requirements from a height of 19.40 feet to 17.41 feet as measured from the flight deck. Refer to Figure 2.1 for a visual reference of all dimensions cited.

4.3 Airfoil Selection – Wombat

Once the initial configuration for the Wombat was decided upon, the airfoil shapes were selected. Criteria were developed from which to base initial selections, and then these selections were evaluated for the best-fit airfoil. These parameters include a value of $C_{L\,max}$ over 1.5 (clean wing), a smooth C_L vs. α curve up to and including stall, a high angle of attack at stall, good transonic behavior while maintaining low-speed characteristics, and a low-drag shape. Two airfoils are used in the wing design: one for the outboard section, and a thicker airfoil for the inboard section to accommodate the increased area seen at the root. The airfoils were evaluated at a Reynolds number of 9.0×10^6. This particular Reynolds number was chosen because this is a standard Reynolds number used in Abbott and Von Doenhoff,[4.1] among many other sources, allowing for direct comparison between airfoils.

A high value for $C_{L\,max}$ is desired to allow a slow approach and landing speed aboard the carrier. A moderate value of 1.5 was chosen as the baseline, since this aircraft has advanced high-lift devices in its design. A smooth C_L vs. α curve around stall insures gradual loss of lift and predictable flight behavior at high angles of attack. A high stall angle of attack allows for better maneuverability, and a larger flight envelope.

The root airfoil needed to be thicker than the tip airfoil to allow for storage of all flight fuel inboard of the wing folds. A thickness-to-chord ratio of 18% was selected for the inboard section and a *t/c* of 12% was selected for the outboard section. A blending of these two airfoil shapes will occur at 23.42% span as measured from the wing root.

After preliminary analysis, and consideration of all these criteria, the following airfoils were selected for possible usage in the wing:

- ROOT AIRFOIL
  - NACA 64_3 – 018
  - NACA 64_3 – 218
  - NACA 64_3 – 418
  - Eppler 748
  - NASA SC(2) – 0518
- TIP AIRFOIL
  - NACA 64_1 – 212
  - NACA 64_1 – 412
  - NACA 64_1 – A212
  - Eppler 662
  - NASA SC(3) – 0712B

[4.1] Abbott, I., and Von Doenhoff, A., *Theory of Wing Sections*, Dover Publications, New York, 1981.

The NACA 64-series airfoils were initially thought to give the best performance in all flight conditions. This series has low drag properties such as low drag coefficients and a drag bucket. The 64-series also features an increasing lift curve slope up to approximately 19% *t/c*.[4.2] The major drawback of this airfoil series is their rather low maximum lift coefficients. Emphasis was then shifted to the design of natural laminar flow (NLF) and supercritical airfoils that combined the low drag properties of the NACA 6-series with high lift coefficients of the NASA low-speed airfoils.[4.3]

A different design approach was taken by aerodynamicist Richard Eppler when he conceived a way to develop a theoretical technique to designing airfoils specifically for each intended application. The method was "simple" enough that others could duplicate his work to design airfoils for their own uses. It uses the application of potential-flow theory together with boundary-layer theory to develop and analyze airfoil designs.[4.4] A detailed computer code and iteration process are part of Eppler's method for designing the correct airfoil for each application. Obtaining Eppler's code would have come at a high cost and the complexity of the program were why this was not explored further.

NASA supercritical airfoils were considered because they combine excellent transonic behavior with acceptable levels of low-speed characteristics.[4.5] Incorporating these airfoils into the wing design allows the aircraft to be aerodynamically efficient in all flight conditions. The development of the supercritical airfoils was started to create suitable airfoil shapes with higher critical Mach numbers, (better transonic performance) and greater maximum lift coefficients (better low-speed characteristics). A higher critical Mach number delays the shock wave-boundary layer interaction to significantly elevated values of free-stream Mach number, thus producing an extended range of subsonic flight.[4.6] Supercritical airfoils are characterized by a large leading edge radius, reduced curvature around half-chord along the upper surface, and substantial aft camber. The overall shape of the airfoil also weakens the magnitude and the effect of the shock wave at high subsonic speeds. The weaker shock provides a more favorable pressure gradient during transonic flight, which is responsible for the increased drag-rise Mach number. Other characteristics of supercritical airfoils are their predictable stall behavior, low drag in cruise, high lift-to-drag ratios, and high maximum lift.[4.7] These predicted benefits have been verified in wind tunnel as well as flight tests.[4.8] The cruise Mach number for the Wombat was decided to be M = 0.675 outbound and M = 0.7 inbound, approximately the M_{DD}, with a dash speed of M = 0.75, all at 35,000 feet, which constitutes a significant portion of the transonic region; therefore the NASA SC(2)-0518 and the NASA SC(3)-0712B will be used as the root and tip airfoils, respectively. Figures 4.2 and 4.3 show the plots of C_L vs. α and the overall shape of the airfoil for the SC(3)-0712B and Figures 4.4 and 4.5 present the same information for the SC(2)-0518.

[4.2] "Aircraft Design and Development," seminar, Virginia Tech, 1973, 13-2.

[4.3] Torenbeek, E., *Synthesis of Subsonic Airplane Design*, Nijgh-Wolters Noordhoff University, 1976.

[4.4] Eppler, R., *Eppler Airfoil Design and Analysis Code*, Springer-Verlag, Berlin, Germany, 1990.

[4.5] Harris, C.D., "NASA Supercritical Airfoils: A Matrix of Family-Related Airfoils," NASA TP-2969, March 1990.

[4.6] Ayers, T.G., "Supercritical Aerodynamics Worthwhile Over a Range of Speeds," *Astronautics and Aeronautics*, August 1972.

[4.7] Harris, C.D. "NASA Supercritical Airfoils: A Matrix of Family-Related Airfoils," NASA TP-2969, March 1990.

[4.8] Cahill, J.F. and Cooper, B.L., "Flight Test Investigation of Transonic Shock-Boundary Layer Phenomena" AFFDL-TR-68-84, 1968.

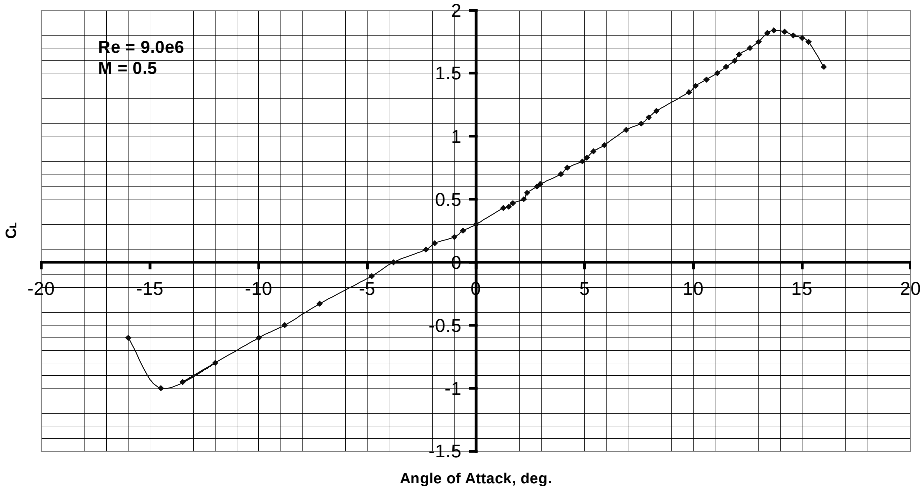


Figure 4.2 – C_L versus α for the NASA SC(3)-0712B Airfoil
(taken from NASA Supercritical Airfoils)

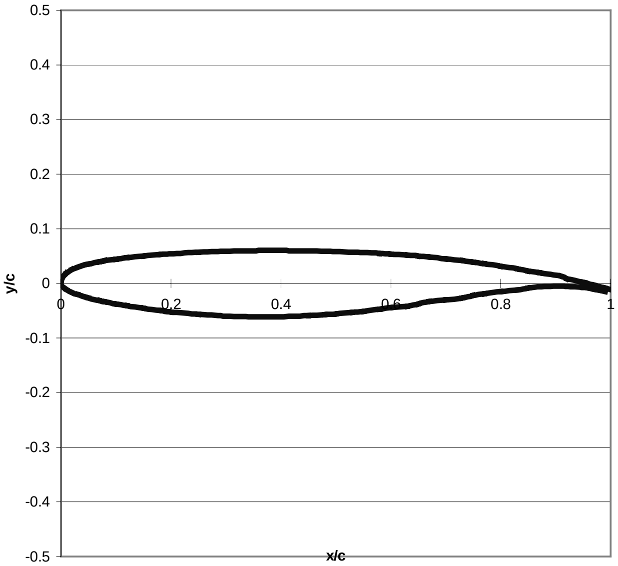


Figure 4.3 – Shape of the SC(3)-0712B Airfoil
(taken from NASA Supercritical Airfoils)

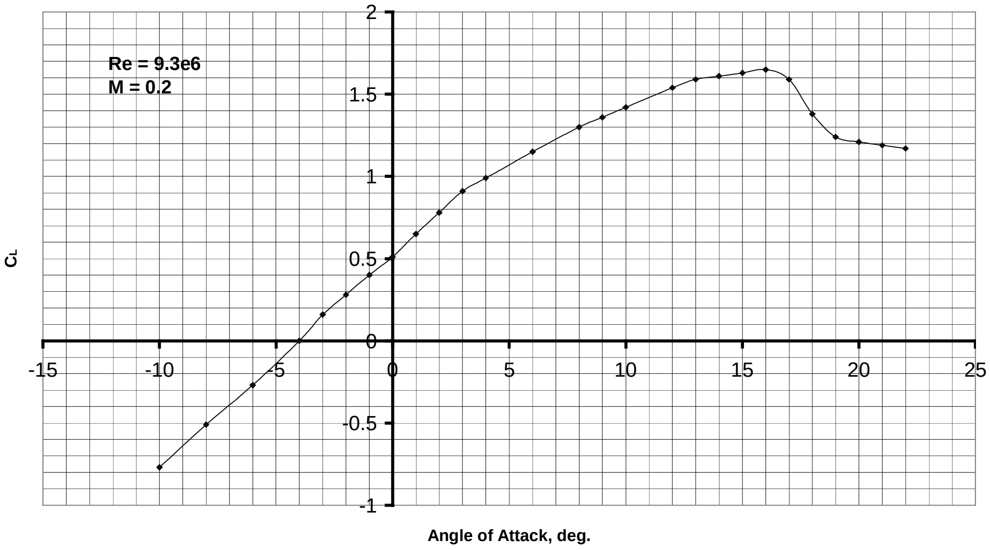


Figure 4.4 – C_L versus α for the NASA SC(2)-0518 Airfoil
(taken from NASA Supercritical Airfoils)

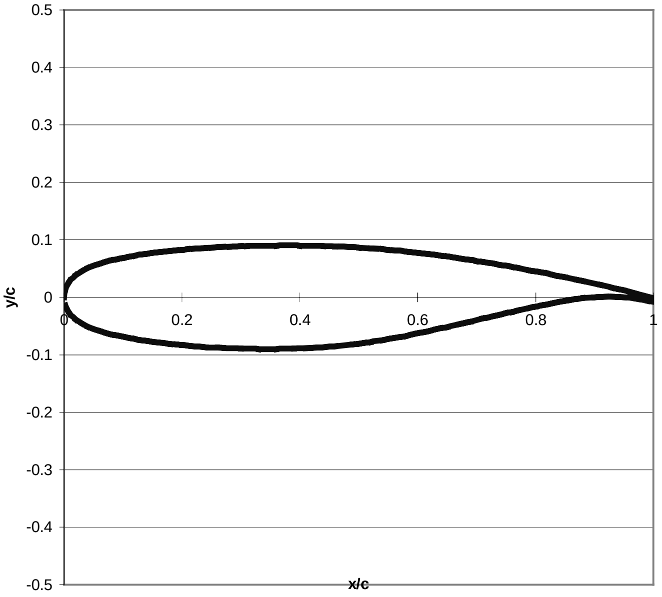


Figure 4.5 – Shape of the SC(2)-0518 Airfoil
(taken from NASA Supercritical Airfoils)

4.4 Aerodynamic Parameters – Wombat

The first aerodynamic parameter calculated was the three-dimensional lift curve slope. This is needed during conceptual design for a number of reasons: to establish the wing incidence angle, to calculate the drag-due-to-lift, and to perform stability analysis.[4.9] The following equation is the semi-empirical formula to calculate the lift curve slope (per radian). The equation is accurate up to the drag divergent Mach number, but still applies with reasonable accuracy up to Mach 1 for a swept wing aircraft.[4.10]

$$C_{L\alpha} = \frac{2\pi AR}{2+\sqrt{4+\frac{AR^2}{k^2}(1-M^2)(1+\frac{\tan^2\Lambda_{1/2}}{1-M^2})}}$$

The k in this equation is a measure of how close the two-dimensional lift curve slope is to the real value of 2π. This was estimated as 0.95, or 95% of the true value. The lift curve slope was calculated for a range of Mach numbers up to the maximum Mach number and used in the previously mentioned calculations.

The next parameter found was the three-dimensional maximum lift coefficient. For high aspect ratio wings with moderate sweep, the maximum lift depends mostly on airfoil characteristics. Sweeping the wing reduces the maximum lift coefficient, so a compromise must be made in sweep angle. Following the DATCOM method for compressibility effects on lift, and formulas for high aspect ratio wings, the three-dimensional maximum lift coefficient was found to be $C_{L\,max} = 1.56$.[4.11] This is the "clean wing" maximum lift coefficient, meaning no flaps or other high-lift devices are deployed. The angle of attack for maximum lift coefficient was also calculated to be $\alpha_{C_{L\max}}$ of 13.61° according to Raymer's method.

Using Virginia Tech professor, Dr. William Mason's skin friction code[4.12], the parasite drag was calculated. Dr. Mason's code, FRICTION provides an estimate of laminar and turbulent skin friction whose values are valid through the entire Wombat flight envelope. The input to the program requires geometric information and either the Mach number and altitude, or the Mach number and the Reynolds number. Combining the results from this program with calculations of the wave drag (according to Raymer) produces the following plot of drag versus Mach number at various altitudes.

[4.9] Raymer, D.P., *Aircraft Design: A Conceptual Approach*, AIAA, Washington, D.C., 1992.

[4.10] Etkin, B. and Reid, L.D., *Dynamics of Flight – Stability and Control*, John Wiley & Sons, Inc., 1996.

[4.11] Wootton, L.R. "The Effect of Compressibility on the Maximum lift Coefficient of Aerofoils at Subsonic Speeds," *J. of the R.Ae.S.*, Vol. 71, July 1967.

[4.12] http://www.aoe.vt.edu/aoe/faculty/Mason_f/MRsoft.html

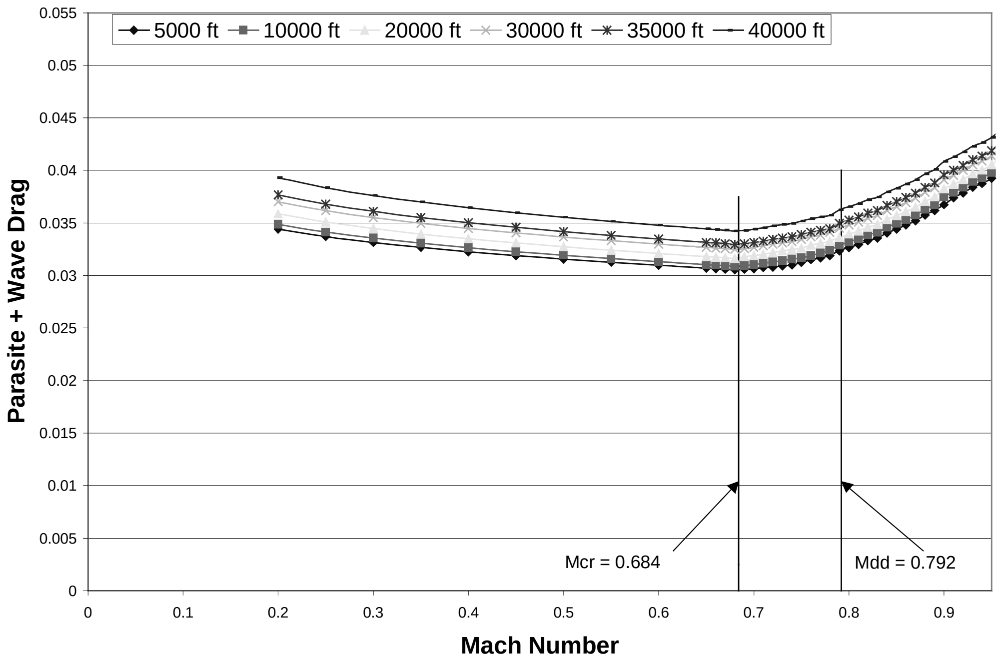


Figure 4.6 – Parasite and Wave Drag versus Mach Number at Various Altitudes and the Cruise C_L

The parasite drag was broken into components so that a buildup could be constructed in order to visually examine where the drag comes from. Table 4.1 shows this component drag buildup. This breakdown was made for takeoff and landing, and cruise conditions. As can be seen in the following table, some components are only used the takeoff and landing portions of the mission, such as landing gear and flaps.

Table 4.1 – Drag Buildup

Wombat *Drag Buildup*	**Mach 0.20** **SL**	**Mach 0.65** **35,000 feet**	**Mach 0.70** **35,000 feet**
ΔC_{D0}			
Basic Aircraft	0.02029	0.02692	0.02690
Empennage	0.002841	0.005341	0.005334
Arresting Hook	0.0001858	n/a	n/a
Fuel Probe	0.0001147	0.0002289	0.0002284
Fuel Pods	0.0004634	0.0007540	0.0007537
Landing Spoilers	0.003592	n/a	n/a
Aileron Damper	0.0002807	0.0003653	0.0003649
Windshield	0.0001014	0.0001786	0.0001782
Landing Gear	0.005871	n/a	n/a
Flaps	0.001098	n/a	n/a
ΔC_{D0} TOTAL	0.03484	0.03379	0.03376

A drag polar was created by plotting the lift coefficient versus the drag coefficient for cruise conditions of M = 0.7 and altitude of 35,000 feet. The L/D_{max} can be found on this plot as the maximum of the ratio of the two coefficients. Figure 4.7 shows this drag polar. The L/D_{max} was found to be 11.55 in cruise corresponding to a C_L of 0.63.

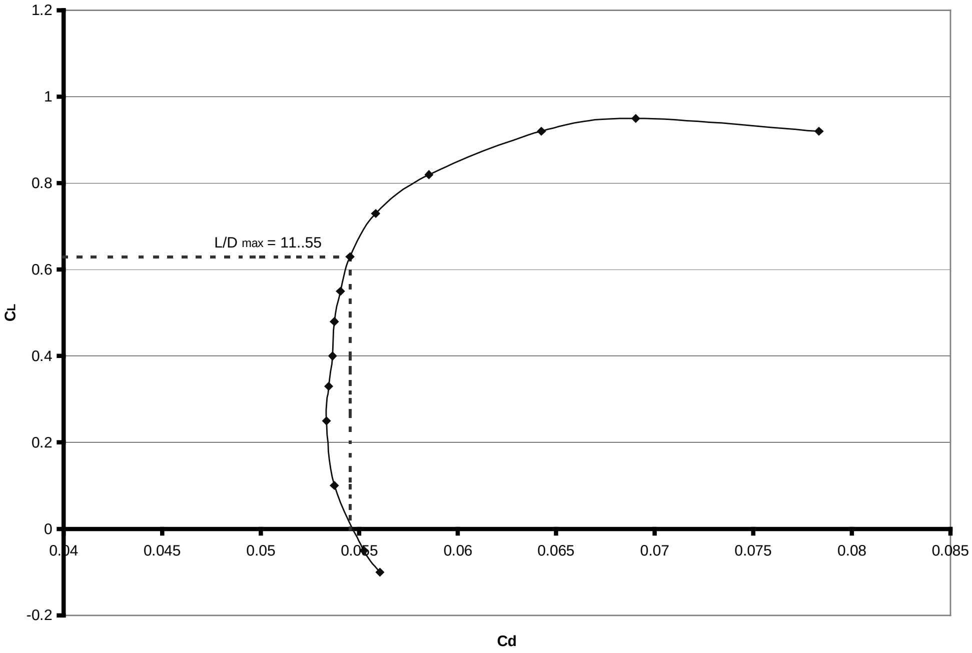


Figure 4.7 – Drag Polar for Wombat

In all previous calculations, an Oswald efficiency factor of 0.70 was assumed based on studies of similar comparator aircraft. A zero-lift drag coefficient, C_{D0}, of 0.0325 was calculated. This is a moderate value for C_{D0}, but is justified because the surface of the Wombat wing will be a combination of composites and aluminum, lowering the drag found on similar aircraft.

4.5 High-Lift Systems – Wombat

The Wombat has advanced high-lift devices used in approach and takeoff and landing conditions. Trailing edge flaps are used to increase the airfoil camber, which in turn increases the $C_{L\ max}$. Single-slotted Fowler flaps provide the most added lift improvement without drastic complexity. The Fowler flap is mechanized to move rearward as well as downward when it is deflected, effectively increasing the wing area in combination with increasing the camber. Although wind tunnel testing would provide a better value for the estimated $C_{L\ max}$, several sources approximate this benefit using a number of different airfoils. According to NACA TR 534, 0.30c Fowler flap defected 20.0º increases the $C_{l\ max}$ to 2.05, and deflected 40º increases the $C_{l\ max}$ to 2.43. These values correspond to three-dimensional lift coefficients of 1.74 and 2.08, respectively. All of these values are based on the clean wing $C_{l\ max}$ of 1.84, and $C_{L\ max}$ of 1.56. The Fowler flaps will be used on approach and takeoff and landing with deflections between 20º and 40º. Figure 4.8 shows the effects of the flaps on the lift curve. Leading edge flaps or slats are not used on the Wombat configuration due to the large leading edge radius of the chosen airfoils.

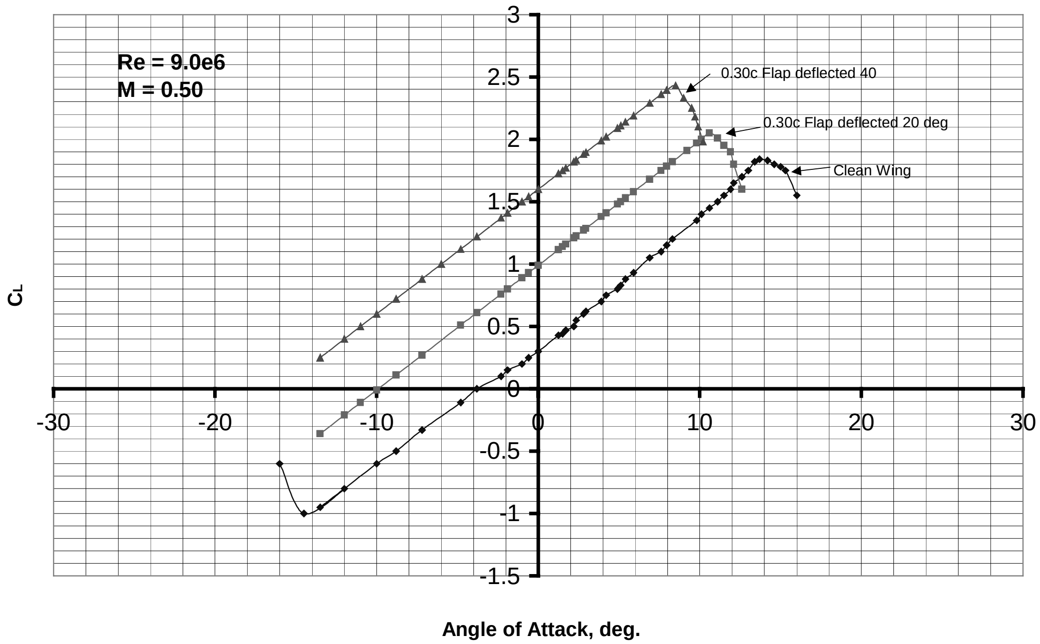
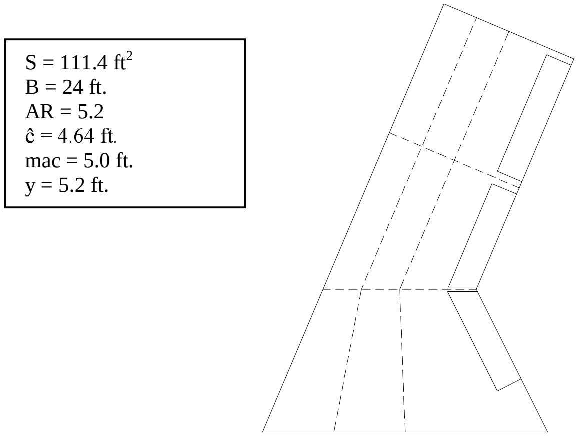


Figure 4.8 - C_l versus α for Clean Wing and Flaps Deflected

4.6 Planform – Joey

Figure 4.9 shows the configuration of the Joey wing with principal dimensions. The length of the Joey fuselage is 8.0 feet, with a height of 2.23 feet. The folded dimensions of the Joey are 8.0’ x 8.8’ x 4.215’ (l x w x h). The taper ratio of the inboard wing panel of the Joey is $\lambda = 0.495$ with root and tip chord lengths of 8.0 and 3.96 feet respectively. The taper ratio of the outboard panel is one. The mean aerodynamic chord, *mac*, used together with the wing area to non-dimensionalize the pitching moment, was calculated as 5.0 feet and is located 5.2 feet from the aircraft centerline. Sweep angles were defined at the leading edge, ¼ chord and ½ chord locations. A value of 26.57˚ was used as the initial leading edge sweep, providing $\Lambda_{1/4} = 14.03^\circ$ and $\Lambda_{1/2} = 0^\circ$. The wing was redesigned to integrate the NLF properties into the configuration. Beyond a leading edge sweep of approximately 24.0˚, NLF is interrupted and its benefits go unrealized.[4.13] For this reason the leading edge was swept up to 23.0˚ giving $\Lambda_{1/4} = 10.94^\circ$ and $\Lambda_{1/2} = -2.16^\circ$. This design incorporated no dihedral into the mounting of the wing. Refer to Figure 2.2 for a visual reference of all dimensions cited.

[4.13] Dodbele, S.S., “Design Optimization of Natural Laminar Flow Bodies in Compressible Flow,” NASA CR-4478, December 1992.



$S = 111.4\ \text{ft}^2$
B = 24 ft.
AR = 5.2
$\hat{c}$ = 4.64 ft.
mac = 5.0 ft.
y = 5.2 ft.

Figure 4.9 – Configuration of the Joey Wing

4.7 Airfoil Selection – Joey

Criteria were again chosen from which to base the initial selections of possible airfoil designs for the Joey. These parameters include a value of $C_{L\ max}$ over 1.7 (clean wing), a smooth C_L vs. α curve up to and including stall, a high stall angle of attack, low stall speed capability, low drag characteristics, laminar flow design and a 13-17% thick airfoil. The airfoils were evaluated at a Reynolds number of 6.0×10^6.

The Joey will fly slower than the Wombat, with a cruise Mach number equal to the critical Mach number of 0.49, and therefore will require a high, clean $C_{L\ max}$. Also, the Joey will not have advanced high-lift devices in its design; instead, flap systems will be used requiring a higher lift coefficient from the wings.

A smooth C_L vs. α curve is again desired to ensure a gradual loss of lift and predictable flight behavior at high angles of attack. A high angle of attack at stall allows for better maneuverability, and a larger flight envelope.

Natural laminar flow design produces extremely low drag in all flight conditions. Associated with natural laminar flow designs is a drag bucket, which provides efficient flight even at deviations from design flight conditions. A moderately thick airfoil is used in the design of the wings to allow for increased volume capacity for fuel and electrical equipment storage.

After preliminary analysis, the following airfoils were selected for the UAV:

- NACA 63_2-215 mod B
- NASA MS(1)-0313
- NASA NLF(1)-0215
- NASA NLF(2)-0415

With the advances of the modern-day computer, more research has gone into the benefits of and the methods for achieving NLF. The methods implemented for designing airfoils with long runs of NLF seem to be mainly trial and error methods using linear stability theory to evaluate the effect of changing the pressure distribution.[4.14] However, a computer code was written by Professor Mark Drela of MIT called XFOIL, which is an interactive program for the design and analysis of subsonic airfoils. A relatively simple user interface with multiple menus and submenus, each with many commands and routines, help the user get useful results. Viscous analysis of preexisting airfoils can be performed by inputting the airfoil geometry into the program and choosing the Mach number, Reynolds number, and/or the angle of attack at which the calculations will be carried out. A full or partial inverse method can be employed such that all or part of existing airfoil geometry can be modified to meet a wanted pressure distribution.[4.15] The selected airfoils for the Joey were input into XFOIL and evaluated at the Reynolds number and Mach number previously mentioned. Based on results obtained from these runs of the program, the NASA NLF(1)-0215 best suits the needs of this UAV application. The NLF(1)-0215 has a design lift coefficient of 0.20, and a thickness of 15%. Further analysis confirmed a previous concern that the airfoil has too much lift, and upon release from the Wombat it could possibly pitch up and strike the aircraft. The large camber found on this airfoil was the main reason that this catastrophe could occur. Using XFOIL and the partial inverse method, some camber was taken out of the bottom surface while keeping the geometry of the top surface and maintaining all the NLF properties the airfoil was originally designed for. The redesigned NLF(1)-0215 airfoil has a t/c of 13.582%. Figure 4.10 shows the C_L vs. α curve for the original NLF(1)-0215 airfoil, and Figure 4.11 is a plot of the shape of the original and redesigned airfoils. From Figure 4.10, the large value of C_{L0} can be seen, which is responsible for the undesired lift at Joey release. Figure 4.12 plots the pressure coefficient versus the distance along the airfoil for the redesigned NLF(1)-0215. A more favorable pressure gradient is seen using the redesigned airfoil.

[4.14] Dodbele, S.S., “Design Optimization of Natural Laminar Flow Bodies in Compressible Flow,” NASA CR-4478, December 1992.

[4.15] http://raphael.mit.edu/xfoil/

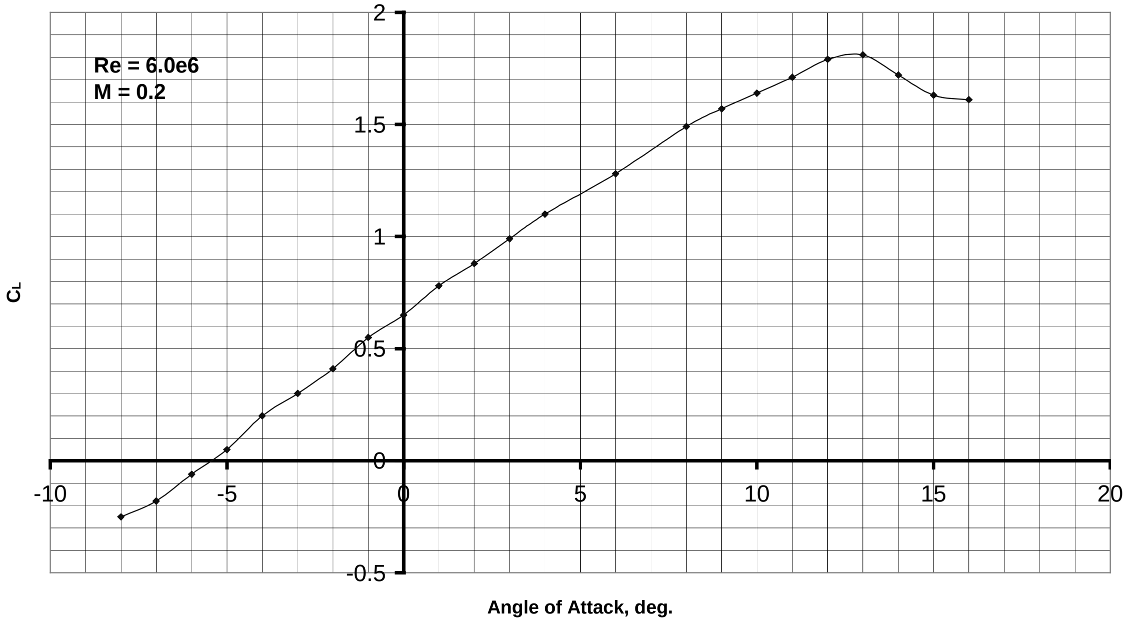


Figure 4.10 – C_L versus α for the NASA NLF(1)-0215 Airfoil

(taken from Raymer text)

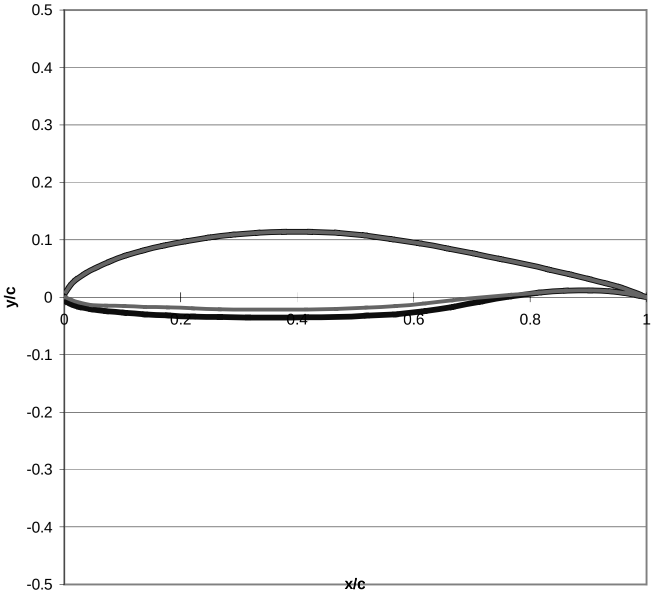


Figure 4.11 – Shape of the NLF(1)-0215 Airfoil, Original (blue)and Redesigned (red)

(taken from Raymer text)

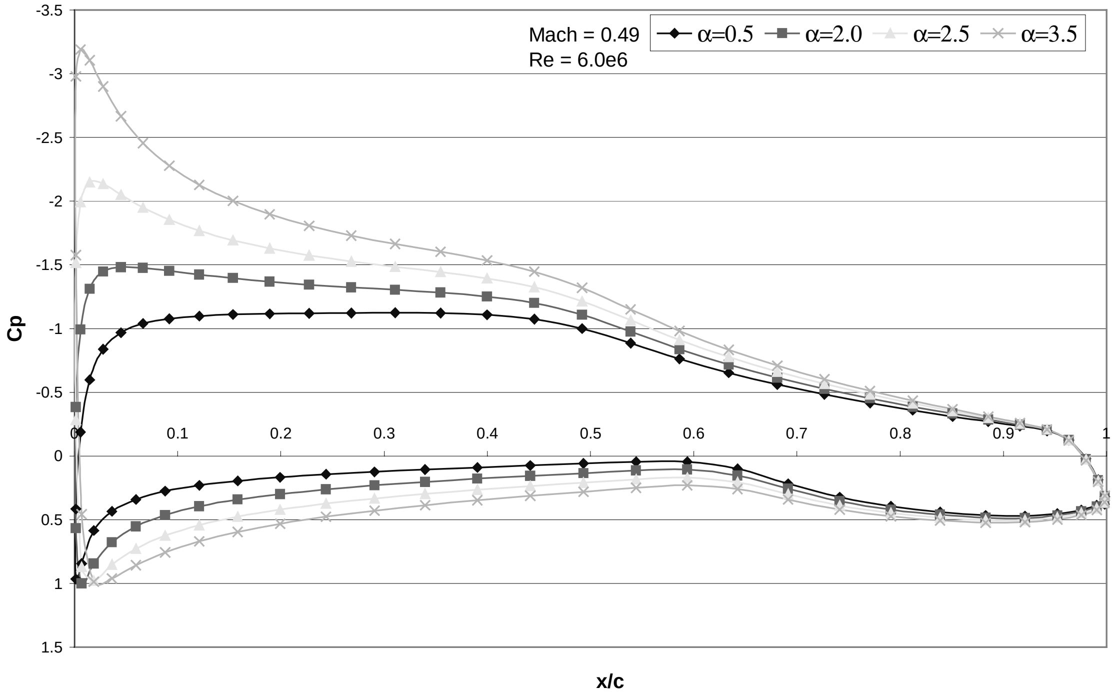


Figure 4.12 – Pressure Coefficient versus Chord Distance for the Redesigned NLF(1)-0215 Airfoil

4.8 Aerodynamic Parameters – Joey

The first aerodynamic parameter calculated was the three-dimensional lift curve slope. The same equation (previously cited) was used for both aircraft to calculate this variable. Mach number was again varied up to the maximum Mach and the lift curve slope was calculated at each value. Using the same method for estimating the maximum lift coefficient (clean wing) as the compound wing, the Joey's $C_{L\ max}$ was found to be 1.63, corresponding to an $\alpha_{C_{L\max}}$ of 14.56˚. An Oswald efficiency factor of 0.80 was assumed based on similar numbers used in other UAV concepts. The value for C_{D0} was approximated as 0.020 and is justified because of the use of composite materials on the outer skin of the UAV, which, with the lack of rivets and seams, greatly reduces the overall drag of the aircraft.

4.9 High-Lift Systems – Joey

The Joey has no high-lift system since takeoff and landing are not part of the flight mission. Being a flying wing design, the Joey will naturally have more lift available at any given condition. The Joey uses trailing edge plain flaps for mid span elevons, inboard wing elevators, and split ruddervator drag flaps on the outer panel. The Joey does not have large maneuver requirements; therefore, only elevator flap deflection is needed for trimmed flight. Stability and control calculations show that the elevons and elevators need a few degrees of deflection to maintain steady, level flight. This configuration is shown in more detail in Figure 2.2.

CHAPTER 5 – STRUCTURES

5.1 Structures Methodology

The primary design driver from a structural standpoint is commonality between airframes. This influences not only the individual components of each aircraft, but also the structural elements of the designs. Common structural design reduces maintenance requirements, manufacturing costs, and logistic requirements for spare parts. Cost and simplicity are also important criteria for this design. Complex designs drive up the cost of production and increase the costs of inspection and repair. Cost is also related to material selection; use of expensive materials needs to be carefully weighed with respect to the advantages that they provide. These three factors were considered in the design of the primary structure for the Wombat and Joey. Each of their influences was considered and will be discussed in the following sections. Other design drivers are also considered in the design of each component and will be discussed in the sections where they are relevant.

5.2 Structural Design – Wombat

5.2.1 Overview

When the missions were evaluated with respect to the critical aircraft load requirements, they were found to be similar in magnitude. Cruise and loiter are governed by steady level flight and involve 1 g loading. Carrier takeoff and landing involve large loads but these are limited to 3.5 g by the RFP for all versions. The only major load difference between missions is the fuselage load due to internal pressurization for the passenger version COD. This is the only mission that requires the entire hull to be pressurized. The other missions do not involve people behind the front wing attachment bulkhead and therefore do not require cargo bay pressurization.

Designing the Wombat with only one airframe will cause the bulkheads, longerons, and skin thickness to be over-designed for all but one mission. Considering the Navy's use of the aircraft in performing each of these missions, it would be more efficient to design two airframes with different pressurization requirements. In addition to performing the other missions, the unpressurized Wombat will be capable of serving in a COD capacity but strictly as a cargo carrier. The pressurized Wombat will only perform the COD missions.

Figure 5.1 depicts the layout of the individual structural elements of the Wombat. Differences in the two designs are noted on the drawing and the remaining components are common to each aircraft. The tail and wing members are shown in red and the fuselage members are shown in blue. The top view is symmetric about the centerline and shows two viewpoints: the upper portion shows a view looking down from above and the lower portion is the view looking up from below the aircraft. Cross-sectional views have also been added to shown how critical components fit together.

FIGURE 5.1

CSA WOMBAT

PRIMARY STRUCTURAL DESIGN

DRAWN BY: DAVID O'BRIEN
ADAM R. JONES

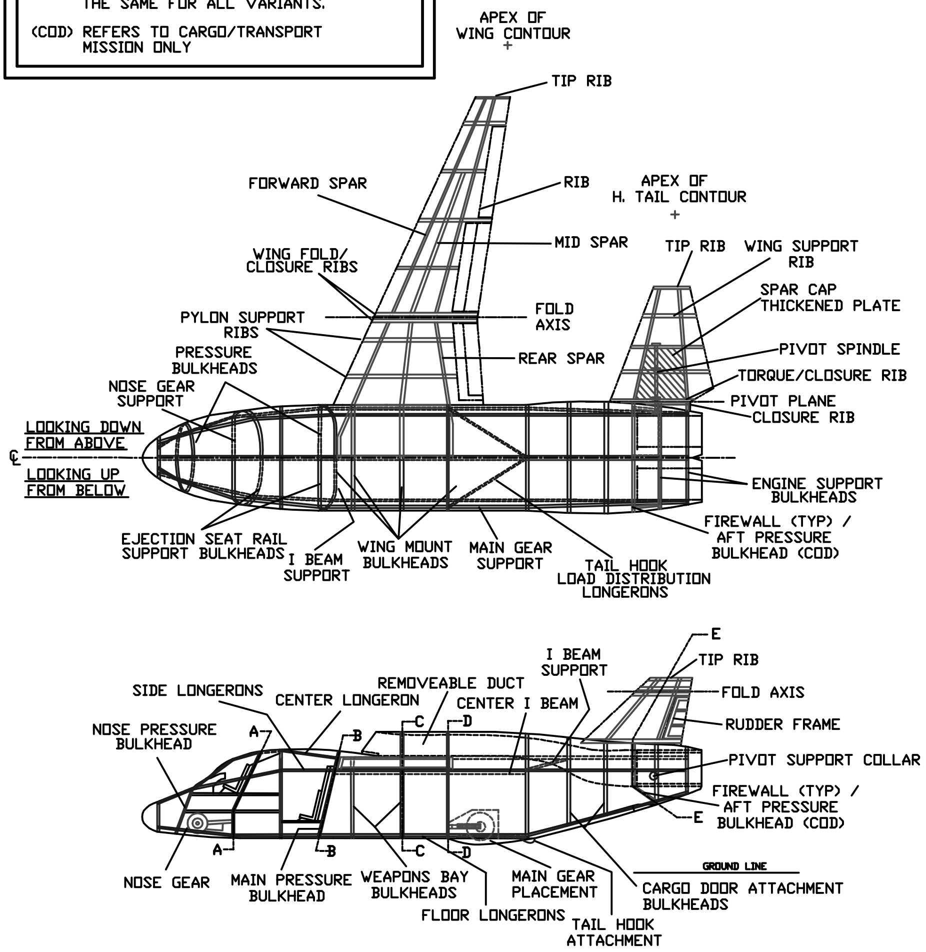
DATE:
4/30/01

NOTE: STRUCTURE IS SYMMETRIC ABOUT CENTER LINE.

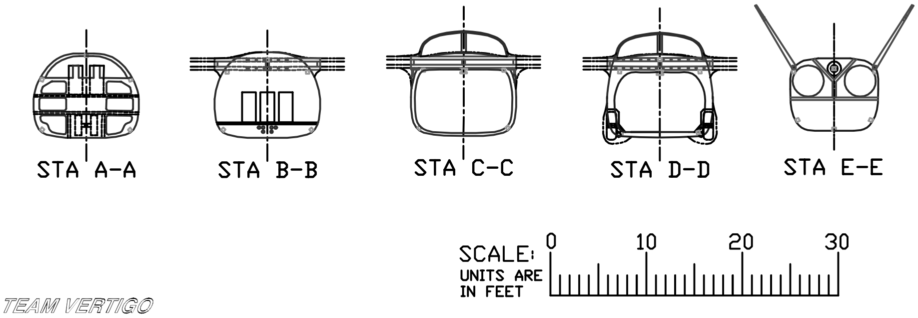
FUEL IS NOT STORED OUTBOARD OF WING FOLD.

STRUCTURAL MEMBER PLACEMENT IS THE SAME FOR ALL VARIANTS.

(COD) REFERS TO CARGO/TRANSPORT MISSION ONLY



CROSS-SECTIONAL VIEWS
LONGERONS SHOWN IN GREEN



TEAM VERTIGO

5.2.2 V-n Diagram – Wombat

The Wombat is required to have a structural limit load factor of 3.5. The negative limit load factor was set at –1.5, typical of similar aircraft. This is shown on the V-n diagram in Figure 5.2. The gust loads are also plotted based on a rough air gust of 38.5 knots, a cruise gust of 20.7 knots, and a dive gust of 14.8 knots. These gust loads are based on a standard gust determination method outlined in reference 5.3. From Figure 5.2, it is clear that gust loads are not critical to the maneuvering capability of the Wombat. The maneuver envelope is outlined in red and calculated for the AEW mission.

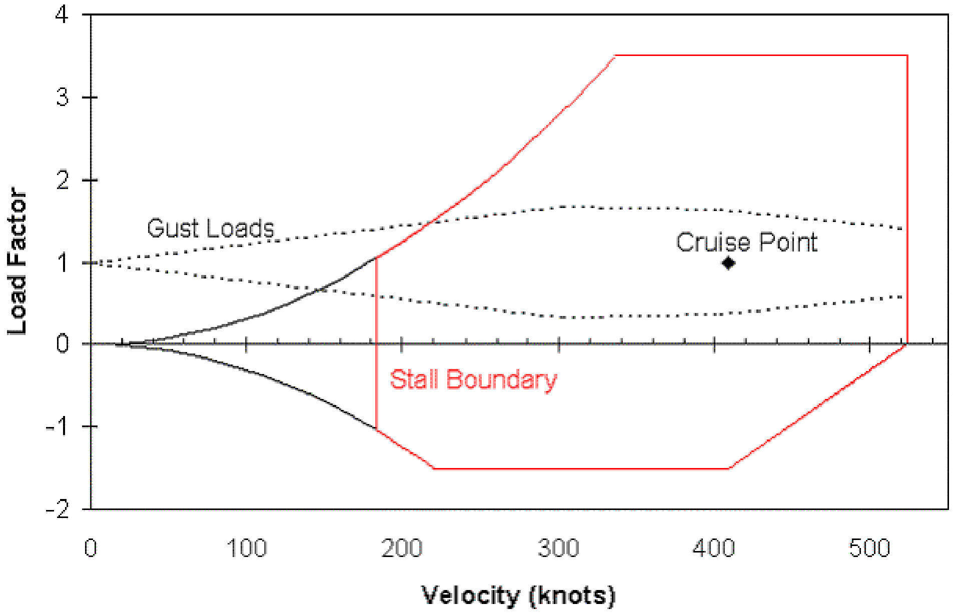


Figure 5.2 – Wombat V-n Diagram (35,000 ft)

5.2.3 Wing and Tail Elements – Wombat

The wing is designed with three spars to distribute the loads and to facilitate wing folding. The center spar provides the main support for the wing when folded. The forward and rear spars secure the wing when unfolded and serve as the typical wing box. The primary wing structure is shown in Figure 5.3. Primary ribs are numbered in Figure 5.3 and their functions are listed in Table 5.1. The wing design is common for both versions of the CSA.

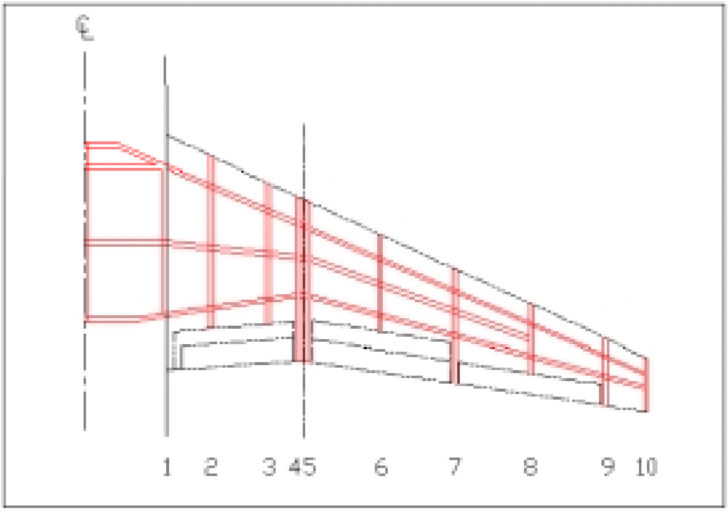


Figure 5.3 – Wombat Wing Structure

Table 5.1 – Primary Rib Functions

Rib Number	Function (Other than airfoil shape support)
1	Fuselage Attachment
2 & 3	Pylon Support and Control Surface Support
4 & 5	Wing Fold Closure and Control Surface Support
6, 7, 8, & 9	Control Surface Support
10	Wing Tip Rib

The horizontal tails are all flying surfaces each supported by two spars, five ribs and a spindle as shown in Figure 5.1. Thickened doubler plates are located on the tail surfaces around the pivots to support the bending and torsion moments exerted on the tails and translate them into adjacent spars and ribs. The spindles translate the loads of the tails into the fuselage structure via collars that are built into a bulkhead. The vertical tails are each supported by two spars and four ribs. Two ribs are located at the tip and root for closure and the other two ribs are located on each side of the fold. The vertical tail spars are mounted on two bulkheads to translate loads into the fuselage structure.

5.2.4 Fuselage – Wombat

The fuselage of the aircraft consists of 14 bulkheads and 6 longerons. The bulkheads are numbered in Figure 5.4 and their functions are listed in Table 5.2. The forward section in all variants of the aircraft is pressurized for the pilots and crew. The rest of the fuselage is designed for pressurization in the COD version only. The firewall is located in front of, between, and below the engines. Five of the longerons run the entire length of the fuselage and the sixth longeron runs from the tail to the tail hook support beams. The longerons were located to prevent discontinuities between sections, which impart localized bending moments that tend to shear bulkheads. In general, there are two longerons along the bottom at the edges, two in the upper half along the sides, and one that runs down the middle of the upper portion of the fuselage. Longerons are best shown in the cross-section views of Figure 5.1.

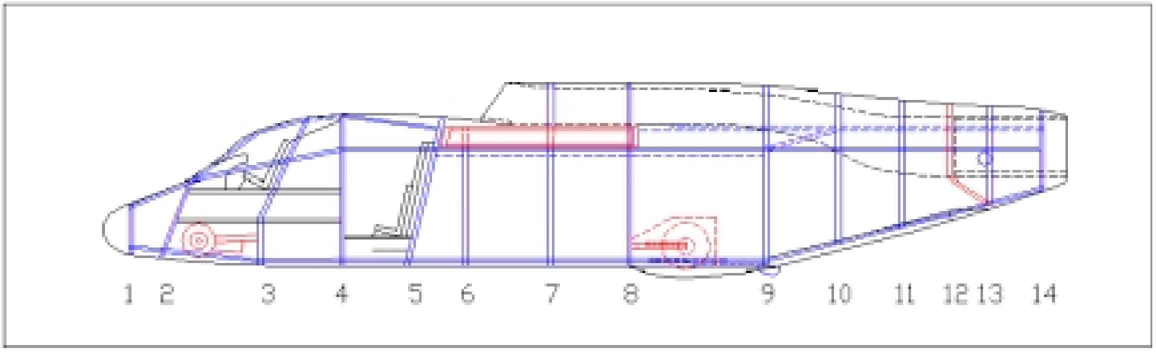


Figure 5.4 – Wombat Fuselage Structure

Table 5.2 – Bulkhead Functions

Bulkhead Number	Function
1	Forward Bulkhead
2	Forward Pressure Bulkhead
3	Nose Gear Support and Ejection Rail Support
4	Aft Cockpit Bulkhead and Crew Door Support
5	Rear Nose Pressure Bulkhead, Ejection Rail, Forward Weapon Bay Support and Forward Wing Mount Bulkhead
6	Weapon Bay Support and Wing Mount
7	Weapon Bay Support, Wing Mount, and Duct Mount
8	Rear Wing Mount Bulkhead, Main Gear Support, Rear Weapon Bay Support, and Duct Mount
9	Arresting Hook Support, Duct Mount, and Cargo Door Support
10 & 11	Cargo Door Support, Duct Mount, V. Tail Support (11)
12	Firewall, Aft Pressure Bulkhead (COD), V. Tail Support, and Engine Mount
13	Engine Mount, H. Tail Spindle Support (Collar), and Cargo Door Support
14	Engine Mount

The key issues associated with the fuselage assembly were the wingbox carry-through and the large weapons bay location. The wingbox is attached to four bulkheads, which will translate wing forces into the fuselage structure. The weapon bay was also a big issue when designing the Wombat. Not only do the weapons need to be deployed from this fuselage section, but two Joeys as well. The Joeys require a wide area for their deployment and torpedoes determined the length of the bay, since it was determined that the fuselage would be oversized if the torpedoes were not internally stationed. In addition, stationing the torpedoes on the wing pylons would reduce the ability for overload or expanded mission capabilities. Taking these constraints into account, the floor longerons are placed at the edges of the weapon bay and four bulkheads are located along the weapon bay.

5.2.5 Material Selection – Wombat

The material selection for the Wombat was primarily driven by cost. Low cost can be achieved by reducing the TOGW or by using cheaper materials. The most efficient way to gain a mass savings is to pursue an improvement in density and secondly strength. The best way to achieve this is by pursuing a high strength to weight ratio. Composites typically have the highest strength to weight ratios, which is why their usage has been increasing in the recent years. Although the operating cost of the aircraft is reduced through the use of composites, the manufacturing and maintenance/repair costs are typically higher than those of metal alloys. The Wombat design attempts to minimize the life-cycle cost of the aircraft by balancing reductions in operating costs with reductions in maintenance/repair costs.

The material usage for the Wombat is shown in Figure 5.5. Bulkheads and longerons are made of a high strength aluminum alloy because aluminum is more resistant to shear and exhibits better yielding properties. The firewall surrounding the engine will use a titanium alloy for its high strength to weight ratio and high temperature resistance[5.1]. The skin of the aircraft was chosen to be an aluminum alloy because aluminum has a better damage tolerance than composite materials[5.2]. The spindle of the horizontal tail and landing gear are made of high strength steel because of the large loads applied on these components. The remaining components are predominately made of graphite epoxy to reduce the TOGW of the Wombat.

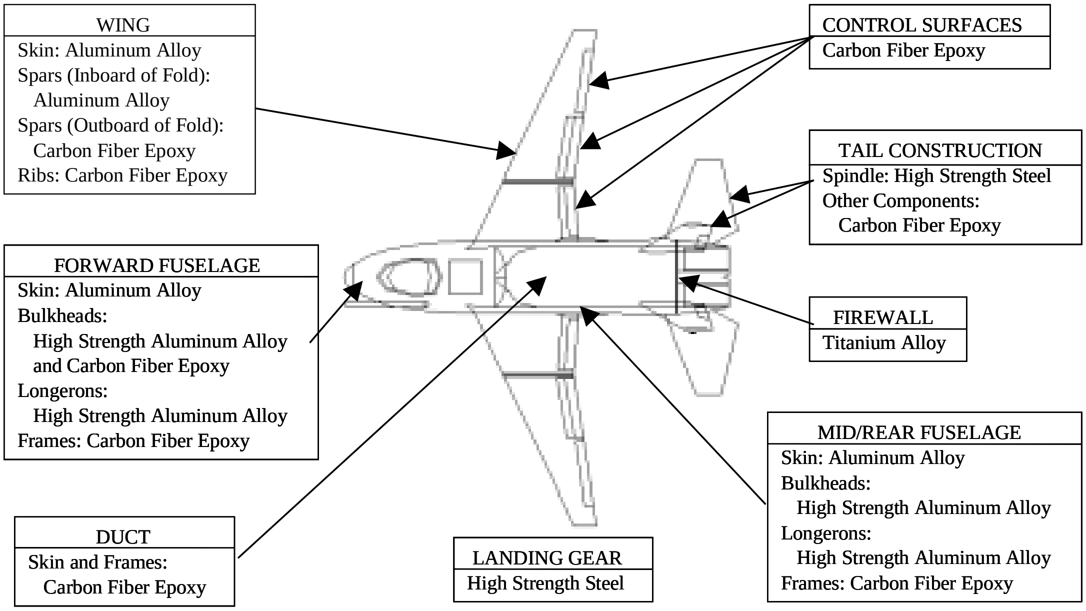


Figure 5.5 – Material Selection for the Wombat

[5.1] Buhl, H., ed., *Advanced Aerospace Material*, Springer-Verlag, New York, 1992.

5.3 Structural Design – Joey

5.3.1 Overview

The Joey is designed to expand the Wombat's mission capabilities by being deployed during flight. Since the Joey is required to fit inside of the wombat, two folds are required on each wing. In addition, this aircraft is deployed and retrieved from an extendible arm during its mission. These factors dictate where load bearing elements must be located. The Joey is a small aircraft, though, and only requires a few structural elements. This allows the Joey's structure to be inexpensive to manufacture and maintain. The structure of the Joey is shown below in Figure 5.6.

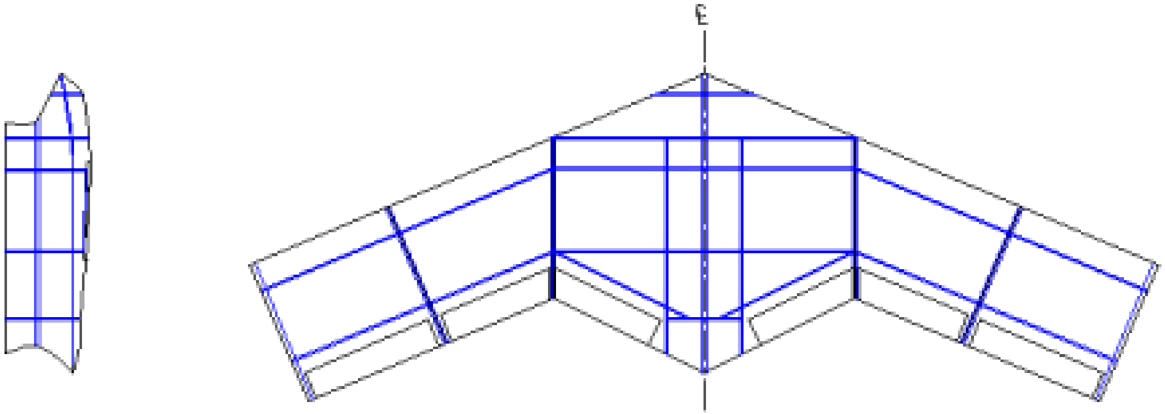


Figure 5.6 - Joey Structural Drawing

5.3.2 V-n Diagram – Joey

The Joey is required to have a structural limit load factor of 3.5. The negative limit load factor was set at –1.5. This is shown on the V-n diagram in Figure 5.7. The gust loads are also plotted based on a rough air gust of 38.5 knots, a cruise gust of 20.7 knots, and a dive gust of 14.8 knots. These gust loads are based on the same method used to determine the Wombat's gust loads. From Figure 5.7, it is clear that gust loads are not critical to the maneuvering capability of the Wombat at operating altitude. The maneuver envelope is outlined in red and calculated for the AEW mission.

[5.2] Flower, H.M.,. ed., *High Performance Materials in Aerospace*, Chapman & Hall, 1995.

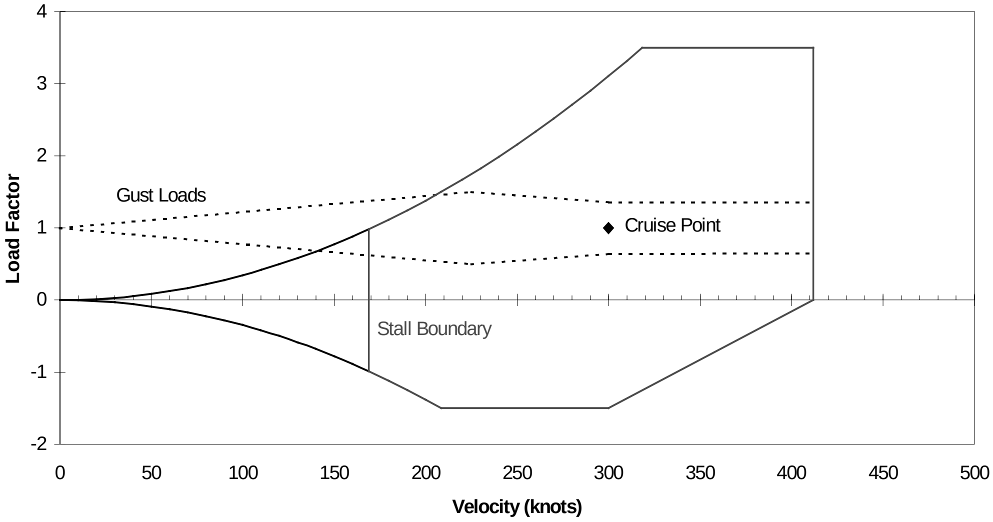


Figure 5.7 – Joey V-n Diagram (35,000 ft.)

5.3.3 Wing Elements – Joey

The wing of the Joey utilizes a typical wingbox with two spars. The spars translate the wing loads into the fuselage and also support the jury struts used when the wing is folded. Since the wing is not very long ,only four ribs are needed per semispan outboard of the innerfold. The ribs support the control surfaces and provide closure at the wing folds and tip.

5.3.4 Fuselage – Joey

The fuselage consists of five bulkheads and three longerons. The four aft bulkheads support the engine, wing box spars, and the firewall that surrounds the engine. The three longerons also support the firewall. The upper longeron distributes the loads associated with the retrieval arm to the rest of the fuselage. In addition, the fuselage also contains a rib at the wing root to provide closure at the wing root when the wing is folded.

5.3.5 Material Selection – Joey

Carbon fiber epoxy was chosen as the primary material for use with the Joey. This is because the Joey is small compared to most aircraft and experiences smaller loads. The only exception to this is the firewall and portions of the bulkheads. The firewall is going to be made of the same titanium alloy used to make the Wombat's firewall. Aluminum alloys will be used for portions of the bulkhead to provide support for the loads associated with retrieval, since composites would probably not support these loads well and need frequent repair because of it[5.3]. Given the similarities between this design and that of the B-2, historical data on the use of composites is already in

---

[5.3]. "Design of Durable, Repairable, and Maintainable Aircraft Composites," SAE Commercial Aircraft Composite Repair Committee, Warrendale, PA., 1997.

existence and will reduce the cost of their use on the Joey. Figure 5.8 graphically depicts the material usage for the Joey.

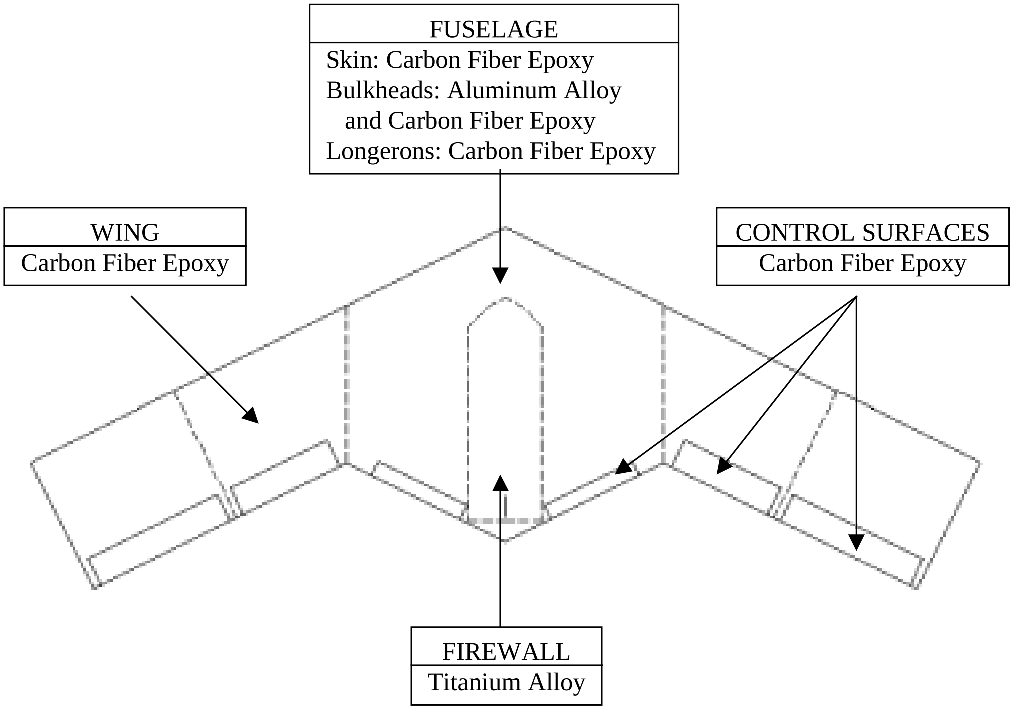


Figure 5.8 – Material Selection for the Joey

CHAPTER 6 – STABILITY AND CONTROL

6.1 Overview

The Wombat uses four sets of control surfaces, which is shown in Figure 2.1. The longitudinal control system consists of a 198 ft^2 all-flying tail, or stabiliator, which provides pitching moments. The stabilator has a volume coefficient of 0.53. The lateral control system consists of two 12.5 ft^2 ailerons located on the outer half of the outboard wing section to provide the primary rolling moments. Two 11.2 ft^2 spoilers, located forward of the outboard wing flaps, can be used to supplement the ailerons when large rolling moments are required. The directional control system consists of two 13.6 ft^2 rudders to provide yawing moments. Each rudder is part of the two 59.6 ft^2 vertical tails, which are inclined at an angle of 30.4° outboard with respect to the vertical. The vertical tails have a combined volume coefficient of 0.27. The stabilator has a deflection range of ±15°, while the ailerons and rudders have deflection ranges of ±25°. The Wombat will be equipped with a fly-by-wire control system, a longitudinal Stability Augmentation System (SAS), and a direct lift control system. Direct lift control is described in section 6.3.

The stability and control analysis was performed using a variety of techniques. Two Fortran codes were used, one written by Jacob Kay[6.1] which calculates stability and control derivatives using a vortex ring variation of the vortex lattice method, and one written by Joel Grasmeyer[6.2] , which calculates lateral-directional stability and control derivatives using DATCOM methods. Kay also prepared a Microsoft Excel file[6.3], which performs control power checks. Techniques were also used from Etkin and Reid[6.4], and Roskam.[6.5] [6.6] [6.7]

6.1.1 Design Philosophy

Although the Wombat must perform four missions, the stability and control analysis was performed for the AEW mission only. The AEW mission is the heaviest and involves the most CG travel, making it the worst-case scenario for stability and control. It is important that the Wombat remains stable and controllable at critical conditions during its mission. One such critical condition occurs during the Joey recovery process, when the aircraft achieves its aft most CG location. Details of the stability and control issues surrounding the Joey deployment and retrieval processes can be found in section 6.4. Other critical conditions include maneuvering flight (found in

---

[6.1] http://www.aoe.vt.edu/aoe/faculty/Mason_f/JKaydblp.f

[6.2] http://www.aoe.vt.edu/aoe/faculty/Mason_f/LDstab.f

[6.3] http://www.aoe.vt.edu/aoe/faculty/Mason_f/VTnascpc.zip

[6.4] Etkin, B., and Reid L., *Dynamics of Flight: Stability and Control*, 3rd ed., John Wiley & Sons, Inc., New York, 1996.

[6.5] Roskam, J., "Methods for Estimating Stability and Control Derivatives of Conventional Subsonic Airplanes," University of Kansas, Lawrence, 1973.

[6.6] Roskam, J., *Airplane Design Part VI: Preliminary Calculations of Aerodynamic, Thrust and Power Characteristics,* Roskam Aviation and Engineering Corporation, Ottawa, 1987.

[6.7] Roskam, J., *Airplane Design Part VII: Determination of Stability, Control, and Performance Characteristics: FAR and Military Requirements,* Roskam Aviation and Engineering Corporation, Ottawa, 1988.

[6.8] Abzug, M.J. and Larrabee, E., *Airplane Stability and Control: History of the Technologies That Made Aviation Possible,* Cambridge University Press, 1997, Ch. 12.4.

section 6.4), engine out and steady sideslip (section 6.5), and dynamic handling qualities such as phugoid oscillations, short period oscillations, Dutch roll, and time to roll, all of which can be found in section 6.6.

6.2 Wing Placement and Control Surface Sizing

The wing was placed at its current location, 1.5 feet aft of its original location, to move the aircraft neutral point further aft, making the aircraft more stable. During most of the mission, the CG location stays between 43% and 50% of the wing's *mac*. The wing was mounted just below the top of the fuselage with a 2° incidence and 4.22° of anhedral. The stabilator was mounted just a few inches lower, relative to the wing.

The ailerons were cut in half from their original size, which spanned most of the outboard wing section. The inner half of the wing section was needed for additional Fowler flaps. As can be seen in section 6.6, the smaller ailerons still provide sufficient control power to meet time to roll and Dutch roll requirements. Calculations show that the original sizes of other control surfaces provide sufficient control power to meet all requirements.

6.3 Direct Lift Control

Direct lift control, or DLC, is a very useful system that provides a way to change wing lift without changing angle of attack, which is functional in landing situations. Rear DLC is used during carrier landings as a means of rapid adjustments to the flight path angle. With DLC there is an immediate response that the aircraft undergoes, as compared to waiting for the aircraft to respond to changes in elevator angle. The mechanisms that enable DLC to work are two spoiler segments, located inboard on each wing, that move independently to provide the correct dispersion of lift. Typically, the spoilers are set to deploy to an 8˚ up position during carrier landings and then manipulated from this position to obtain proper DLC. Changes in spoiler position are controlled by the cockpit control column, managed by either the pilot or the autopilot.[6.8]

6.4 Longitudinal Stability, Control, and Trim

Table 6.1 shows the important longitudinal stability and control derivatives, which were calculated using methods by Kay[6.1], Roskam[6.5 6.6 6.7], and Etkin and Reid[6.4]. The Wombat remains stable throughout its mission, with a single exception. As was mentioned in the previous section, the CG location remains between 43% and 50% *mac* throughout most of the mission. Figure 6.1, which is a plot of the CG movement throughout the AEW mission, shows that the CG only travels aft of 50% *mac* once, and it remains there only briefly. The Wombat's cruise neutral point was estimated to be at 52% *mac*, meaning the aircraft is at least 2% stable throughout its mission, with the one exception. This mission aft CG location occurs during the Joey recovery process, just after the first Joey is recovered. At this point the CG location is slightly aft of the neutral point, corresponding to a static margin of about minus two percent, meaning that the Wombat is slightly unstable. The fact that the Wombat has less than a 5% static margin for much of its mission, including the brief period of instability, is the reason that it needed to be equipped with the SAS.

The Wombat's maneuvering requirements were analyzed to determine if the aircraft possessed adequate longitudinal maneuverability. Calculations show that the Wombat can handle a pull-up maneuver at its structural load limit factor of 3.5-g's at its dash speed of 425 knots at 35,000 feet without stalling or exceeding stabilator deflection limits. Under these conditions, the aircraft must fly at an angle of attack of 10.2° with a stabilator deflection of –5.8°. Under low speed conditions, such as at takeoff and landing, the Wombat's maneuvering capability is much more restricted. At takeoff, it can only perform 1.3-g maneuvers and at landing it can only perform 2-g maneuvers. Anything greater would cause the aircraft to stall.

Steady 1-g trim conditions were analyzed to determine what kind of changes must be made during the Joey deployment and retrieval processes. Trim conditions were also analyzed for the cruise out and cruise back. Of particular interest is the change in conditions that occur immediately following retrieval of the first Joey, which is the aft most CG location (53% *mac*).

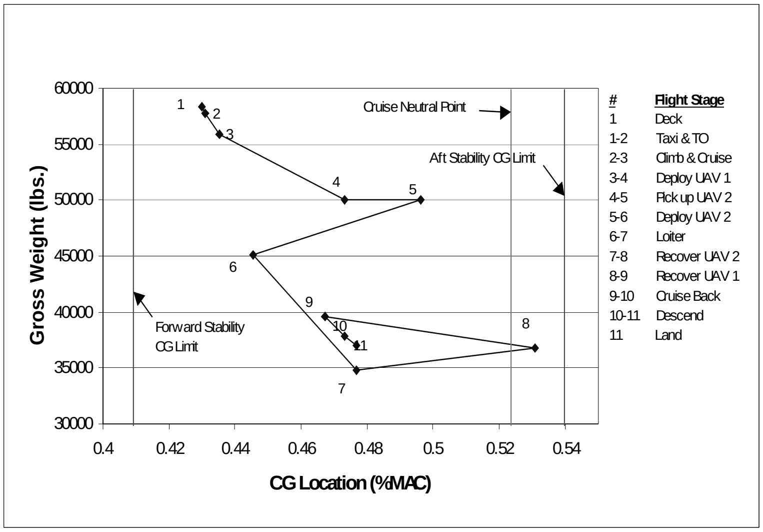


Figure 6.1 – AEW CG Movement

Table 6.2 shows the trim conditions for the cruise out and Joey deployment process, and Table 6.3 shows the trim conditions for the Joey recovery process and the cruise back. The Wombat's fly-by-wire control system will be designed to accommodate these rapid changes.

Table 6.1 – Longitudinal Stability and Control Derivatives

Flight Parameters	Take-off	Cruise	Loiter	Landing
Weight (lb)	56,700	56,000	35,000	39,000
Mach	0.2	0.7	.49	0.2

Altitude (ft)	0	35,000	35,000	0
Longitudinal Derivatives				
$C_{L\alpha}$	4.5808	5.6380	4.9867	4.5808
C_{Lq}	6.3762	7.0373	6.5880	6.3762
$C_{m\alpha}$	-0.1868	-0.2834	-0.0710	-0.0233
C_{mq}	-9.4871	-10.6428	-9.9229	-9.4871
$C_{m\dot{\alpha}}$	-3.850	-4.771	-4.183	-3.850
Static Margin	0.0548	0.0719	0.0197	0.0069
Elevator Control Power				
$C_{L\delta e}$	0.4786	0.5160	0.4913	0.4786
$C_{m\delta e}$	-0.9414	-1.0440	-0.9805	-0.9414

Table 6.2 – Trim Requirements for Cruise Out and Joey Deployment at 35,000 ft.

Flight Stage	**Cruise Out**	**Loiter**	**Loiter**	**Loiter**
Number of Joey's Deployed	0	0	1	2
Mach	0.7	0.49	0.49	0.49
Weight (pounds)	56,000	55,000	48,200	41,400
C_L	0.44	0.86	0.76	0.65
Elevator Deflection (deg)	-0.43	-2.04	-0.54	-0.89
Angle of Attack (deg)	0.41	5.51	4.14	2.95

Table 6.3 – Trim Requirements for Joey Recovery and Cruise Back at 35,000 ft.

Flight Stage	**Loiter**	**Loiter**	**Loiter**	**Cruise Back**
Number of Joey's Recovered	0	1	2	2
Mach	0.49	0.49	0.49	0.7
Weight (pounds)	30,000	35,800	41,600	40,000
C_L	0.47	0.56	0.65	0.31
Elevator Deflection (deg)	-0.17	0.01	-0.66	0.07
Angle of Attack (deg)	0.83	1.85	2.96	-0.91

6.5 Lateral-Directional Stability, Control, and Trim

Table 6.4 is a listing of the important lateral-directional stability and control derivatives, which were calculated using a combination of methods by Kay[6.1], Grasmeyer[6.2], and Roskam[6.5 6.6 6.7]. The most important control requirements for the Wombat to meet are to counter the moments caused by engine-out and steady sideslip.

Both cases were examined using Kay's methodology. Engine-out trim was analyzed during takeoff and at wave-off with zero stores and reserve fuel weight, which is often the most critical case. At takeoff, it was found that with the remaining engine at maximum thrust, a sideslip angle of 1.32° was generated. To counter this, the rudders must be deflected 8.9°, and the ailerons must be deflected 5.9°. Under the described wave-off conditions, the aircraft only weighs 23,860 pounds and can land at a lower speed of 92 knots. Compensating for engine-out under these conditions requires larger rudder and aileron deflections, 18° and 12° respectively, but is still within the limits. Since the Wombat will be flying from carriers, which are maneuvered to orient themselves with the wind, the sideslip case was analyzed at cruise conditions, with a 30-knot crosswind. The Wombat is able to maintain a 0° flight path angle by flying at a bank angle of 4.3° and deflecting the rudders 12.5°, and the ailerons 4.7°.

Table 6.4 – Lateral-Directional Stability and Control Derivatives

Flight Parameters	Take-off	Cruise	Loiter	Landing
Weight (lb)	57,260	55,000	35,000	39,000
Mach	0.2	0.7	.49	0.2
Altitude (ft)	0	35,000	35,000	0
Lateral-Directional Derivatives				
C_{lp}	-0.4657	-0.5442	-0.4946	-0.4657
C_{np}	-0.2170	-0.2173	-0.2223	-0.2170
C_{yr}	0.4127	0.4387	0.4231	0.4127
C_{lr}	0.5568	0.2162	0.2874	0.6017
C_{nr}	-0.3500	-0.3155	-0.3203	-0.3549
$C_{y\beta}$	-0.7932	-0.8040	-0.7977	-0.7932
$C_{l\beta}$	-0.2128	-0.1405	-0.1595	-0.2220
$C_{n\beta}$	0.1000	0.1185	0.1149	0.1000
Aileron Control Power				
$C_{y\delta a}$	0.000	0.000	0.000	0.000
$C_{l\delta a}$	-0.0915	-0.1186	-0.1005	-0.0915
$C_{n\delta a}$	0.0008	0.0014	0.0010	0.0008
Rudder Control Power				
$C_{y\delta r}$	0.1174	0.1256	0.1208	0.1174
$C_{l\delta r}$	0.0922	0.0034	0.0034	0.0922
$C_{n\delta r}$	-0.0374	-0.0400	-0.0384	-0.0374

6.6 Dynamics and Handling Qualities

An analysis of the Wombat's handling qualities was performed using a combination of methods by Kay[6.3], Roskam[6.7], and Etkin and Reid[6.4]. Military aircraft must meet requirements for longitudinal handling qualities such as phugoid and short period oscillations, and lateral-directional qualities such as spiral mode, time to roll and Dutch roll. The aircraft's handling qualities, as well as the requirements specified in MIL-F-8785C[6.7] for class II, category B aircraft can be found in tables 6.5 and 6.6. The Wombat is able to meet the all of the requirements throughout its mission without the assistance of the SAS.

Table 6.5 – Longitudinal Handling Qualities

	Phugoid	**Short Period**
MIL-F-8785C Requirement	$\xi_p \geq 0.04$	$0.30 \leq \xi_{sp} \leq 2.0$
Takeoff	0.071	0.82
Cruise	0.062	0.48
Landing	0.071	1.02

Table 6.6 – Lateral-Directional Handling Qualities

	Roll	**Dutch Roll**			**Spiral Mode***
MIL-F-8785C Requirement	$t_{30deg} \leq 2.3$ sec	$\xi_d \geq 0.08$	$\omega_{nd} \geq 0.4$	$\xi_d\omega_{nd} \geq 0.15$	$L_\beta N_r - N_\beta L_r > 0$
Takeoff	1.75 sec	0.30	0.877	0.263	0.267
Cruise	0.799 sec	0.152	1.63	0.248	0.777
Landing	1.46 sec	0.363	1.12	0.407	0.638

* The expression $L_\beta N_r - N_\beta L_r > 0$ is not a MIL requirement, but rather an acceptable condition for spiral stability[6.7].

6.7 Stability and Control for the Joey

The Joey's control system consists of one set of 2.2 ft^2 inboard elevators, one set of 2.2 ft^2 mid-span elevons, and one set of 2.7 ft^2 split rudders at the tips. This control system is similar to the one used in the B-2 Spirit, which features three sets of elevons and one set of split rudders. The elevons will be used primarily to generate rolling moments, but could also act as elevators should the need arise. This situation is unlikely given the limited situations the Joey will encounter. The split rudders open like a book to create yawing moments. Table 6.7 shows stability and control derivatives calculated using methods by Kay and Roskam.

The Joey has only one mission requirement, which is to loiter and cruise to and from the Wombat. Trimming the Joey is easily accomplished with very small elevator deflections, on the order of half a degree. Any necessary changes would be minimal and easily handled by the Joey's fly-by-light control system. The only critical condition during the Joey's mission is its recovery. It is important that the Joey remain stable during this delicate retrieval process. Since the Joey has only minimal inherent stability, it will also require an SAS for the control system. The retrieval process will likely require several quick, but small, control surface adjustments, which will be handled by the control system. In the event of an emergency or malfunction, a manual override can be engaged. The recovery process can be simplified somewhat by aligning the Wombat and Joey with the prevailing wind.

Table 6.7 – Joey Stability and Control Derivatives

	Loiter
Weight (lb)	6,800

Mach number	0.49
Altitude (ft)	35,000
Longitudinal Derivatives	
$C_{L\alpha}$	4.423
C_{Lq}	4.204
$C_{m\alpha}$	-0.0340
C_{mq}	-1.0334
Elevator Control Power	
$C_{L\delta e}$	0.5245
$C_{m\delta e}$	-0.5245
Lateral-Directional Derivatives	
C_{lp}	-0.289
C_{np}	-0.1348
C_{yr}	0.000
C_{lr}	0.1924
C_{nr}	-0.0161
$C_{y\beta}$	-0.2065
$C_{l\beta}$	-0.1206
$C_{n\beta}$	0.004895
Elevon Control Power	
$C_{l\delta a}$	-0.2272
$C_{n\delta a}$	0.02935

CHAPTER 7 – PERFORMANCE

7.1 Overview

Analysis was performed on the Wombat to determine whether the aircraft would meet or exceed the RFP stipulated point performance and mission requirement. Using methods described by Anderson's *Aircraft Performance and Design*, Roskam's *Airplane Design Part 1*, and Brandt's *Introduction to Aeronautics: A Design Perspective*, Microsoft Excel worksheets were created to calculate the various performance characteristics of both the Wombat and the Joey.

7.2 Wombat and Joey Point Performance Requirements

As stipulated by the RFP, the Common Support Aircraft must meet several point performance and carrier suitability requirements. Each variant must have a take-off single-engine rate of climb (SEROC) of no less than 200 ft/min, with a launch wind over deck (WOD) of no more than zero knots. They must also have an approach SEROC of no less than 500 ft/min with an approach WOD of no more than 5 knots. These requirements assume use of a C-13-2 catapult launch system and a Mark 7 Mod 3 arresting gear system. A dash speed of 425 knots at loiter altitude is another point performance requirement.

Joey performance requirements did not require analysis at launch and landing, since launch and recovery of this aircraft is near steady state at loiter altitude. Analysis was performed on the Joey to determine its maximum and dash speeds.

With all variants having the same propulsion system, a decrease in weight would result in better performance. Therefore, analysis was only performed on the AEW family, which has the largest TOGW. Initial sizing gave TOGW estimates for the AEW at 57,258 pounds. Several aerodynamic properties were needed for performance calculations, and determined mainly from geometric characteristics as explained in previous sections. Standard day, static sea level thrust of 20,000 pounds was used in all calculations.

7.2.1 Dash Speed Requirement

With basic aerodynamic characteristics calculated, a thrust available vs. thrust required curve was generated Figure 7.1 shows values at sea level, and loiter altitudes of 35,000 ft and 40,000 ft. Thrust available varies with velocity and with altitude, using the high bypass turbofan engines according to the following equation:[7.1]

$$T/T_{SL} = [0.568 + 0.25(1.2 - M)^3]\left(\frac{\rho}{\rho_{SL}}\right)^{0.6}$$

Thrust required was varied according to equations in sections 5.1 through 5.8 of Anderson's *Aircraft Performance and Design*[7.2], with attention being paid to drag divergence effects at transonic-mach numbers.

[7.1] Mattlingly, J.D., Heiser, D., *Aircraft Engine Design*, AIAA, 1987.

[7.2] Anderson, J.D., *Aircraft Performance And Design*, McGraw-Hill Higher Education, 1999.

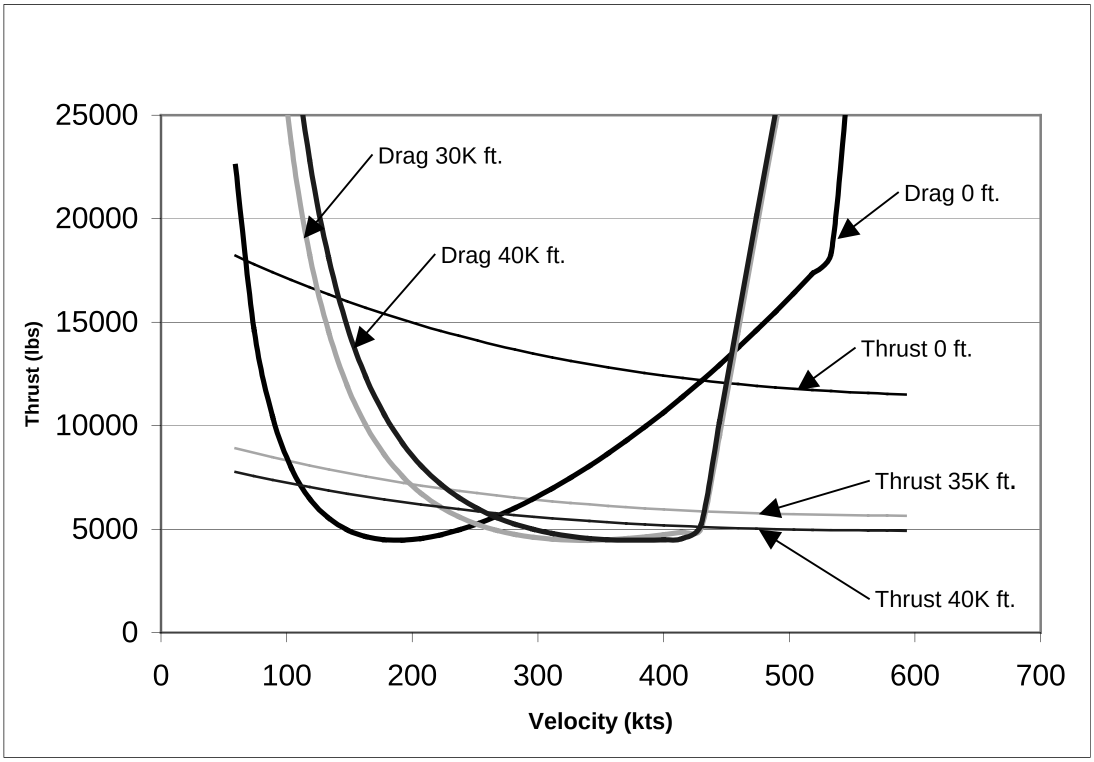


Figure 7.1 – Wombat Thrust-Drag Curves

Maximum velocities for the Wombat were determined from the intersection of the power available and power required curves. These velocities were determined to be 433 knots and 429 knots for loiter altitudes of 35,000 feet and 40,000 feet, respectively, exceeding the minimum dash speed of 425 knots at loiter altitude.

Initial sizing for the Joey determined a TOGW of 6,751 pounds. For the Joey, aerodynamic properties shown in previous sections were used in calculating performance characteristics. Static sea level thrust of 2,400 pounds was used. Figure 7.2 plots the thrust-velocity curves at loiter altitudes of 35,000 feet and 40,000 feet for the Joey. Maximum velocity for the Joey was determined to be 430 knots and 433 knots at loiter altitudes of 35,000 feet and 40,000 feet respectively and far removed from the wing's drag rise of 465 knots.

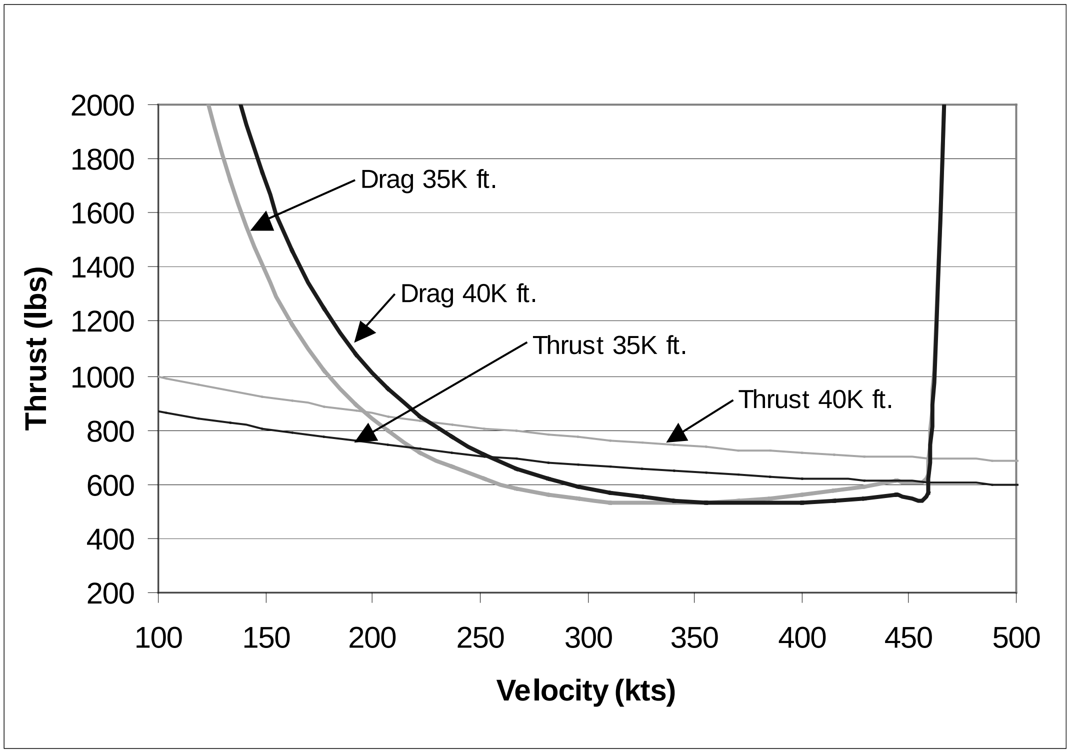


Figure 7.2 – Joey Thrust-Drag Curves

7.2.2 Rate of Climb Requirements:

Launch ROC and approach ROC vary solely upon aircraft weight and wind over deck (WOD) speed. Launch speed off a C-13-2 catapult with an aircraft weighing 58,000 pounds and zero knots WOD was determined to be 137 knots according to Figure 7.3, giving a SEROC of 621 ft/min, exceeding the minimum requirement of 200 ft/min.

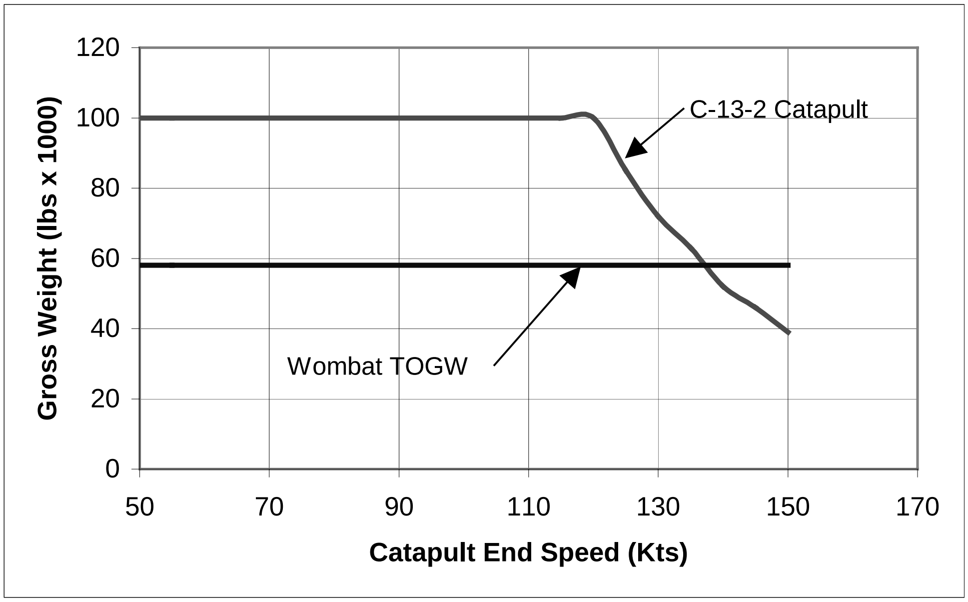


Figure 7.3 – Catapult End Speed (Launch speed) versus Weight[7.3]

Applying a factor of safety of 1.15 to the stall speed, approach speed was determined, making sure the Mark 7 Mod 3 arresting gear could handle the aircraft weight and speed. With a fuel dump at 2,258 pounds from TOGW and an approach speed of 118 knots, SEROC was determined to be 502 ft/min, meeting the requirement 500 ft/min for approach SEROC. See Figure 7.4.

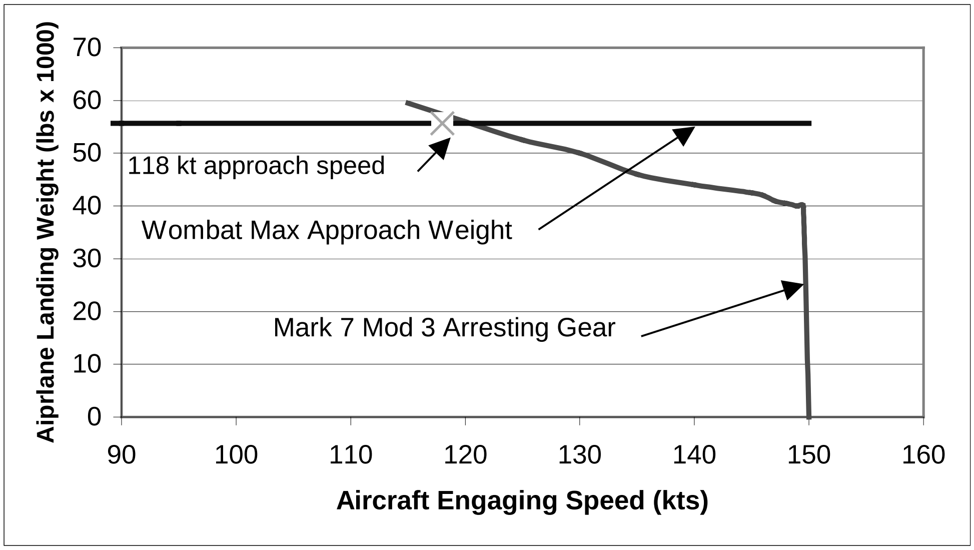


Figure 7.4 – Aircraft Engaging Speed (Approach Speed) versus Weight[7.3]

Rate of Climb performance for the Wombat variants varies with altitude as seen in Figure 7.5.

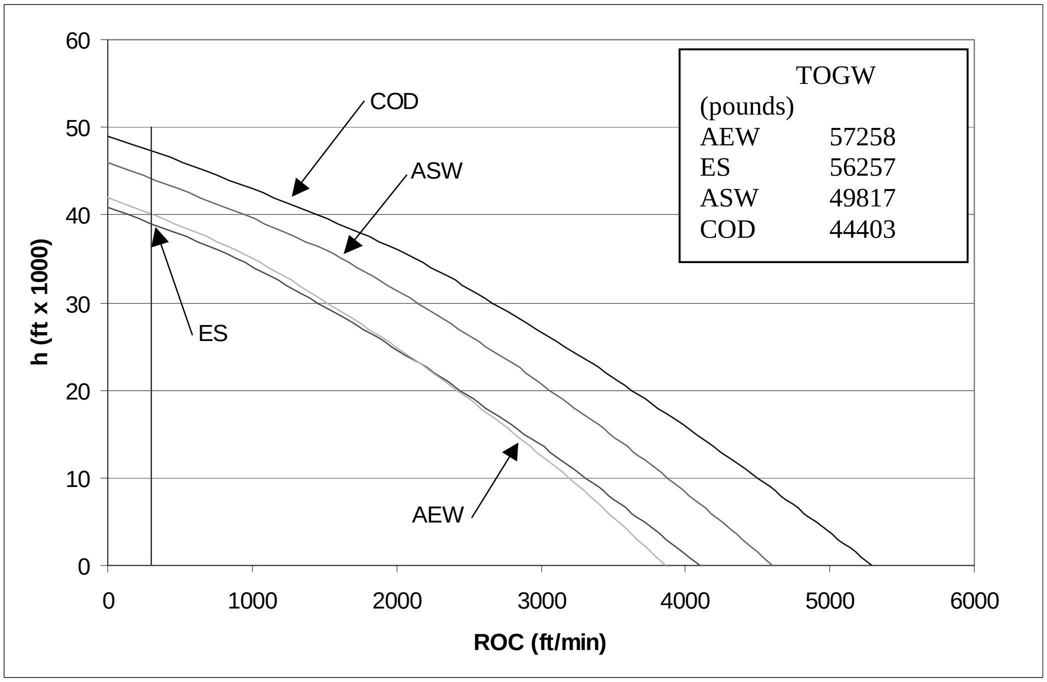


Figure 7.5 – Rate of Climb versus Altitude

At a ROC of 300 ft/min, Wombat variant cruise ceilings are determined as stipulated in the MIL-SPECs. The ES mission variant has the lowest ceiling at 39,000 feet, with AEW, ASW, and COD variants following at 40,000 feet, 45,000 feet and 48,000 feet, respectively.

7.3 Individual Mission Requirements

Climb performance was determined at maximum rate of climb where excess power is a maximum. Cruise performance was determined at conditions for maximum range, when L/D is maximum, with attention being paid to C_{Do} variations over transonic mach numbers. Loiter performance was determined at conditions for maximum endurance, or L/D_{max}.[7.4] Mission fuel burn for the wombat variants were determined from the speeds, thrusts required, and engine TSFC for the power setting for the mission segments.

After determining speeds at the above conditions for all variants of the CSA, the thrust required to fly at these speeds at given altitudes was determined. The flight time for each segment of the mission was also determined at the various speeds. TSFC varies according to equations provided by John Gundlach[7.5] using a static sea level TSFC of 0.35 pounds fuel/(pounds thrust *hr) for the Wombat and a static sea level TSFC of 0.69 lb fuel/(pounds

---

[7.4] Bertin, B., Stiles, R.J., Brandt, S., and Whitford, R., *Introduction to Aeronautics: A Design Perspective,* AIAA, 1997.

[7.5] Gundlach IV,J.F., Naghshineh, A., Gern, F., Tetrault, P., Ko, A., Schetz, J.A., Mason, W.H., Kapania, R.K., Grossman, B., Haftka, R.T., "Multidisciplinary Design Optimization and Industry Review of a 2010 Strut-Braced Wing Transonic Transport," MAD Center Report 99-06-03, Virginia Tech, Blacksburg, VA, June 1999.

thrust*hr) for the Joey. Fuel burned per segment of each mission was calculated, and total mission fuel burn was determined by summing fuel burned during each segment. Table 7.1 displays mission summaries for the AEW and ES family of aircraft. Table 7.2 displays mission summary for ASW/ASUW, and Table 7.3 displays the COD mission summary.

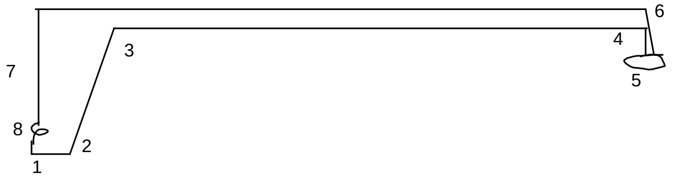
Table 7.1 – AEW/ES Mission Summary

Payload Weight
AEW: (2) 6757 lb Conformal Radar Equipped Joeys
ES: (2) 6132 lb Electronic Survielance Joeys

	Wombat (lb)		Joey (lb)	
	AEW	ES	AEW	ES
TOGW =	58324	55464	6757	6132
Internal Fuel =	17382	16141	2115	1277

Mission Segment	Velocity fps		Mach #		Alt (ft)		TSFC (lb/hr/lb)		Time (min)		Fuel (lb)		Dist (n mile)	
	AEW	ES	AEW	ES	AEW	ES	AEW	ES	AEW	ES	AEW	ES	AEW	ES
1) Warm-up, Taxi, Take off	231.3	233	0.21	0.21	0	0	0.35	0.35	5	5	583.3	583	0	0
2) Climb to BCA	463.6	425	0.42	0.38	32000	32000	0.52	0.5	8.2	7.9	416	346	37.5	32.7
3) Cruise Out at BCA	663	699	0.67	0.71	32000	32000	0.58	0.57	32.5	70.6	1516	3225	212.5	487.3
4) Deploy														
a) Wombat	331	481	0.34	0.5	35000	40000	0.43	0.48	15	15	801	607	0	0
b) Joey	331	429	0.34	0.44	35000	40000	0.73	0.76	7.5	7.5	74	93		
5) Loiter														
a) Wombat	480	440	0.49	0.45	35000	40000	0.49	0.47	270	150	10356	6406	0	0
b) Jeoy	472	567	0.48	0.58	35000	40000	0.77	0.81	270	150	1967	1091		
6) Recover														
a) Wombat	331	481	0.34	0.5	35000	40000	0.43	0.48	15	15	801	607	0	0
b) Jeoy	331	429	0.34	0.44	35000	40000	0.73	0.76	7.5	7.5	74	93		
7) Cruise Back @ BCA	653	658	0.67	0.67	36000	35000	0.62	0.56	38.8	76.8	1886	3273	250	520
8) Descend									0					
9) Reserve														
20 minute loiter	372.7	314	0.33	0.28	0	0	0.49	0.46	20	20	771	677	0	0
5% reserve Fuel	--										700	488	0	0
Totals Wombat									404	360.3	17832	16141	500	1040
Joey									285	165	2115	1277		

Table 7.2 – ASW/ASUW Mission Summary



Payload			Weight				
68 A-size Sonobouys			25 lbs		TOGW =	51361 lb	
(2) MK 54 Torpedoes			800 lbs		Internal Fuel =	13023 lb	
(2) AGM 84 Harpoons			1145 lbs		Wt @ 50% Fuel =	44849 lb	
					Wt @ 80% Fuel =	40943 lb	
Mission Segment	Velocity fps	Mach #	Alt (ft)	TSFC (lb/hr/lb)	Time (min)	Fuel (lb)	Dist (n mile)
1) Warm-up, Taxi, Takeoff	240	0.21	0	0.35	5	583	0
2) Climb to BCA	466	0.42	35000	0.52	7.6	362	35
3) Cruise Out at BCA	665	0.68	35000	0.56	31.1	1253	210
4) Loiter	441	0.43	25000	0.48	270	8392	--
5) Expend Weapons	441	0.43	25000	0.48	--	--	--
6) Cruise Back at BCA	659	0.71	39000	0.56	36.3	1354	245
7) Descend to S.L.	--	0.68	0	--	--	--	--
8) Reserve Fuel Allowance:							
20min S.L. Endurance	295	0.23	0	0.46	20	591	--
5% Total Fuel	--	--	--	--	--	488	--
Totals					370	13023	490

Table 7.3 – COD Mission Summary

Payload		Weight			TOGW =	50531 lbs	
Cargo		10,000 lbs			Internal Fuel =	10560 lbs	
26 Passengers		5200 lbs			Wt @ 50% Fuel =	45251 lbs	
					WT @ 80% Fuel =	42082 lbs	
Mission Segment	Velocity fps	Mach #	Alt (ft)	TSFC (lb/hr/lb)	Time (min)	Fuel (lb)	Dist (n mile)
1) Warm-up, Taxi, Takeoff	244	0.22	0	0.35	5	583	0
2) Climb to BCA	464	0.42	37000	0.52	7.1	330	32
3) Cruise Out at BCA	657	0.67	37000	0.56	231.5	8762	1568
4) Descend to S.L.			0				0
5) Reserve Fuel Allowance:							
20min S.L. Endurance	279	0.25	0	0.45	20	520	0
5% Total Fuel						365	
Totals					263.6	10560	1600

Upon completion of mission summaries for each Wombat variant of aircraft, several performance characteristics for the variants can be concluded. With the AEW variant having the highest TOGW of 58,324 pounds, it has the lowest performance capabilities while meeting all the RFP requirements. With the same power plant and same basic airframe as the base AEW, all the other variants can perform better than required in the RFP. With a TOGW of 50,531 pounds, the COD variant can carry nearly 8,000 pounds of extra cargo and fuel when stressed to the AEW weight, increasing its payload and mission range. The ASW model, having a TOGW of 51,651 pounds, can carry up to 7,000 pounds of extra fuel, increasing its mission radius and loiter time. The ES variant can increase its TOGW nearly 2,000 pounds in fuel on both the Joey and the Wombat, increasing the mission radius or loiter time. Both the Wombat and Joey not only meet the requirements set forth by the RFP, but overwhelmingly exceed all performance requests.

CHAPTER 8 – SYSTEMS

8.1 Avionics Systems

The avionics systems for both the Wombat and Joey platforms were selected from systems listed in the *Aviation Week Aerospace Source Book*.[8.1] It is expected that lighter and more advanced systems will be available during later stages of development and production of these aircraft. Changes in these should not interfere with the layout of the platforms. Upgrades should improve weight and installed dimension issues while using the same interfaces as older models.

8.1.1 Wombat Avionics and Systems

The avionics in the Wombat are a combination of already established systems and systems still in development. Datalinks will be upgraded to the newer Link 16 standard. A GD3000 by General Dynamics Information Systems is the mission/data processing computer. The Avionics Management System (AMS-2000), by Honeywell, will be the same system that is used on the P-3 and C-130. An AN/APX-111 by BAE Systems currently used on F/A-18s is employed as the IFF interrogator/transponder. The radar altimeter is the APN-194, a US Navy standard, produced by Honeywell. The INS/GPS system to be used is the H-764G, by Honeywell, currently used on both fighters and transports in all services. The Doppler radar navigation system will be the AN/APN-218 manufactured by Litton Systems Inc, now Northrop Grumman.

The Wombat also contains a control station for the Joey. This system is based on the JSTARS ground control station that is currently mounted on a Humvee vehicle for land use. The Wombat will also have a Multi-Information distribution system low volume terminal (MIDS LVT), developed by Harris Corp., as a near real-time datalink between UAVs and surface ships for command, control, communication and intelligence functions. This system is currently in development to replace the JTIDS terminals used on E-2Cs and other AWACS platforms and is already planned for integration on U.S. Navy aircraft.[8.2] The Wombat will also use the new JSTARS VHF/UHF communication system made by Raytheon Co. This is a secure communications system with built-in anti-jamming functions.

The ASW variants will contain a weapons system management module (WMS-Maritime) developed by Smiths Group PLC for use on maritime patrol aircraft such as the P-3 and Nimrod.

Figure 8.1 shows the inboard profile for the Wombat.

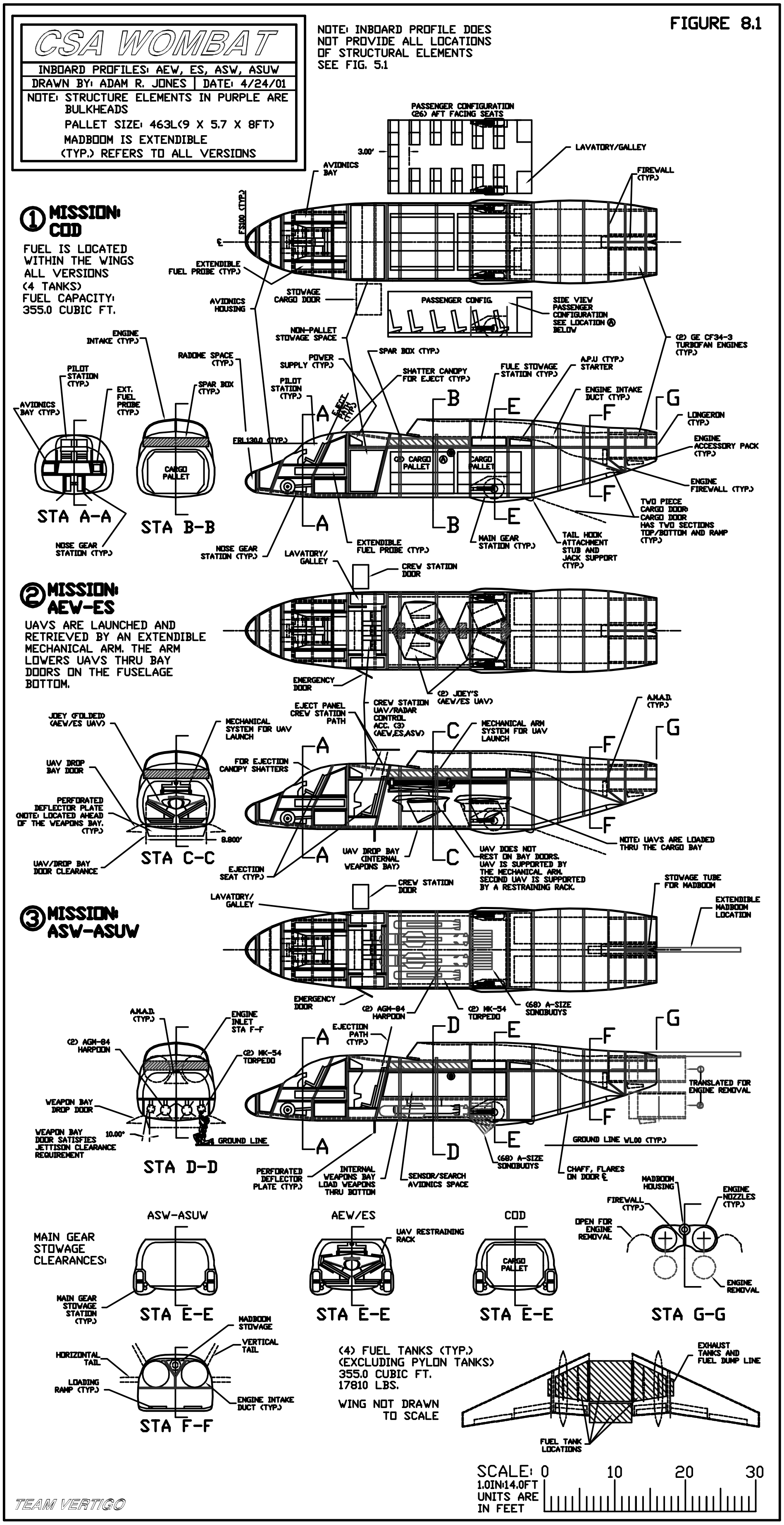
8.1.2 Joey Avionics and Systems

The radar system in the Joey will not be the AN/APS-145 system currently used on the E-2C Hawkeye platform. Instead, the conformal radar discussed in the concept phase will be implemented. This will be more than adequate for the AEW mission and suitable for integration in the Joey. This system is proving to be much lighter and versatile compared to existing systems. The British Nimrod system uses active electronically scanned arrays, but on a larger scale than what will be integrated into the Joey platform. The Joey will use the Tactical Common

---

[8.1] *Aviation Week Aerospace Source Book*, January 2001.

[8.2] http://www.fas.org/man/dod-101/sys/ac/equip/mids-lvt.htm



CSA WOMBAT
INBOARD PROFILES: AEW, ES, ASW, ASUW
DRAWN BY: ADAM R. JONES | DATE: 4/24/01
NOTE: STRUCTURE ELEMENTS IN PURPLE ARE BULKHEADS
PALLET SIZE: 463L(9 X 5.7 X 8FT)
MADBOOM IS EXTENDIBLE
(TYP.) REFERS TO ALL VERSIONS

NOTE: INBOARD PROFILE DOES NOT PROVIDE ALL LOCATIONS OF STRUCTURAL ELEMENTS SEE FIG. 5.1

FIGURE 8.1

① MISSION: COD

FUEL IS LOCATED WITHIN THE WINGS ALL VERSIONS (4 TANKS) FUEL CAPACITY: 355.0 CUBIC FT.

② MISSION: AEW-ES

UAVS ARE LAUNCHED AND RETRIEVED BY AN EXTENDIBLE MECHANICAL ARM. THE ARM LOWERS UAVS THRU BAY DOORS ON THE FUSELAGE BOTTOM.

③ MISSION: ASW-ASUW

MAIN GEAR STOWAGE CLEARANCES:

(4) FUEL TANKS (TYP.)
(EXCLUDING PYLON TANKS)
355.0 CUBIC FT.
17810 LBS.

WING NOT DRAWN TO SCALE

SCALE: 1.0IN:14.0FT UNITS ARE IN FEET

Data Link (TCDL) by Harris Corp., as a wideband datalink. This unit was specifically designed for use on UAV platforms.

The Joey will use the KN4072 GPS/INS unit, produced by Kearfott, and designed specifically for the Global Hawk UAV. The vehicle management system will be the Modular Integrated Avionics Group (MIAG) developed by BAE Systems for the Pioneer UAV system. The air data computer is also made by Kearfott, the MADC-108.

Figure 8.2 shows the inboard profile for the Joey.

8.2 Radar System

Radar integration is critical to the Airborne Early Warning mission. Current radar systems can be placed in anything from rotodomes to conformal radar arrays. Research and development of new forms of radar has been very productive in the past decade.[8.3] The development of conformal array radar utilizing electronically steered arrays is a key technology in the design of this Common Support Aircraft. Conformal radar allows the entire radar system to be housed internal to the airframe of the aircraft. The conformal radar components must be carefully positioned so that it covers a complete field of view, leaving no blind spots in the area of surveillance.

The Boeing EX CSA concept, as shown in Figure 8.3, uses a conformal radar system mounted atop a canard, high aft-wing design to get a 360° view of the battlefield. The conformal radar is housed within the triangle shaped assembly connected to the broad vertical tail.[8.4] The F-22 Raptor uses active electronically scanned array radar bundles developed by Northrop Grumman and Raytheon in its radome. The individual transmitter/receiver elements are the size of a brick and are mounted, as space permits, in arrays.[8.5] The same technology is being used in the development of the Joint Strike Fighter. The same concept is used, but the radar bricks are expected to be reduced to the size and shape of a ceramic wall tile, as shown in Figure 8.4[8.6]. The cost of these individual tiles is expected to drop drastically to just over $200 from an initial projection of $10,000[8.6]. This expected cost reduction will be a result of manufacturing advances and the product usage in a variety of platforms such as the Super Hornet. The lifespan of these radar modules is anticipated to be 15 to 20 years.

THIS PAGE BELONGS TO FIGURE 8.2….JOEY INBOARD PROFILE

[8.3] Fulghum, D.A., "New Radar Design Uses Unique Building Blocks," *Aviation Week and Space Technology*, 11 September 2000, 60-61.

[8.4] http://popularmechanics.com/sci/9309STMIAM.html

[8.5] Fulghum, D.A. "Cool, Small, Cheap Defines Flexible Next-Generation Radar," *Aviation Week and Space Technology*, 11 September 2000, 61-62.

[8.6] http://www.eltaisrael.co.il/site/catalog/AEWsys_2.asp

FIGURE 8.2

JOEY-AEW/ES UAV

INBOARD PROFILE

DRAWN BY: ADAM R. JONES

DATE: 4/24/01

NOTE:

STRUCTURE ELEMENTS ARE DRAWN IN BLUE FOR CLARITY.

TOTAL FUEL CAPACITY: 42 CUBIC FT. (6 TANKS) 2100.0 LBS.

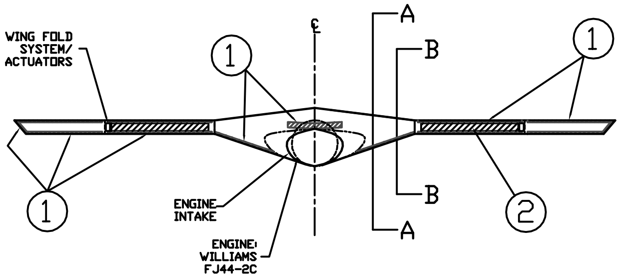
UAV IS SYMETRICALLY PROPORTIONED ABOUT ℄

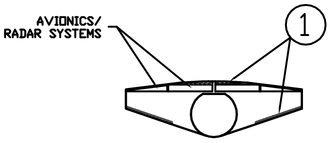
SCALE: 0 5 10

UNITS ARE IN FEET

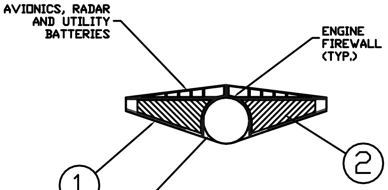
① RED HATCHED AREAS REPRESENT ALL RADAR AND/OR ELECTRONIC SURVEILLANCE.

② BLACK HATCHED AREAS DENOTE FUEL TANK LOCATIONS (6 TANKS).

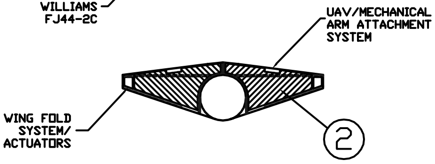




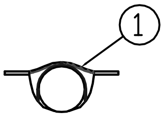
STA C-C



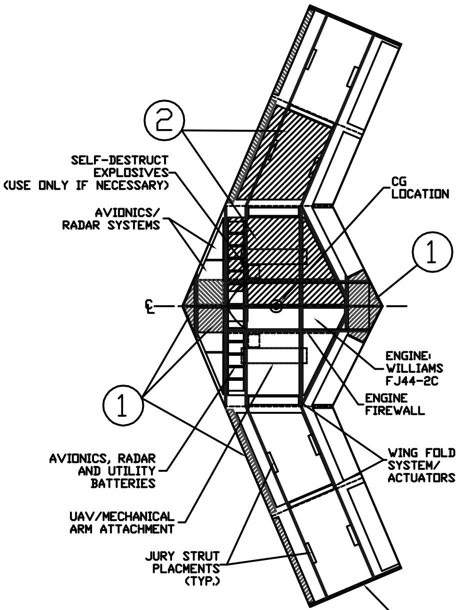
STA D-D

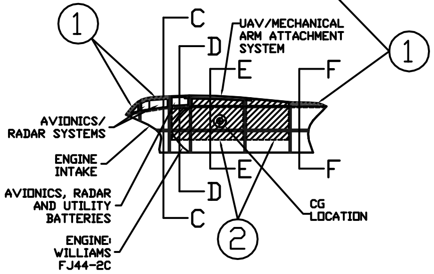


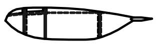
STA E-E



STA F-F

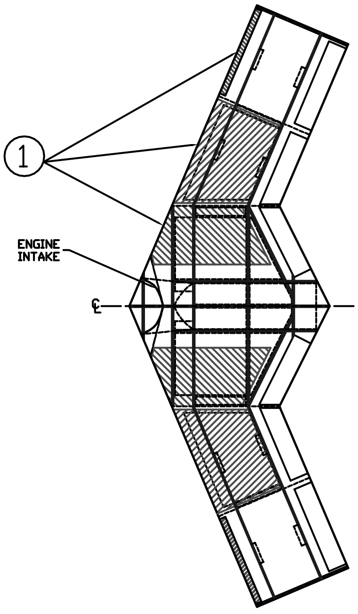






STA A-A

STA B-B



TEAM VERTIGO

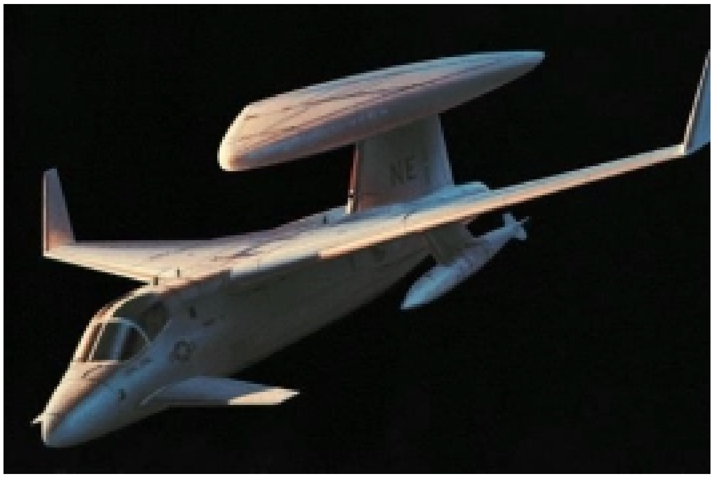


Figure 8.3 – Boeing EX CSA Concept[8.4]

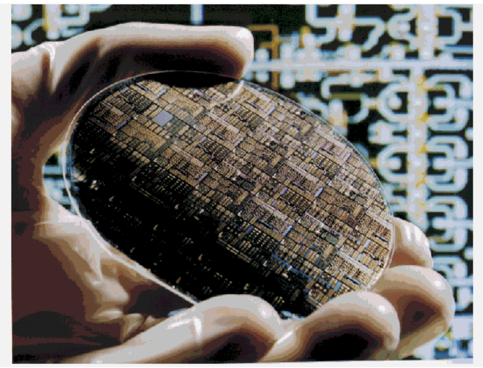


Figure 8.4 – Individual Radar Element[8.6]

The sensor range of 400 of the smaller tile arrays is predicted to be 300 nautical miles. This is quite reasonable for an airborne early warning system, since the E-2C has range of approximately 350 nautical miles. Conformal radar also allows a faster tracking time. A rotodome takes approximately 20 to 40 seconds to acquire a target, while conformal radar only takes 2 to 4 seconds.[8.7]

Electronic sensors will be included in the equipment suite to fulfill the electronic surveillance mission. These are expected to have a much better range than the current sensors.

The weight of all these sensors is much less than the weights specified in the RFP. The radar and sensor weight of 12,000 pounds, specified in the RFP, is excessive and with the substitution of conformal radar will be radically reduced. Each module of the radar only weighs several ounces; therefore, with supporting equipment, each full array would weigh approximately one pound. The radar weight is expected to be approximately 400 pounds. The weight would be doubled for the added weight of electronic signals surveillance equipment. Signals processing

---

[8.7] http://www.eltaisrael.co.il/site/catalog/AEWsys_2.asp equipment would be an additional 1,000 pounds. This results in approximately 2,000 pounds for a radar/signals package.[8.8] This weight reduction allows the possibility that the airborne early warning and electronics surveillance missions could be combined. This allows maximum use of time, fuel, and money to get as much information from a single mission as possible.

The use of conformal radar is definitely a viable technology for the initial operational capability of the Common Support Aircraft. This technology is already in production. Cost of the units will be reduced due to the variety of platforms it is already being designed for in the next 5 to 10 years. Electronic sensor weight has dropped in cost and weight due to advancements in manufacturing and processing speed. The F-22 Raptor will use only the equivalent of Pentium class processors in its systems. Given that current commercial technology is at 1.5 gigahertz system quality will be greatly increased.

8.3 Cockpit Systems

The Wombat's cockpit is based upon that of the Airbus A-340.[8.9], which features hands on throttle and stick (HOTAS), as shown in Figure 8.5. In the extreme event of an avionics failure, back-up buttons and controls are placed strategically throughout the cockpit, primarily on the main instrument panel and center pedestal, Figures 8.6 and 8.7 respectively. The main instrument panel holds six display screens: the primary flight display, navigational display, engine and warning display, GPS / INS navigation, system display, and radar / UAV / fuel probe display.

The latter display is specific to this aircraft, and changes automatically between the three modes during flight, or manually by a push button. The radar display mode is on by default and during the Joey's flight. During the Joey's deployment or retrieval, a camera mounted underneath the aircraft shows the Joey's position on the display, and may alert the pilot or co-pilot of any potential problems. During fueling or refueling, the view is switched to another small camera to reassure the pilot of correct positioning and operation.

A HOTAS system is used with the sidesticks positioned on the left side of the pilot and right side of the co-pilot. The sidesticks are modeled after those in the U.S. Air Force F-16.[8.10] The mounted controls allow the pilot and co-pilot accessibility to multiple controls, which are of key importance to specific flight modes.

The cockpit design allows optimum visibility for the pilot and co-pilot. The pilot and co-pilot have a view of 15˚ over the console and nose of the aircraft, and a 114˚ peripheral view. The pilot has a view over the left side of 27˚, equal to the co-pilot's view over the right side.

[8.8] Fulghum, D.A. "New Radar Design Uses Unique Building Blocks," *Aviation Week and Space Technology*, 11 September 2000, 60-61.

[8.9] http://www.bird.ch/nilsalegren/a340/cockpit/flightdeck.html

[8.10] http://www.8ung.at/multipit/hotas/hotas.htm

[8.11] http://www.migman.com/ref/nf/ModAirComb2.htm

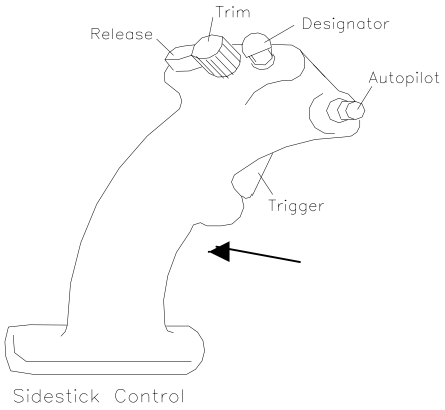


Figure 8.5 – HOTAS Sidestick Control[8.11]

MAIN PANEL FIGURE 8.6

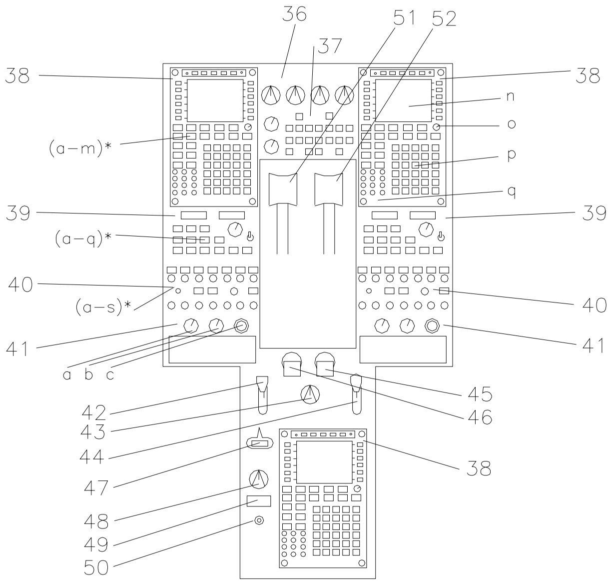


Figure 8.7 – Center Pedestal

*Items listed below as seen in figure from top left to bottom right.

36. Switching
37. ECAM (Electronic Centralized Aircraft Monitoring)
38. MDCU (Multifunction Control and Display Unit)
    a. DIR
    b. PROG
    c. PERF
    d. INIT
    e. DATA
    f. F-PLN
    g. RAD NAV
    h. FUEL PRED
    i. SEC F-PLN
    j. Blank Programmable Button
    k. MCDU MENU
    l. AIR PORT
    m. Blank Programmable Button
    n. Display Screen
    o. Brightness
    p. Alphabetical Keys
    q. Numerical Keys
39. Radio Management Panel
    a. ACTIVE
    b. STBY/CRS
    c. Radio Communication Selection Keys
    d. VHF 1
    e. VHF 2
    f. VHF 3
    g. HF 1
    h. SEL Light
    i. HF 2
    j. AM
    k. On/Off Switch
    l. NAV Push Button
    m. VOR (Radio Keys)
    n. ILS (Radio Keys)
    o. MLS (Radio Keys)
    p. ADF (Radio Keys)
    q. BFO (Radio Keys)
40. Audio Control Panel
    a. VHF 1
    b. VHF 2
    c. VHF 3
    d. HF 1
    e. HF 2
    f. INT
    g. CAB
    h. PA Volume Control
    i. PA Push Button
    j. INT RAD Switch
    k. On Voice
    l. Reset
    m. VOR 1
    n. VOR 2
    o. MKR
    p. ILS
    q. MLS
    r. ADF 1
    s. ADF 2
41. Cockpit Lighting
    a. Flood LT or RT Main PNL Knob
    b. INTEG LT or RT Knob
    c. Door Unlock
42. Speedbrake
43. Engine Start
44. Flaps
45. ENG 2
46. ENG 1
47. Parking Brake
48. Rudd Trim Selector
49. Rudd Trim Direction Window
50. Reset Push Button
51. ENG 1 Throttle
52. ENG 2 Throttle

8.4 Landing Gear

The Wombat's main landing gear, Figure 8.8, has a cracked link located below the trailing oleo system and it retracts directly aft. It is based upon the 1966 British patent number 1,116,464.[8.12] A beam and shock absorber are pivoted at two points fixed to the aft wing spar attach bulkhead of the aircraft, connected with a link to retract the landing gear. Upon retraction, the main landing gear is stored in side fuselage pods.

The main landing gear extends 15˚ aft of vertical, measured from the beam, and has a turnover angle of 54˚. The angle off vertical from the main wheel deck contact point to the center of gravity is 14˚, and the tip back angle is 18˚.[8.13]

The nose gear, Figure 8.9, is modified from the F-18 incorporating shrink technology to reduce development and logistical costs. The nose tires measure 22" x 5.5", support a load of 21,443 pounds, and have a footprint area of 94.9 square inches.

The two main tires are Type VII, nominally measuring 36" x 11" (actually manufactured as 35.1" x 11.5") by Goodyear, and have previously been used on U.S. Naval aircraft.[8.14] The wheel diameter is 16 inches. The flat tire radius is 11 inches, and rolling radius is 14.75 inches. The tire has ribbed tread, a ply rating of 24, and an internal pressure of 235 psi. Each tire weighs 72.9 pounds, but supports a load of 26,500 pounds. The main tires carry a load of 25,520 pounds each. The loads on each tire give the main wheels a footprint area of 108.6 square inches.

The main landing gear has a 24-inch stroke to meet the carrier-based aircraft sink rate requirement of 24 ft/s. The nose gear stroke is 18.5 inches.

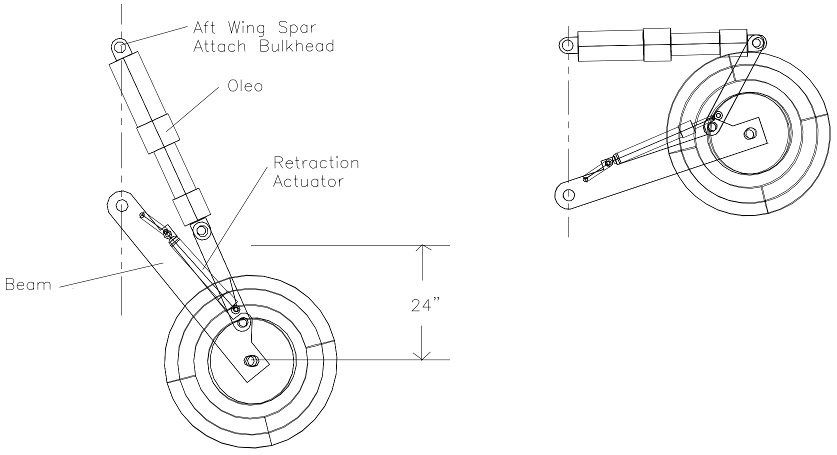


Figure 8.8 – Main Landing Gear Extended and Retracted Geometry

---

[8.12] *Aircraft Undercarriages*, Electro-hydraulics Ltd., 19 Oct. 1966, No. 46552/65, Heading B7G.
[8.13] Kirschbaum, N. and Mason, W.H., *Aircraft Design Handbook,* VPI Aircraft Design Series, 1993-94.
[8.14] http://www.goodyear.com/aircraft/img/db_airdatabook.pdf

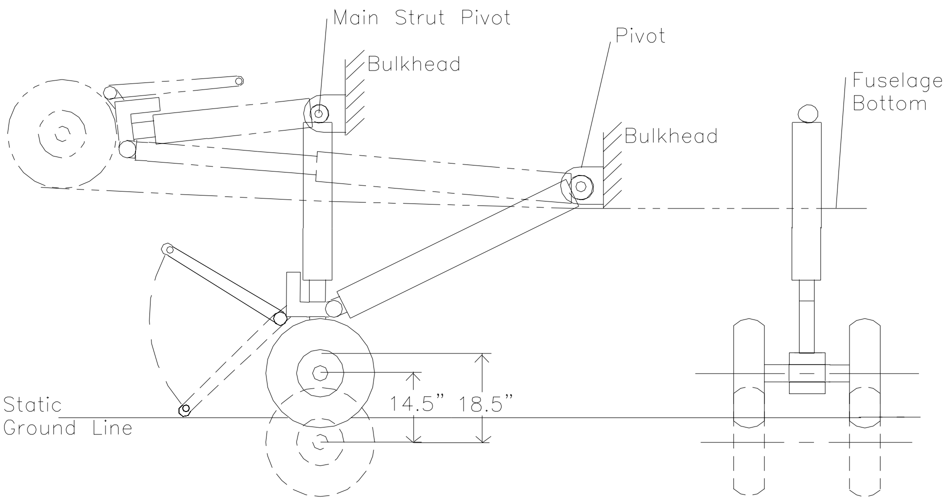


Figure 8.9 – Wombat Nose Gear, modified from F-18

8.5 Weapons Systems

The AIAA RFP states that the CSA will use advanced weapons since the aircraft's initial operation date is set well into the future. The ASW/ASUW variant will perform the mission that carries and deploys weapons and sonobuoys. Anti-submarine and surface warfare missions call for the latest advancements in torpedo systems and ASMs. The best propulsion system for a minimized missile weight is the parameter that drives the selection process of the missile system.

Submarine warfare requires an advanced torpedo. Balancing the appropriate proportions of warhead tonnage and overall weight is crucial to air-dropped weaponry. Currently the MK-50 ALWT, as shown in Figure 8.10, is the best aircraft carried torpedo in the U.S. Navy's inventory.[8.15]

Figure 8.10 – Mk-50/54 [8.15]

The Navy is currently developing a Lightweight Hybrid Torpedo (LHT) designated the MK-54. This torpedo combines the advanced search and homing capability of the MK-50 with the propulsion system of the earlier MK-46. This will further improve the Navy torpedo inventory's performance in shallow water. The MK-54 is expected to be available in 2003, with improvements in target acquisition and weapons placement accuracy.[8.16] By

---

[8.15] http://www.fas.org/man/dod-101/sys/ship/weaps/mk-50.htm
[8.16] http://www.fas.org/man/dod-101/sys/ship/weaps/mk-54.htm

time of the Wombat's projected initial operation date, the MK-54 should be thoroughly tested and battle-ready; therefore, this LHT has been chosen as the torpedo of choice aboard the ASW/ASUW concept variant.

The current missile system used aboard the S-3B Viking to accomplish the ASW/ASUW mission is a combination of AGM and ASM's: the AGM-84 Harpoon, Figure 8.11, and the AGM-65 Maverick. The Harpoon is an all-weather, over-the-horizon, anti-ship missile originally produced by McDonnell Douglas, now Boeing. The missile is capable of launch from submarines, surface ships, and aircraft such as the S-3B, A-6 or F/A-18.

Figure 8.11 – AGM-84 Harpoon[8.17]

Continuous improvements have been made to the Harpoon since its introduction during the early 1970's. These upgrades have maintained the Harpoon as the primary anti-ship missile in the Navy's arsenal. The Harpoon Block II upgrade program has almost reached completion, which will enhance the current version of the Harpoon, the AGM-84D. Harpoon Block II will provide more accurate long-range guidance system by incorporating an integrated Global Positioning System/Inertial Navigation System (GPS/INS). This will allow for easier discrimination between targets and nearby land and shorelines by using uploaded GPS information. Initial engineering and manufacturing development of Harpoon Block II began in 1998, with a forecasted initial operational capability in 2001. With the affordability and capability of this advanced weapon, it will be incorporated into the design of the ASW/ASUW Wombat variant.[8.17] The four wing pylons mounted on the inboard wing panels can accommodate up to 2000 pounds of stores. This can include overloads of the above weapons or mines, MK80 bombs, the newly developed joint strategic standoff missiles, ECM pods, or 300 gallon auxiliary fuel tanks. These pylon loads broaden the operational versatility of the wombat.

8.6 Joey Launch and Retrieval System

8.6.1 Concept Description

Early dirigibles, such as the U.S.S Akron (ZRS-4) and U.S.S. Macon (ZRS-5), which launched and recovered Curtiss "Sparrowhawk" biplanes in the 1930's[8.18] , such as that depicted in Figure 8.12, acted as far

---

[8.17] http://www.fas.org/man/dod-101/sys/smart/agm-84.htm
[8.18] http://www.ciderpresspottery.com/ZLA/greatzeps/american/Akron_Macon.html

ranging scouts and inspired the idea for a mid-air retrieval system to capture and stow a UAV. Although the early capture devices were pilot-operated and imprecise, technology has advanced to the point that a fully automated system is now feasible for accurately accomplishing this same task under today's demanding military flight conditions.

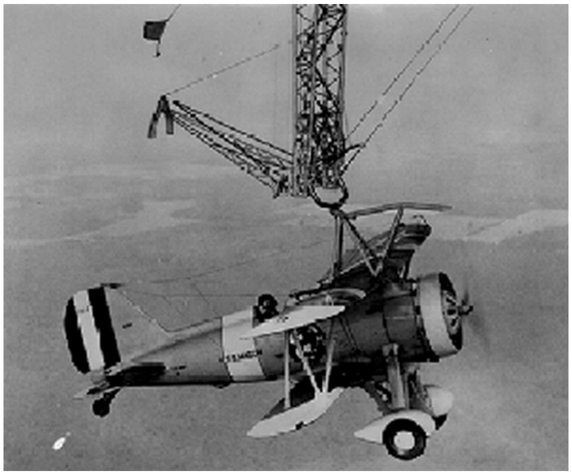


Figure 8.12 – U.S.S. Macon (ZRS-5) capturing F9C-2 Curtiss "Sparrowhawk"[8.18][8.19]

The Wombat carries two Joeys for the ES/AEW missions. The aft Joey is held in place resting on a restraining rack behind the weapon bay door. The forward Joey is secured to the launching arms throughout the flight until readied for deployment.

The launch and retrieval system consists of two pairs of scissors-shaped arms that hold two modified 30 inch bomb racks, joined by a large rotating screw that is threaded in both directions; the fore section threaded clockwise, and the aft section threaded counter-clockwise, as seen in Figure 8.13. By oppositely threading the screw, the arms are able to move together and apart by turning the screw in one direction. This eliminates the need for a separate system for the front and rear sections of the arm, and allows the screw to be moved along the upper bulkhead more readily. The screw revolves about an AM-350 structural stainless steel shaft that runs the length of the cargo bay, and acts as a second track for screw to be translated on, although the overhead bulkhead sustains most of the system weight. This pivot shaft serves two purposes aside from being a simple axle: 1) the shaft prevents the system from swaying under side forces incurred in flight, and 2) the shaft helps disperse some of the stresses encountered to the bulkheads.

[8.19] http://www.aero-web.org/database/aircraft/getimage.htm?id=307

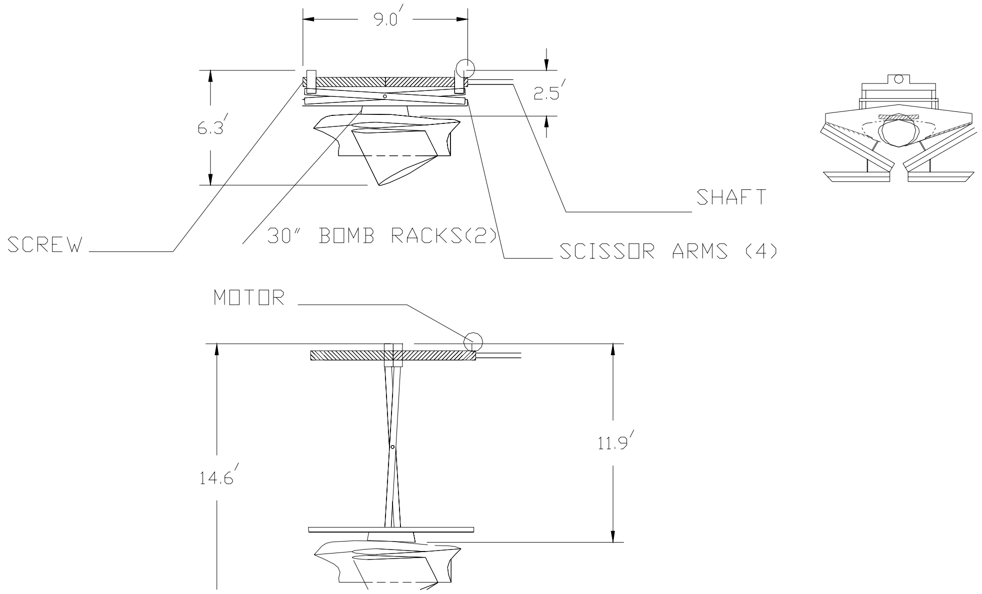


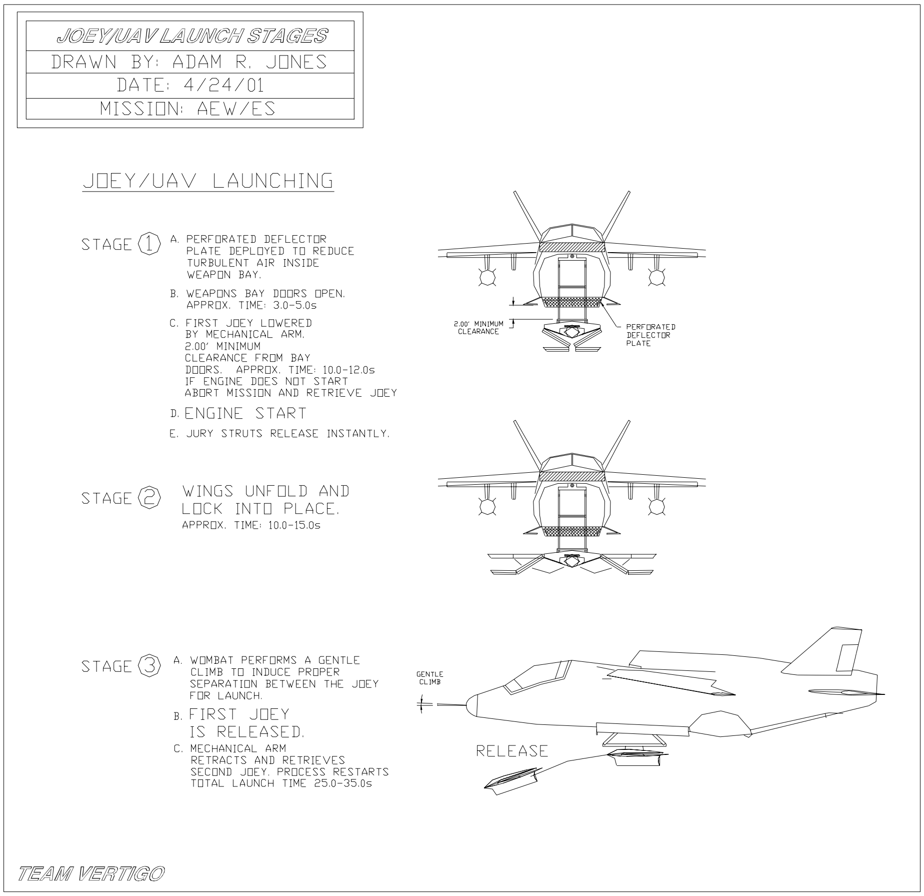
Figure 8.13- Launch and Retrieval System

A twin set of Aluminum 2024-T4 arms, each capable of bearing 34,000 pounds/in^2, was chosen because two sets of arms increases stability during operation and flight. Also, two pairs allow smaller individual arms to be used, saving weight and costs since high strength alloys are not needed. Under the 3.5-g conditions specified, each 2 x 2 inch arm will bear approximately 26,845 pounds/in^2 with a Joey attached in the higher stress, retracted position. The range of motion of the arms is between 3.5º and 86.5º from the horizontal. The two bomb racks attached to the arms were chosen because they provide a method of attachment that is proven secure under high stresses.

The Joey launch and recovery system can be easily removed onboard a carrier, allowing the aircraft to be changed from the ES/AEW platform to the ASW/ASUW or a sea-based COD platform by sliding in a floor, in a matter of hours, eliminating the need for other aircraft to accomplish these tasks. The pivot rod inside the screw is removed first through the rear cargo door of the aircraft. Next the arms are removed from their positions on the screw, and the screw is taken out through the weapon bay. Finally, the motors and sliding supports are removed and the new ASW/ASUW or COD configuration is installed. The ease of removal will also benefit maintenance procedures, allowing easy access to the system, while the aircraft is free to carry out other missions.

8.6.2 Joey Launch Procedure

The forward Joey, attached to the arms, is stored in position for release. The operator opens the weapon bay doors, drops a deflector plateand starts the forward motor to drive the screw. The Joey is lowered 30 inches or greater below the aircraft, clearing the weapon bay doors, where the Joey's wings are then extended, as seen in Figure 8.14. The pilot of the Wombat provides a slight positive angle of attack as the Joey is deployed. Upon release, the arm is retracted and a separate drive structure moves the arm rearward to pick up the aft Joey. An aft motor attached to the rear bulkhead then lifts the second Joey into position. The drive structure then returns the arm with the Joey to the forward position, allowing the forward motor to resume control of the screw. The launch process is then repeated. Two separate motors are employed in order to minimize the necessary moving parts on the system. Further, with no motor attached to the screw, no undesirable vertical motion will occur during the transition between the fore and aft positions with a simple ratchet system, disengaged by the motors, to prevent slipping. Figure 8.14 shows the launch process graphically.



JOEY/UAV LAUNCH STAGES
DRAWN BY: ADAM R. JONES
DATE: 4/24/01
MISSION: AEW/ES

JOEY/UAV LAUNCHING

STAGE ①
A. PERFORATED DEFLECTOR PLATE DEPLOYED TO REDUCE TURBULENT AIR INSIDE WEAPON BAY.
B. WEAPONS BAY DOORS OPEN. APPROX. TIME: 3.0-5.0s
C. FIRST JOEY LOWERED BY MECHANICAL ARM. 2.00' MINIMUM CLEARANCE FROM BAY DOORS. APPROX. TIME: 10.0-12.0s IF ENGINE DOES NOT START ABORT MISSION AND RETRIEVE JOEY
D. ENGINE START
E. JURY STRUTS RELEASE INSTANTLY.

STAGE ②
WINGS UNFOLD AND LOCK INTO PLACE.
APPROX. TIME: 10.0-15.0s

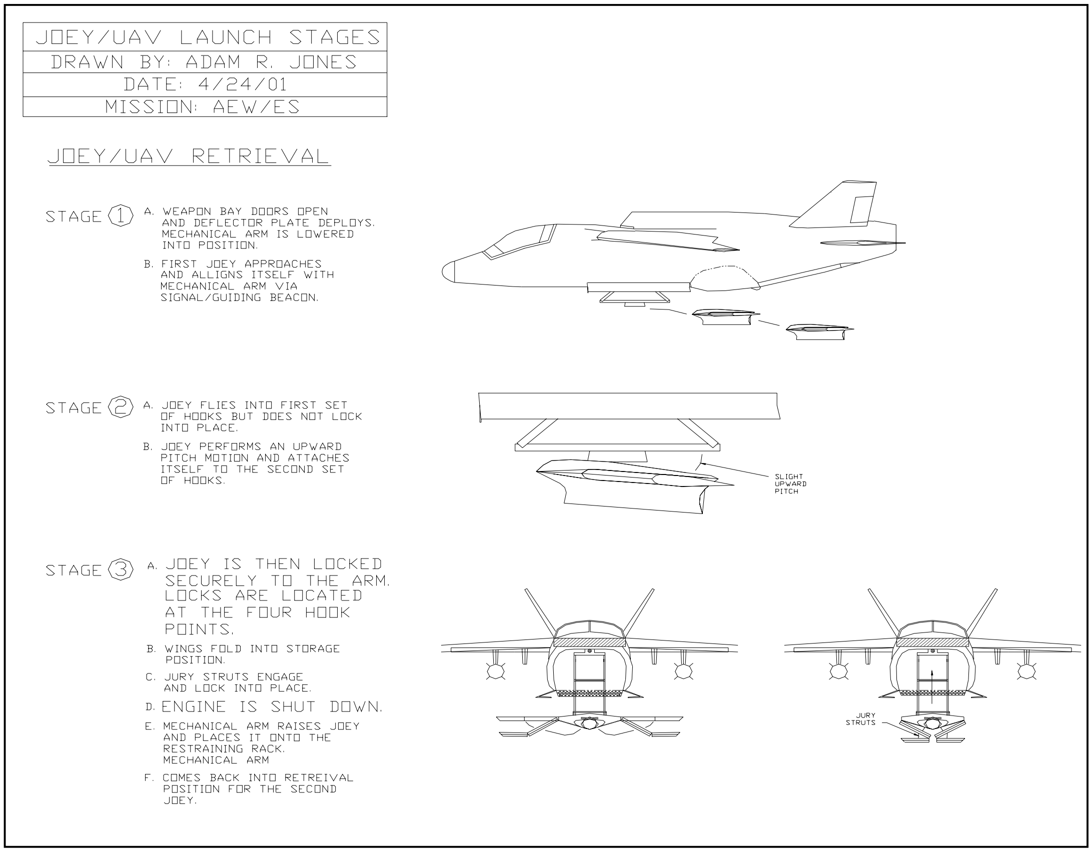
STAGE ③
A. WOMBAT PERFORMS A GENTLE CLIMB TO INDUCE PROPER SEPARATION BETWEEN THE JOEY FOR LAUNCH.
B. FIRST JOEY IS RELEASED.
C. MECHANICAL ARM RETRACTS AND RETRIEVES SECOND JOEY. PROCESS RESTARTS TOTAL LAUNCH TIME 25.0-35.0s

Figure 8.14- Joey Launch Sequence

8.6.3 Joey Recovery System

The first Joey is guided into position beneath the mothership by means of an automatic system first developed for mid-air refueling Air Force UCAV's[8.20]. This system can be aided by an operator onboard the mothership by means of a video camera on the recovery arm. The arm is lowered into the fully deployed position;

the forward arrest rod is raised on the Joey, and the automated system takes control of the recovery. When the forward arrest rod on the Joey is in contact with both racks, a powered rack locking mechanism is employed to latch it in place and then the rods are locked in place. After the fore section is secure, the Joey raises the rear arrest bar and pitches, raising it into position. When both bars are secure, the wings on the Joey are folded and secured below the UAV. The Arm is retracted into the fuselage and the Joey is secured into the aft storage rack. The process is repeated for the second Joey, which is stored on the arm until off-loaded onboard the carrier. The Joey retrieval process is shown graphically in Figure 8.15.



JOEY/UAV LAUNCH STAGES
DRAWN BY: ADAM R. JONES
DATE: 4/24/01
MISSION: AEW/ES

JOEY/UAV RETRIEVAL

STAGE ①
A. WEAPON BAY DOORS OPEN AND DEFLECTOR PLATE DEPLOYS. MECHANICAL ARM IS LOWERED INTO POSITION.
B. FIRST JOEY APPROACHES AND ALLIGNS ITSELF WITH MECHANICAL ARM VIA SIGNAL/GUIDING BEACON.

STAGE ②
A. JOEY FLIES INTO FIRST SET OF HOOKS BUT DOES NOT LOCK INTO PLACE.
B. JOEY PERFORMS AN UPWARD PITCH MOTION AND ATTACHES ITSELF TO THE SECOND SET OF HOOKS.

STAGE ③
A. JOEY IS THEN LOCKED SECURELY TO THE ARM. LOCKS ARE LOCATED AT THE FOUR HOOK POINTS.
B. WINGS FOLD INTO STORAGE POSITION.
C. JURY STRUTS ENGAGE AND LOCK INTO PLACE.
D. ENGINE IS SHUT DOWN.
E. MECHANICAL ARM RAISES JOEY AND PLACES IT ONTO THE RESTRAINING RACK. MECHANICAL ARM
F. COMES BACK INTO RETREIVAL POSITION FOR THE SECOND JOEY.

Figure 8.15- Joey Retrieval Sequence

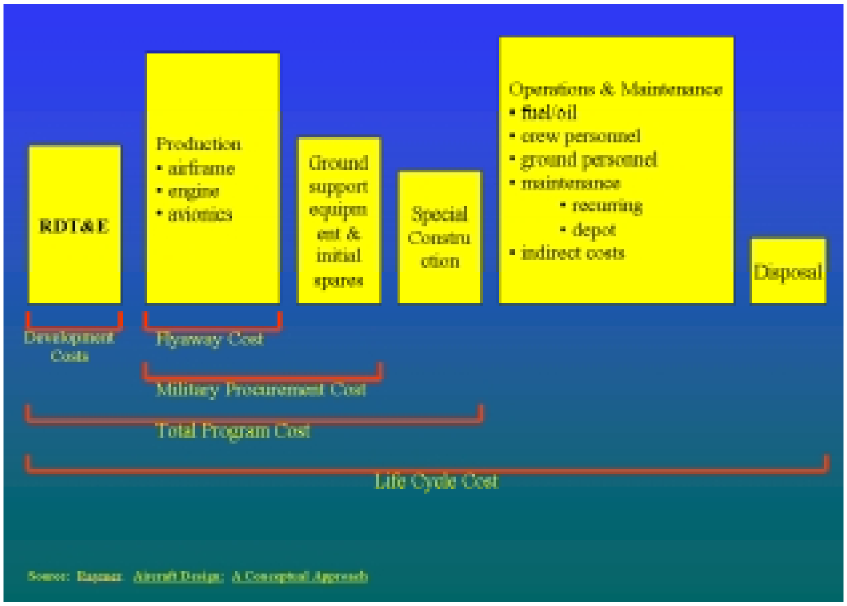
[8.20] *Flight International*, 29 January to 4 February 1997, page 12.

CHAPTER 9 – COST, MAINTENANCE AND MANUFACTURING

9.1 Cost and Maintenance Analysis

Cost is a very important, sometimes the most important, aspect of any military program. On many occasions cost overruns have led to the demise of valuable programs such as the Navy's A-12 carrier-based stealth attack aircraft. When aircraft companies compete for a contract, the customer, in this case the government, must make a decision between designs which all fit the requirements set in the RFP. Often the deciding factor is the cost of the program. Through cost comparisons and historical trend analysis, the CSA mothership/UAV design concept should achieve a low life-cycle cost due to the high commonality between the Wombat airframes and the total system survivability and maintainability aspects.

More often the military is looking not only at the initial procurement or fly-away cost of an aircraft, but at the entire life cycle cost. Figure 9.1 shows the factors that can be a part of the life-cycle costs. The blocks are sized to be approximately proportional to the actual cost of each factor. It can be readily seen that a large portion of the total cost occurs after the aircraft is initially delivered to the customer.



Source: Raymer. Aircraft Design: A Conceptual Approach

Figure 9.1 – Elements of Life-Cycle Cost

The mothership/UAV configuration allows maintenance to be performed on only portions of the total system while the aircraft can remain mission capable, dramatically increasing the time that the system is in mission readiness. For example, if there is a problem with a system on a Joey, that particular UAV can be swapped out for maintenance, and replaced by another, leaving the system fully capable. Or if there is a problem with the Wombat, the Joeys may be removed and inserted into another Wombat, again providing mission readiness with little to no significant downtime. Any time an aircraft is down for maintenance and unable to perform its mission means is time that the Navy is essentially paying for nothing. If the system can be kept operational nearly 100% of the time than the cost per operational hour is reduced. This highly flexible system architecture provides this operational cost reduction aspect.

During this preliminary design phase initial cost estimates were made primarily from comparisons to similar aircraft already developed. Statistical analysis of historical cost trends was also performed. The costs of the aircraft that the CSA is meant to replace are as follows:

- E-2C $51 million per A/C, operating cost of $13,000 per mission
- C-2A $39 million per A/C
- S-3B $27 million per A/C, operating cost of $9,000 per mission
- ES-3A $33 million per A/C(Source: Reference [9.1])

The E-2C's high cost is due to the radar system and related equipment. The Wombat mothership is most comparable to the C-2A in that it is essentially a transport aircraft, which does not require the radar system or advanced surveillance electronics. It does require the Joey deployment/retrieval system as well as extra crew stations for operation of the Joeys. Cost is also generally proportional to aircraft weight and the Wombat-AEW is heavier than the C-2A and E2-C. These factors, in addition to the fact that it is a new design should lead to a higher cost than the C-2A, but less than the E-2C. A cursory estimate has been made at $45 to $50 million per aircraft. The cost of the Joey can be estimated as somewhat comparable to the Air Force's Global Hawk UAV, which performs electronic surveillance missions, although the Global Hawk is larger and has a very extensive SigInt system. The proposed Joey will be smaller, but employs new expensive radar technology. An initial flyaway cost estimate of the Joey can be made at approximately $15 million.

These initial cost estimates may seem high, however the flexibility of the system justifies the cost. It may be possible to purchase fewer Wombat airframes because there are only two airframe variants, the pressurized fuselage COD version and the re-configurable fuselage ASW/ASUW,AEW, and ES version. The wing, tail surfaces, propulsion system, landing gears, arrestment hook, and cockpits are common on all variants. The latter variant allows for one airframe to be configured for three different missions, foregoing the need for three different airframes. This three-to-one reduction in necessary aircraft significantly reduces the program's procurement cost.

Another cost estimation method was used as an alternative. It is a "cost estimating relationship" (CER) based on a statistical curve fit. This particular method was developed by the RAND Corporation and is known as "DAPCA IV" (Development and Procurement Costs of Aircraft).[9.2] It is intended to provide reasonable estimates for several types of aircraft, including transports and bombers.

Curve fits based on empty weight, maximum velocity, and production quantity are used to calculate approximate values for engineering hours, tooling hours, manufacturing hours, and quality control hours. These values are then multiplied by hourly rates which include employee salaries, benefits, overhead, etc. Support, flight test, materials, engine, and avionics cost are also taken into account. The following graph (Fig. 9.2) depicts cost per aircraft based on production quantity.

[9.1] http://www.fas.org

[9.2] Raymer, D.P., *Aircraft Design: A Conceptual Approach,* AIAA, Washington D.C., 1992.

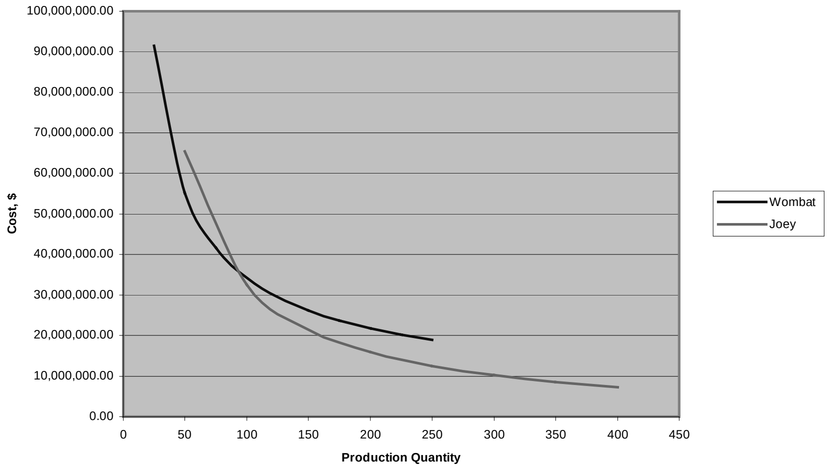


Figure 9.2 – Production Learning Curve

The majority of life-cycle costs are expended during the production phase of a program. If cost-driven manufacturing issues are identified and resolved early in the design process, there can be significant savings during production. As production quantities go up, the cost per aircraft is reduced due to refinements in the manufacturing process that were not made earlier in the program. This "learning curve" effect can clearly be seen in Figure 9.2, with sharp declines in cost with increased production quantity. The cost estimates produced by this model, for a production quantity of 250 Wombat airframes (number stated in RFP) and 400 Joey airframes (2 per ES or AEW mission plus spares) are low in comparison to the previous estimates. This is due to the high production numbers of the aircraft, which should be greater than C-2A and Global Hawk comparable aircraft. This estimation shows the benefit of having a Common Support Aircraft. Rather than building four separate types of aircraft each in low quantities and therefore high cost, one system may be built in high quantities, allowing the production learning curve to really work to the benefit of cost reduction. Table 9.1 summarizes the cost analysis.

Table 9.1 – Cost Estimation per Aircraft

	Estimation based on Comparative Aircraft Analysis (in millions)	**Estimation based on RAND DAPCA IV (in millions)**
Wombat*	$45 - $50	$19
Joey**	$15	$7.3

* Production run of 250

** Production run of 400

Using the RAND DAPCA IV estimates based on the stated production numbers the total program cost is estimated to be 7.67 billion USD. This does not include estimates of total life-cycle cost, however, the CSA again shows its merit in this category. The high commonality between aircraft reduce logistics and support issues, for example, rather than keeping spare parts and trained maintenance personnel for four different aircraft on hand, there needs to be a support infrastructure for only two aircraft, the Wombat and Joey. Operational costs are reduced due to the ability to swap out the major AEW and ES systems by swapping out Joeys when they need to be repaired, reducing downtime. The following figure shows life-cycle costs of two naval aircraft, including the E2-C.

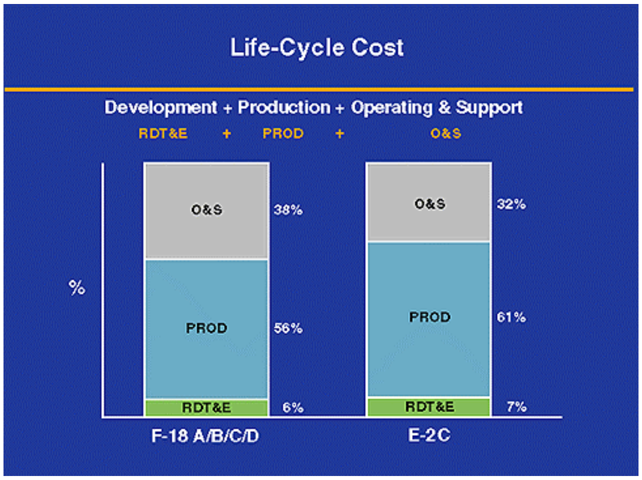


Figure 9.3 – Life-Cycle Cost Comparison[9.3]

Based on this data, it can be estimated that the operating and support costs could make up between 30% and 40% of total life-cycle cost for a naval aircraft. Using this assumption and the total program cost stated above, an estimate of the O&S costs could be made between 3.29 billion USD and 5.11 billion USD. For the reasons stated, the O&S cost should be on the low side of this estimate, and still be conservative. These values lead to a total program life-cycle cost of 10.96 billion USD.

[9.3] http://hurlbut.jhuapl.edu/CVP/costben.htm

CHAPTER 10 –CONCLUSIONS

We have proposed a viable and effective new platform to meet the needs of the 21st century Navy. The requirements set forth in the RFP and how our design fulfills them are listed in the following table for easy reference.

Table 10.1 – RFP Requirements and Design Characteristics

	Characteristic	**RFP Requirement**	**Wombat/Joey**	**Difference**
General	Payload	40 lb/ft^3	Met	None
	Structural Limit	3.5 g's	Met	None
	Aerial Refueling	All missions Give/Take	Met	None
	Crew Size	2 COD/4 Other	Met	None
	Dash Speed	> 425 knots	433 knots	Better
AEW Mission	Avionics/Sensor Weight	12,000 pounds	2000 pounds	Lighter
	Range	250 nm	Met	None
	Loiter (Endurance)	4.5 hr + 20 min	Met	None
ASW/ASUW	A-size Sonobuoys	68	68	None
	Torpedoes	2	2	None
	Anti-ship Missiles	2	2	None
	Expendables Weight	5,200 pounds	Met	None
	Avionics Weight	5,000 pounds	Met	None
	Range	245 nm	Met	None
	Loiter (Endurance)	4.5 hr + 20 min	Met	None
ES	Avionics/Sensors Weight	9,800 pounds	2000 pounds	Lighter
	Range	520 nm	Met	None
	Loiter (Endurance)	2.5 hr + 20 min	Met	None
COD	Avionics	2,000 lb	Met	None
	Payload	10,000 lb cargo, (12 lb/ft^3) or 26 passengers	Met	None
	Range	1600 nm	Met	None
	Loiter	20 min	Met	None
Carrier Suitability	Launch/Approach SEROC	200/500 ft/min	621 ft/min	Better
	Unfolded Dimensions (l x w x h)	60 x 80 x unlimited ft	59.5 x 75 x 19.21 ft	Better
	Folded Dimensions	60 x 76 x 18.5 ft	59.5 x 30.49 x 17.41 ft	Better
	Max TOGW	90,000 pounds	60,000 pounds	Better

Not only does our design solution go above and beyond the abilities stated in the RFP, but provides for unique capabilities that we believe will make the Wombat/Joey system the most attractive design. These include:

- No pilot and crew in Joey to be killed, held hostage, or otherwise compromised, as was the case in April 2001 with the EP-3/China incident.
- Fits with current Naval doctrine calling for the increased use of UAVs.
- The Joey UAV could be used by military services other than the Navy.
- The Wombat provides a manned COD and ASW/ASUW capability, assuaging anyone's fears of being a passenger in an aircraft without a pilot, and solving issues with an unmanned aircraft delivering ordnance.
- Deploying and recovering the Joey in flight resolves the issue of potentially dangerous unmanned landings on a crowded carrier deck.
- The system is very flexible in that it can be reconfigured for the different missions on ship. The two variants of the UAV, ES and AEW, or torpedoes and missiles can be swapped in and out depending on what is needed. Also, If maintenance is required on either the Wombat or Joey, it does not ground the entire system.
- The flexibility of the system leads to it being expandable and upgradeable as new technologies and new requirements emerge, e.g. ECM missions, reconnaissance, etc.
- Carrying the Joey for a portion of the flight increases its range and endurance. There is also the ability to refuel the Joey in flight, allowing for extended endurance.
- Deploying two Joeys effectively doubles the ES/AEW coverage area.
- The common Wombat airframe significantly reduces manufacturing cost.
- The lack of personnel support equipment, such as ejection seats, lowers the complexity and size of Joeys, therefore reducing cost.
- The operational cost of a Joey is lower than that of manned aircraft or satellite systems, due to reduced crew cost and no launch/manning costs, respectively.

As the armed forces adapts to a rapid reaction, high technology force the need for reliable and survivable surveillance platforms has led to an increased role for UAVs. The technologies necessary to produce capable UAVs, including small efficient jet engines and advanced guidance and control equipment, have matured to a level making UAVs very attractive With an increased public call for "casualty-free" conflicts, UAVs are quickly becoming the platform of choice for dangerous missions. The benefits of UAVs are especially felt in the early days of conflicts, when tactical surveillance is essential, but the opposing force's air defenses are still at full strength.[10.1]

Our system is an innovative yet practical and feasible approach to performing those missions desired of a Common Support Aircraft. The UAV aspect of the Wombat/Joey system makes this an attractive approach to performing the AEW and ES missions, while still maintaining the more feasible manned COD aircraft. The design meets the requirements set by the RFP, but provides advanced capabilities to make the Wombat/Joey a leading 21st century aircraft concept.

[10.1] http://www.fas.org/irp/program/collect/docs/97-0349.pdf