2000-01-5535

1998/1999 AIAA Foundation Graduate Team Aircraft Design Competition: Super STOL Carrier On-board Delivery Aircraft

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ABSTRACT

The Cardinal is a Super Short Takeoff and Landing (SSTOL) aircraft, which is designed to fulfill the desire for center-city to center-city travel by utilizing river "barges" for short takeoffs and landings to avoid construction of new runways or heliports. In addition, the Cardinal will fulfill the needs of the U.S. Navy for a Carrier On-board Delivery (COD) aircraft to replace the C-2 Greyhound. Design requirements for the Cardinal included a takeoff ground roll of 300 ft, a landing ground roll of 400 ft, cruise at 350 knots with a range of up to 1500 nm with reserves, payload of 24 passengers and baggage for a commercial version or a military version with a 10,000 lb payload, capable of carrying two GE F110 engines for the F-14D, and a spot factor requirement of 60 feet by 29 feet.

INTRODUCTION

For the past few decades, short-commute center-city to center-city travel has been a desire. This desire, however, has not yet translated into the commercial aircraft market. The complexity of this form factor, coupled with economic impact, makes this promise a challenging one to fulfill. Recent technology advances, and numerous attempts to produce an aircraft of this nature have once again brought the challenge to the forefront. In addition to the desires mentioned above, the severe lack of open space in center-city areas has created yet another design challenge. The military also presents a need for the SSTOL form factor. COD requirements must continue to be satisfied after disposal of the current fleet of such planes.

The mission requirements for a SSTOL transport aircraft were provided in the American Institute of Aeronautics and Astronautics (AIAA) Graduate Team Aircraft Design Competition Request for Proposal (RFP): SSTOL Carrier On-board Delivery (COD) Aircraft [2]. A summary of the mission requirements is provided in Table 1.

Table 1- Mission Requirements

Design Mission Profile
Warm up and taxi for 10 minutes
Take off within a ground roll of 300 ft, SL, SA+27°F
Climb at best rate of climb to best cruising altitude
Cruise at best cruise speed (≥ 350 knots) for 1500 nm
Descend to SL (no credit for range)
Land with fuel reserves within ground roll of 400 ft
Taxi to gate for 5 minutes
Special Commercial Design Requirements
Passenger Capacity: 24 passengers and baggage
Overhead stowage space shall be provided
Weight of passenger and baggage: 200 lbs
Special Military Design Requirements
Can accommodate priority cargo, passengers, or both
Must be capable of carrying two GE F110 engines
Wing folding allowed for spot factor of 60 ft x 29 ft
Maximum payload is 10,000 lbs
Arresting hooks or catapult devices not allowed
Additional Requirements and Constraints
Shall conform to all applicable FAR
Performance requirements standard day unless noted
Technology availability date is 2005

DESIGN PHILOSOPHY AND PROCEDURE

New technologies offer the opportunity for center-city to center-city travel. While many existing aircraft have incorporated some of these technologies, none of them as a whole have proven to be economically viable. To produce an economically viable design for the Cardinal, it was of primary importance to understand and avoid past mistakes in similar designs, capitalize on design elements that proved successful, and include new technologies that would further the favorable performance of the final design.

The mission requirements for the Cardinal required takeoff and landing ground rolls approaching the limits of fixed-wing aircraft. A review of past and current aircraft found two that were similar in size to that expected for the Cardinal and had similar ground roll performance capabilities. The first is the NASA Quiet Short-haul Research Aircraft (QSRA) which utilizes Upper Surface Blowing (USB) flaps to achieve spectacular short field performance for a fixed-wing aircraft. A second aircraft with similar performance is the Canadair CL-84 Tilt-wing. Tilt-wing aircraft are similar to tilt-rotors except that instead of only tilting the engine/rotor, the entire wing is rotated. The QSRA and CL-84 were prototype/research aircraft and never entered production. However, the flight test programs of these aircraft provided a significant amount of data for validating potential approaches to short takeoff and landing for the Cardinal.

The Cardinal team chose to investigate two designs: a tilt-wing aircraft and a fixed-wing aircraft with upper surface blowing (USB) flaps. A complete analysis, design, and optimization of the two approaches was conducted to develop the 'best' design for each aircraft. The design procedure for both aircraft was a spiral development process. In the spiral model, shown in Figure 1, design occurs with multiple iterations through four development phases. These four phases were: planning, risk analysis, engineering, and evaluation and maintenance. During each iteration of the spiral, the design was reviewed and corrections were made. By completing iterations early in the design process, problems were uncovered early on when they could be fixed with a minimal impact on the design schedule.

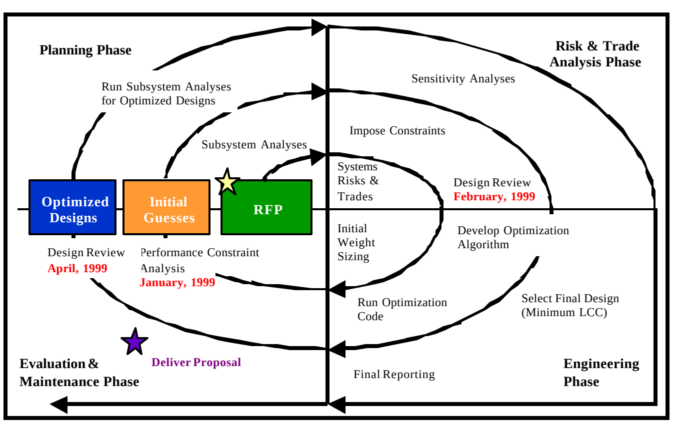

Figure 1- Spiral Development Model

TECHNOLOGY MATURITY ASSESSMENT

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years [24] - the Cardinal team chose to take advantage of this system to evaluate prospective technologies. The RFP states a technology readiness date of 2005. To comply with this restriction, the Cardinal design implements technologies currently at a TRL of Level 5 or higher. While components/technologies of this nature have not been "flight-qualified" or "flight-proven," each of these technologies is predicted to reach TRL Level 9 by 2005. By limiting the range of new technology, the Cardinal implicitly reduces the risk of its design. Figure 2 illustrates the NASA TRL Levels. Note the shaded region that indicates technology levels deemed acceptable for the Cardinal design.

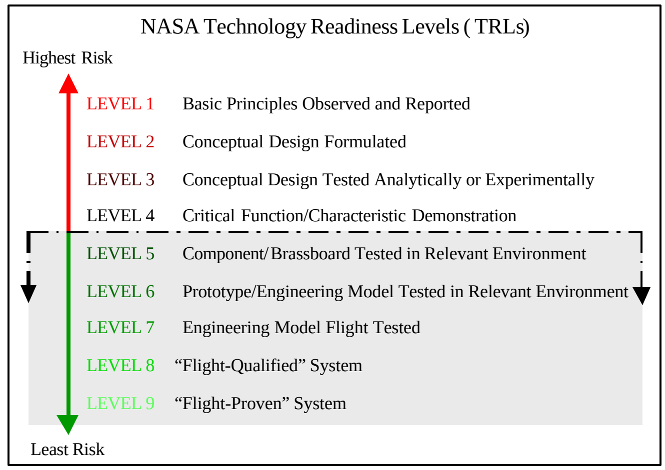

Figure 2- NASA Technology Readiness Levels

USER PREFERENCES AND SAFETY CONSIDERATIONS

This section describes the pilot and passenger preferences between SSTOL and VTOL. Passenger preferences are mainly based on noise, vibration and perceived safety, while user preferences are generally based on control authority. Safety, however, is of primary importance to the user, and thus this section also addresses the safety issues involved in VTOL and SSTOL operations for the same mission.

Reference data from flight tests was the primary source of information in the determination of pilot preferences. An evaluation of the Canadair CL-84 tilt-wing aircraft was performed to analyze pilot preferences between VTOL and STOL scenarios [4]. The scenarios covered in the evaluation included takeoff, hover (for VTOL), climb, and landing. A fixed-wing STOL scenario was also analyzed, which was mainly based on the QSRA flight test data [30,31,9]. SSTOL pilot preferences and safety issues were then inferred from the STOL data.

The fixed-wing SSTOL design was not found to pose safety issues in any flight mission. Both pilot and passenger preferences also favored the fixed-wing SSTOL design. These factors are important for the commercial design because the passenger is the customer. For the military version, the user preferences are important because the pilot is the user of the aircraft. For the military design, of primary importance is the success of the mission, which is highly dependent on the pilot operating the aircraft effectively. Noise considerations also favored the fixed-wing design due to its lower noise levels than that of the tilt-wing.

PRELIMINARY WEIGHT AND PERFORMANCE SIZING

Initial weight and performance sizing was performed to estimate the weight, wing area, and installed thrust/power for both a fixed-wing and a tilt-wing design. The weights of both the fixed-wing aircraft and the tilt-wing aircraft were estimated based on the known mission profile and regression coefficients that relate the empty weight and takeoff weight for a given type of aircraft. This requires the assumption of lift-to-drag ratios, specific fuel consumptions, and propeller efficiencies, where typical values from Reference 32 were used as a guide. Table 2 summarizes the weight sizing results

Table 2- Preliminary Weight Sizing

Weight	*Fixed-Wing*	*Tilt-Wing*
Empty Weight	25,487 lb	34,588 lb
Fuel Weight	12,504 lb	14,635 lb
Takeoff Weight	48,635 lb	59,922 lb

The required landing and takeoff distances were the only constraints considered in the initial performance constraint sizing. Typical statistical relations for takeoff and landing distances [32] do not account for SSTOL or VTOL capabilities, hence approximate models of the full equations of motion for takeoff and landing distance were used for the initial estimates [22]. Sizing for the fixed-wing aircraft was used to find ranges of the thrust-to-weight ratio and the wing-loading that met both the takeoff and landing requirements. An initial value for wing loading was chosen, and iterations on the thrust-to-weight ratio were conducted until the takeoff distance requirement was met. The wing-loading value from the takeoff distance computation was used to calculate the landing ground roll, which is approximately independent of the thrust-to-weight ratio [22]. The assumed maximum lift coefficients were based on a review of upper surface blowing (USB) data from the YC-14 [38].

The goal of the tilt-wing analysis was to find values for wing loading and power loading which satisfied both the takeoff and landing ground roll constraints. Using 'rule-of-thumb' design guidelines for tilt-wing design and NASA windtunnel test data, stable conversion profiles and takeoff/landing speeds were estimated for a tilt-wing configuration. Table 3 summarizes the design points for the Cardinal.

Table 3- Preliminary Performance Sizing

Parameter	*Fixed-Wing*	*Tilt-Wing*
Wing Loading	47 lb/ft^2	86 lb/ft^2
Thrust-to-Weight /Power Loading	0.6	5.7 lb/hp
Wing Area	1,000 ft^2	700 ft^2
Installed Thrust /Power	30,000 lb	10,500 hp

CONFIGURATION SELECTION AND COMPONENT DESIGN

Performance constraints on the aircraft as well as structural and aerodynamic considerations dominated selection of the final configuration. This section describes the design and layout for the fuselage, wing, empennage, and landing gear.

FUSELAGE DESIGN

The cockpit was laid out for a two-crewmember configuration. The seating and window layouts were arranged to meet all applicable FAR and MIL specifications on visibility and component travel for use by a wide variety of crewmember sizes. The center panel of both sides of the cockpit consists of the primary flight display, navigation display, and a full set of electronic flight instruments. A center-mounted autopilot and autothrottle panel is located atop the instrument panel. Beneath the autopilot and autothrottle are the warning display and the system display. The console between the captain and the flight officer consists of a warning display for each crewmember along with the power quadrant and the aircraft central computer for system monitoring.

The cargo hold was laid out by considering the military application cargo. Several initial layouts of the cargo were considered, but the geometric constraints on the size of the aircraft limited the size of the cargo bay and the arrangement of the cargo. The resulting layout (Figure 3) was a two-by-two arrangement of two containers forward, each side-by side, and two containers aft, also side-by-side. A 6" clearance has been provided between the cargo wall and the cargo at all locations, and ample vertical clearance has been included to allow ceiling clearances during loading and unloading.

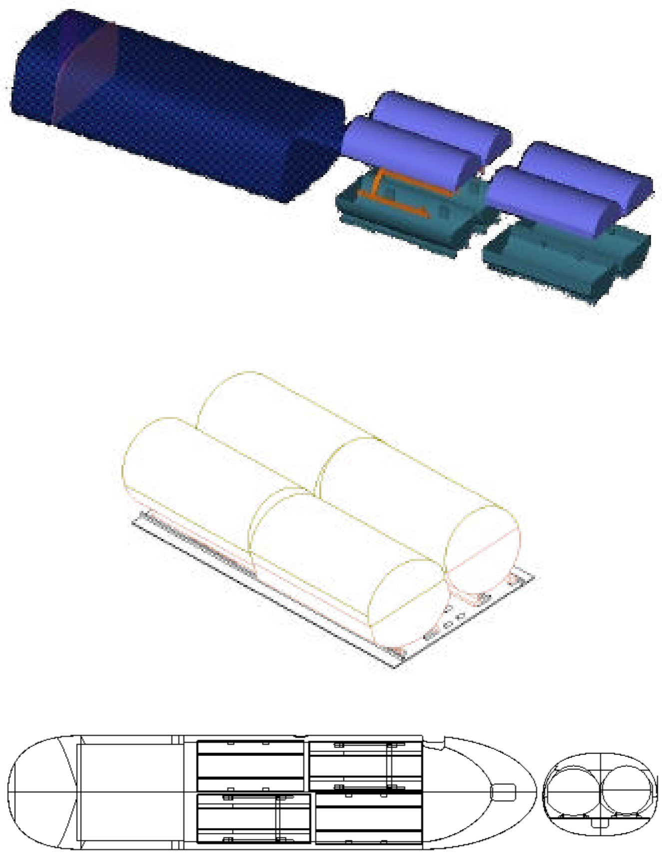

Figure 3- Cargo Layout

The passenger cabin (Figure 4) consists of accommodations for 24 passengers. The seating arrangement is single aisle, with two seats on each side of the aisle, resulting in 12 rows of seats. The seat pitch is 32 inches and the seat width is 19 inches. Windows have been installed in the fuselage for passenger comfort. The passenger cabin is closed off from the aft section of the airplane to allow for baggage and cargo storage. Overhead storage bins for carry-on luggage have been included.

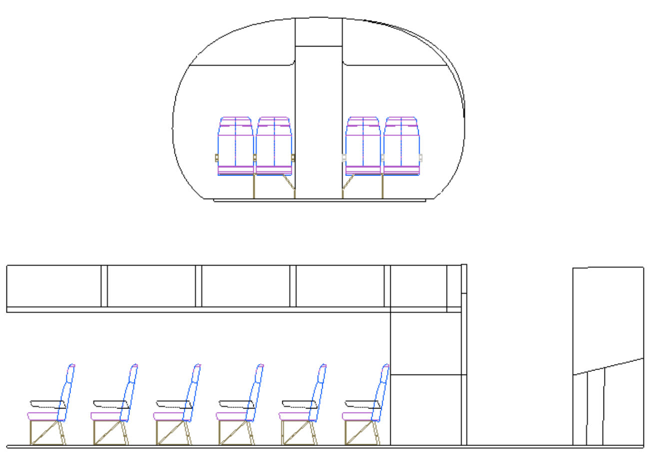

Figure 4- Passenger Cabin Layout

WING DESIGN

Wing designs for both the fixed-wing and tilt-wing configurations were severely restricted by geometric constraints - a 29 ft by 60 ft storage requirement for the military version of the aircraft. U.S. Navy geometric constraints include a desire for a maximum wingspan of 64 ft, a storage height requirement of 18.5 ft, and, if wing folding is used, a maximum height of 24.5 ft while folding [29]. The high wing design was desirable for the tilt-wing because a tilting wing would be very difficult to place in a low- or mid-configuration without interfering with the passenger cabin or cargo hold, and for the fixed-wing mainly for structural considerations for the aft fuselage and cargo door.

The fixed-wing configuration utilized both pivoting and wing folding to comply with the geometric constraints. Due to the rotation of the wing, the wing tips had to be folded upward to avoid interference with the fuselage. Using this storage method permitted the Navy's maximum desirable wingspan of 64 ft while still meeting all geometric constraints. The tilt-wing configuration also utilized wing pivoting and folding devices. Figure 5 shows the final wing pivoting and folding concept and Table 4 summarizes the final geometric parameters for the fixed-wing version.

Table 4- Wing Geometry

Wing Parameter	***Fixed-Wing***
Wing Area, S_{ref}	1150 ft^2
Span, b	64 ft
Aspect Ratio, AR	3.56
Taper Ratio, λ	0.8
Quarter Chord Sweep, $\Lambda_{c/4}$	5°
Root Chord, c_{root}	19.97 ft
Tip Chord, c_{tip}	15.97 ft
Mean Aerodynamic Chord, MAC	18.04 ft
Average thickness to chord, $(t/c)_{avg}$	14 %
Dihedral, Γ	0°
Incidence Angle, i_w	1°
Twist Angle, ε_t	-3°
Fuel Volume	17,505 lb

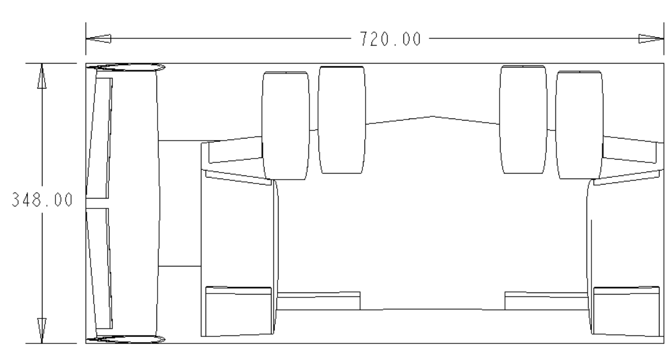

Figure 5- Wing Pivoting and Folding

HIGH LIFT AND POWERED LIFT DESIGN

There are many ways to achieve high lift coefficients using methods such as: upper surface blowing (USB), leading edge blowing, jet flaps, and circulation control wings (CCW). Leading edge blowing, jet flaps, and circulation control wings require significant amounts of bleed air from the engine which reduces propulsive efficiency and sometimes leads to the need for dedicated engines simply to provide sufficient mass flow for the high lift system. Ducts, valves, and associated controls are also required to transport and distribute the bleed air from the engines to its desired location in the leading and trailing edges.

Two different approaches to achieving low takeoff and landing speeds and the associated short takeoff and landing distances were considered for the Cardinal design: Upper Surface Blowing (USB) flaps, and a tilt-wing configuration. In this section, a review of the principles, methodology for analysis, and a risk assessment for using these technologies is presented.

By placing the engines in a way that the exhaust is directed over the upper surface of the wing, the USB system provides boundary layer control (BLC) for the aft part of the wing which is prone to separation. The flaps also deflect the engine exhaust, providing a vectored thrust component. A review of past aircraft designs utilizing upper surface blowing, such as the Boeing YC-14 [38] and the NASA Quiet, Short-Haul Research Aircraft (QSRA) [3,12] indicate that 'equivalent' lift coefficients of 8 to 12 are possible. This equivalent lift coefficient consists of three parts: the lift coefficient of the wing itself, an increase in wing lift coefficient due to 'super' circulation, and the vertical component of thrust due to the jet deflection [25].

The major difficulty in a USB design is analyzing the magnitude of lift coefficients achievable. For the Cardinal design, the high lift system was analyzed using the method presented in Ref. 25. This method uses a combination of theoretical calculations and correlation to experimental results to estimate the lift coefficient for a given angle of attack, flap deflection, and power setting. Figure 13 shows an example of a calculation for the Cardinal in the takeoff configuration. It should be noted that it is difficult to define a maximum lift coefficient, as the lift coefficient varies not only with flap deflection and angle of attack, but also with the momentum coefficient.

To validate the calculations for the blown flaps, the results were compared to data from the QSRA. Flight test data from the QSRA [9,10,30,31] were used to compare the lift coefficients achieved by the QSRA and those computed for the Cardinal. Maximum lift coefficients for the Cardinal were 4-5 in the takeoff configuration and 10-12 in the landing configuration. The lift coefficients achieved by the QSRA and Cardinal for similar flight conditions were within approximately ± 20% [30]. The calculated lift coefficients for the Cardinal seem reasonable compared to those measured for the QSRA. For preliminary design the method used is acceptable, but this is a critical technology for the Cardinal and more detailed calculations would certainly be needed before proceeding beyond preliminary design.

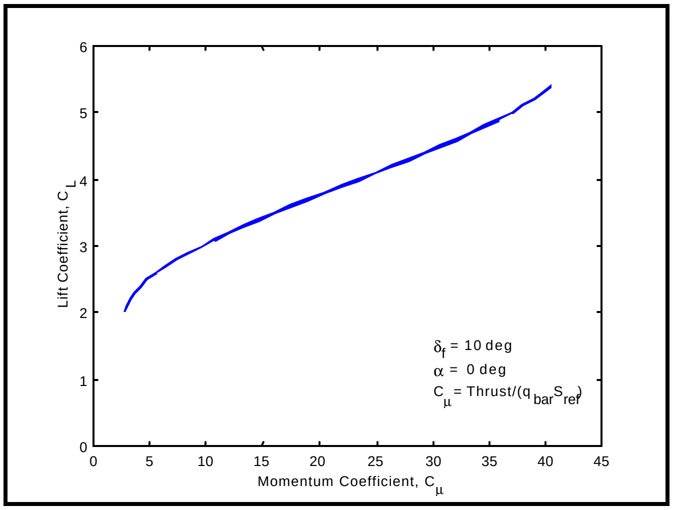

Figure 6- Sample Variation of Lift Coefficient

An alternate configuration considered for the Cardinal was a tilt-wing aircraft. The tilt-wing offers several advantages over a tilt-rotor, such as the Bell/Boeing V-22. Some of these advantages include less download [8] and better short takeoff performance [34]. While the hover characteristics of the tilt-rotor are superior to those of the tilt-wing, the mission requirements of the Cardinal do not require significant amounts of hover such as might be necessary for search and rescue. The short rather than vertical takeoff requirements of the Cardinal also pushed the design team towards a tilt-wing design.

The tilt-wing aircraft relies on a vertical component of thrust and some boundary layer control from the propeller/wing interaction to achieve its short or vertical takeoff and landing characteristics. Although no production aircraft have been built using a tilt-wing configuration, there have been several prototype aircraft built and flight-tested. Some of these include the Chance Vought XC-142A and the Canadair CL-84. In addition, there have been many windtunnel tests made on tilt-wing configurations [13,15]. Like USB, it is difficult to make a 'simple' analysis for a tilt-wing configuration. Many papers and reports have been written on this subject and offer rules of thumb and guidelines which greatly aided in the tilt-wing design analyzed for this proposal [26,34].

For the Cardinal, the method of analysis was based on the method for propeller/wing interaction described by McCormick [25]. This method considers the airflow velocities seen by the wing as a combination of the velocity due to flight and that produced by the propeller. Aerodynamic calculations can then be conducted in the usual fashion, but using the local velocity and angle of attack of the wing.

Due to the unconventional nature of this analysis method, it was desirable to validate it with experimental or flight test results. Data from windtunnel tests [13,15] and flight tests [5,6,27,36] were compared to the computational results for the Cardinal. In general, the results showed all of the same trends. One discrepancy, however, was that the maximum allowable wing angle occurring before stall was consistently underpredicted in the computational results for the Cardinal.

The use of new and emerging technology to achieve better performance and lower costs must be weighed against the risks of using unproven technologies. Selection of a high- or powered-lift methodology is the highest risk aspect of the Cardinal design. Although there have been a significant number of tests of USB and tilt-wings, no production aircraft have implemented either of these technologies. Based on the Technology Readiness Levels (TRLs) both USB and the tilt-wing configuration are a Level 7 technology. This means that an engineering model has been flight tested, but has not been "flight-qualified" or "flight-proven" in everyday operations.

EMPENNAGE

Preliminary tail sizes were initially estimated using the volume coefficient method [20]. The volume coefficient sizing method relies on the fact that similar aircraft tend to have similar volume coefficients. However, the unconventional design of the Cardinal (large wing chords and relatively low wingspan) made it difficult to obtain reasonable results from this method. Instead of volume coefficients, the horizontal tail sizing used a longitudinal X-plot or scissors plot [20]. An X-plot shows how the static margin varies with the position and size of the horizontal tail.

The U.S. Navy carrier height requirement coupled with the required upsweep angle required for takeoff rotation constrained the span of the vertical tail. The vertical tail area was sized to meet One Engine Inoperative (OEI) minimum control speed requirements. A balancing moment due to the asymmetric thrust and the windmilling drag of the inoperative engine must be generated at 1.2 times the landing stall speed without stalling the vertical tail. Due to the large vertical tail reference area and the height constraint, twin vertical tails placed as end plates on the horizontal tail were used. Table 5 summarizes the relevant horizontal and vertical tail geometry parameters.

Table 5- Empennage Geometry

Parameter	***H. Tail***	***V. Tail***
Reference Area, S_{ref}	190 ft^2	208 ft^2
Span, b	29 ft	14 ft
Aspect Ratio, AR	4.43	1.88
Taper Ratio, λ	0.8	0.8
Sweep, $\Lambda_{c/4}$	5°	5°
Root Chord, c_{root}	7.28 ft	8.25 ft
Tip Chord, c_{tip}	5.82 ft	6.60 ft
Mean Aero. Chord, MAC	6.58 ft	7.46 ft
Avg thickness to chord, $(t/c)_{avg}$	12 %	10 %
Dihedral, Γ	0°	N/A
Volume Coefficient, $V_{h/v}$	0.2068	0.0617

LANDING GEAR

To allow the aircraft to take off and land without problems, the longitudinal location of the main landing gear is driven by aerodynamic requirements. The Cardinal's upsweep clearance angle was designed to comply with the pitch angle necessary for takeoff and landing. Furthermore, the tip-over angle [11] between the aft limit for the center of gravity and the bottom of the main tires should be greater than the upsweep clearance angle to prevent the center of gravity of the aircraft from traveling aft of the main gear pivot point during takeoff rotation. The Cardinal design meets this criteria with a minimum longitudinal tip-over angle of 21°.

The nose gear must carry enough loads for the aircraft to be able to steer while maneuvering on the ground. Therefore, a load percentage for the nose gear of 8%-20% of the airplane weight is required, with values closer to 8% preferred [11]. The nose gear load percentage for the Cardinal was 9% for the military version and 15% for the commercial version. The landing gear could not interfere with the cargo space; therefore, it was decided to place the gear in blister fairings on the sides of the fuselage. Furthermore, the turnover angle should be less than 54° for aircraft-carrier-based vehicles, and less than 63° for land-based vehicles [11]. The Cardinal achieved this clearance with the implementation of kneeling landing gear.

PROPULSION SELECTION & INSTALLATION

Propulsion systems were selected for two configurations: the tilt-wing with four turboprop engines, and the fixed-wing with four turbofan engines. Because complete performance information is often proprietary and not publicly available, there were a limited number of engines for which data was available.

For the tilt-wing design, the engine described in "1989 AIAA/United Technologies-Pratt & Whitney Engine and Propeller Data Package" [1] was selected. The engine was chosen mainly because its specifications and available data met the design specifications and were publicly available. Four turboprop engines geared to two propellers comprise the propulsion installation for the tilt-wing. This configuration eliminates the need for cross-shafting between the engines for engine out control in a two-engine configuration.

The geometric constraints limit the span of the wing so it must be folded or pivoted. Folding alone did not work for the four-engine configuration because the engines could not fit on the unfolded section of the wing. Instead, the more costly and heavier pivoting wing and wing folding were necessary for the four-engine configuration. The pivoting wing allows the wing span to be nearly the fuselage length, and thus there was enough space to arrange all four engines.

For the fixed-wing design, either two or four turbofans were considered. Two-engine configurations have the advantage of requiring fewer maintenance hours and slightly higher efficiency compared to the smaller engines that would be used in a four-engine configuration. However, the FAR minimum climb gradients for engine out would require severe oversizing of the engines for the Cardinal. Also, the USB flaps depend on engine flow and cross-shafting of the engines (as done in the YC-14 [38]) would be necessary if there was only a single engine on each wing. This would make the engines 'custom' built and relatively expensive.

The ALF502 turbofan engine was selected as representative of a high bypass-ratio turbofan engine for the four-engine fixed-wing configuration. The ALF502 was chosen primarily because it has similar thrust and complete performance data was available [23]. The data allowed for a complete analysis and scaling of the engine thrust and specific fuel consumption data. The engines for the fixed-wing design were placed far forward of the wing (Figure 7) for upper surface blowing over the wing.

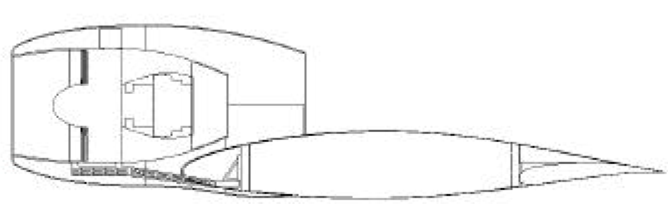

Figure 7- Turbofan Engine Installation

Engine performance data is provided by the manufacturer for a range of altitudes and speeds or Mach numbers. The data is normally 'uninstalled' data and must be corrected for losses from installing them on the aircraft. To calculate the installation losses, a turboprop performance method and a turbofan performance method were used [32]. Because data for only one engine was available, a scaling methodology was applied to the baseline engine data [20]. An engine scaling factor, ESF, was used to scale the baseline engine (i.e. dimensions, thrust, fuel flow) to create new performance data for a scaled engine with the same technology level.

In addition to scaling at constant technology level, a technology scaling factor was applied. The RFP allows for a technology availability date of 2005. The maximum cruise specific fuel consumption (sfc) of the baseline engine was compared to the maximum efficiency of modern high bypass engines at transonic cruise which have maximum efficiencies between 34% - 38% [20]. The baseline engine data was scaled to account for the actual sfc of the baseline engine and the predicted sfc of engines predicted to be available in 2005. Figure 8 contains the installed cruise carpet plot for the turbofan engines used on the final version of the Cardinal.

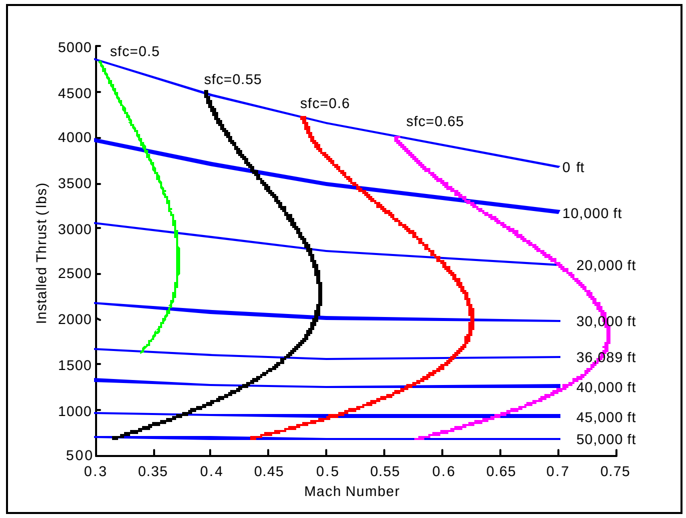

Figure 8- Maximum Cruise Carpet Plot for Turbofans

STRUCTURAL LAYOUT

The structural layout was based on structural configurations of existing cargo aircraft such as the C-130 [32], and consists of standard frames, longerons, ribs, and spars along with the specialized structural components for lifting surface integration and cargo floors and doors. Efforts to make use of advanced materials where useful and cost effective have been made. Systems design was based on standard systems layout of passenger and military aircraft with attention to applicable FAR and MIL specifications [32].

The structural arrangement of the Cardinal was based on typical structural spacing and example structural arrangements presented in Reference 32. The Cardinal wing structure is a conventional rib and spar arrangement. The wing spars are located at 25% and 70% of chord which allows the 30% chord flaps and ailerons to be attached directly to the rear spar. For the empennage surfaces, spars are located at 25% and 75% chord with

25% chord rudders and elevators attached to the rear spars. Rib spacing for the wing and empennage surfaces is 24 inches. The fuselage frame depth is 3 inches with a spacing of 24 inches. Fuselage longerons are spaced every 12 inches. The structural arrangement is shown in Figures 9-11.

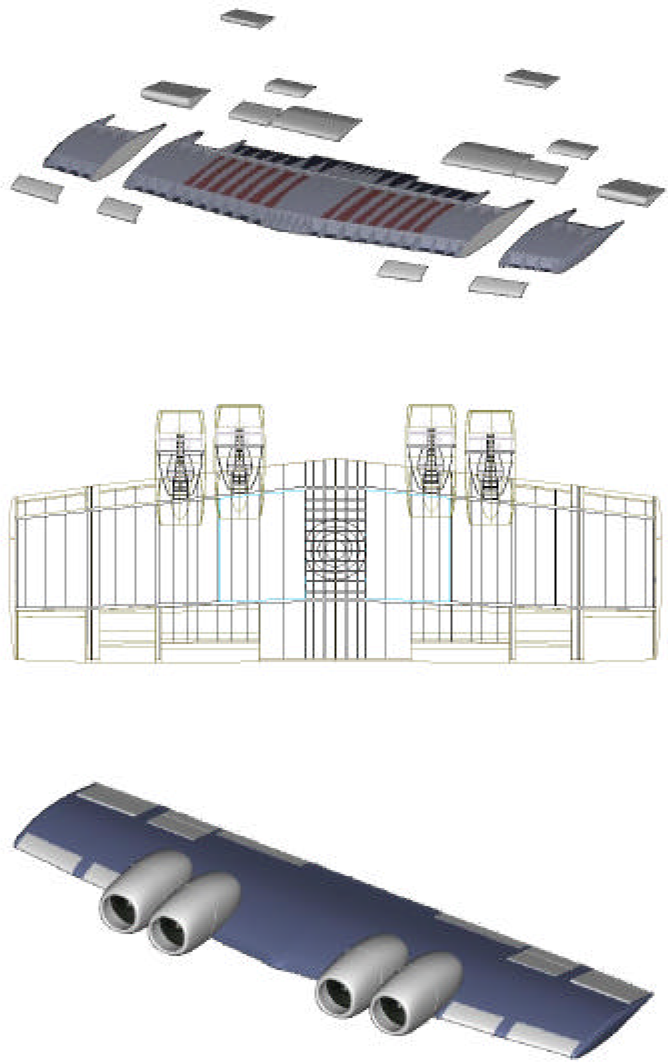

Figure 9- Wing Structural Arrangement

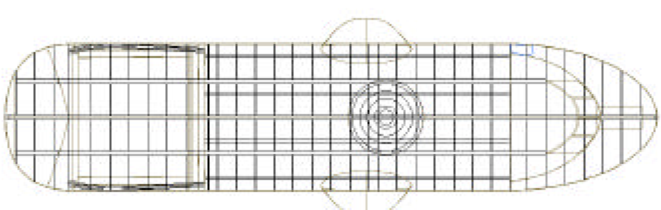

Figure 10- Fuselage Layout

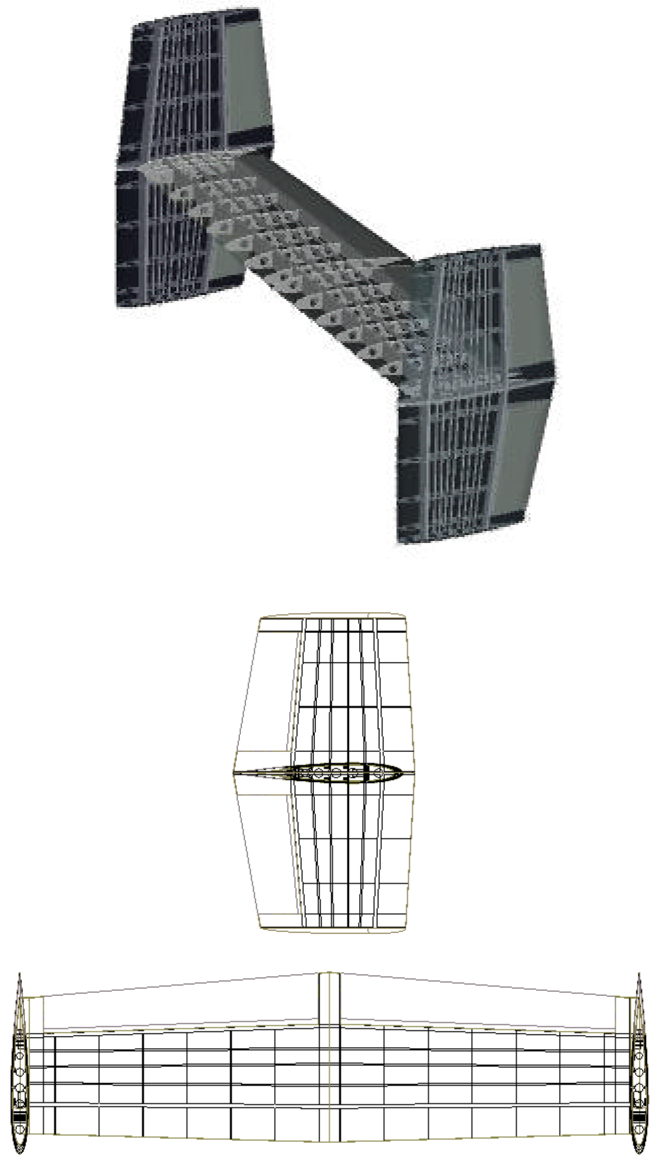

Figure 11- Empennage Structural Arrangement

WEIGHTS AND BALANCE

An estimate of the vehicle loads is the first step in the process of aircraft weight estimation. A speed - load factor (V-n) diagram represents the maximum load factor the airplane would be expected to experience as a function of speed. The maneuver diagram represents the maximum load factor the plane can achieve aerodynamically. Atmospheric disturbances also exert loads on the airframe. The magnitude of these loads is represented by the gust diagram. The limit load factor may be read from the plot as the maximum load factor experienced by the airplane and may occur on either the gust or the maneuver line. The ultimate load factor is then 1.5 times the limit load factor as determined from the V-n diagram. The V-n diagram, shown in Figure 12 for the Cardinal, was constructed using the methods in References 32 and 20.

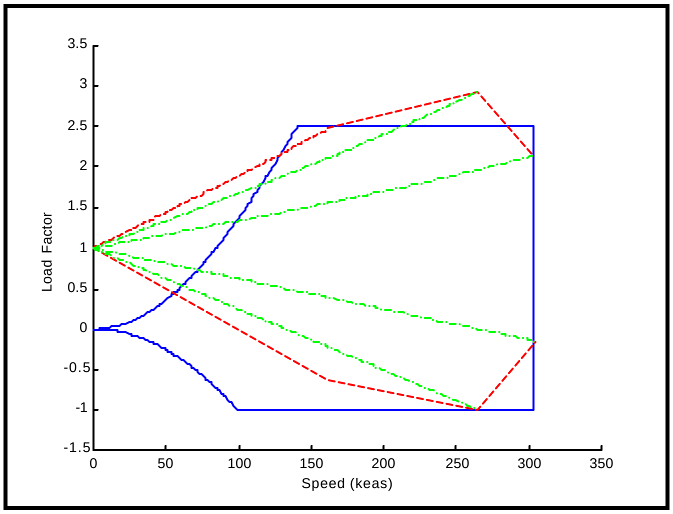

Figure 12- V-n Gust and Maneuver Diagram

The component weights for structural components and systems for the Cardinal were estimated using equations based on statistical correlation of existing aircraft. These relations included methods from the US Air Force (USAF), US Navy (USN), Torenbeek, and General Dynamics (GD) as discussed in References 32 and 37. Where multiple methods were available, the component or system weight computed by each method was used to compute an average weight. Many of the component weights are functions of the takeoff weight, therefore it was necessary to make an initial guess for the takeoff weight. After computation of the component weights using this initial guess, a takeoff weight can be calculated. If the calculated takeoff weight differs from the initial guess, the calculated takeoff weight is used to recompute the component weights. This process continues until the takeoff weight converges. Convergence usually takes 3-4 iterations. The component center of gravity locations were placed using guidelines in References 20 and 32. Table 6 summarizes the component weight breakdown for the final design of the military and commercial versions of the Cardinal.

The airplane center of gravity location (and how it moves as the plane is loaded and unloaded) affects landing gear placement, the ability of the aircraft to rotate during takeoff, and stability/control. The following configurations were analyzed to determine the range over which the center of gravity would be expected to vary: (a) full fuel with military payload, (b) full fuel with commercial payload, (c) no fuel with military cargo, and (d) no fuel with commercial cargo. The center of gravity excursion was found to be approximately 5% of the wing MAC; the center of gravity never moves aft of the main gear.

Table 6- Component Weight Breakdown

Component	***Weight (lbs)***	
	Military	***Commercial***
Wing	3322	2966
Horizontal Tail	509	509
Vertical Tail	438	438
Fuselage	3457	3457
Nacelles	1125	1125
Nose Gear	274	274
Main Gear	1232	1232
Engines	4334	4334
Fuel System	676	676
Propulsion	374	374
Flight Controls	669	669
Hydraulic	501	501
Inst. & Avionics	853	853
A/C & Pressurization	1283	1283
Electrical System	1741	1741
Oxygen	65	65
APU	401	401
Furnishings	223	2056
Baggage Handling	26	26
Auxiliary	255	255
Paint	226	226
Empty	**22027**	**23460**
Trapped Fuel & Oil	251	251
Crew	400	600
Fuel	14483	13883
Payload	10000	4920
Takeoff	**46761**	**43114**

DRAG ESTIMATION

A standard drag build-up approach was used to estimate the drag polar. Drag for each major airplane component was calculated according to guidelines in Ref. 20. Total drag was estimated from three sources: parasite drag, induced drag, and compressibility drag.

Parasite drag accounts for skin friction, roughness, and pressure drag associated with each airplane component. The induced drag for the Cardinal in cruise was estimated using the standard equation for drag due to lift. As outlined in Ref. 20, this method took into account fuselage interference effects, wing twist effects, and viscosity effects. For the wing/body, the induced drag was calculated as a function of the wing/body lift coefficient. For the horizontal tail, the trim drag term was calculated as a function of the lift coefficient for the horizontal tail. Compressibility drag takes into account the effects of Mach number. Figure 13 shows the drag polar for the cruise configuration.

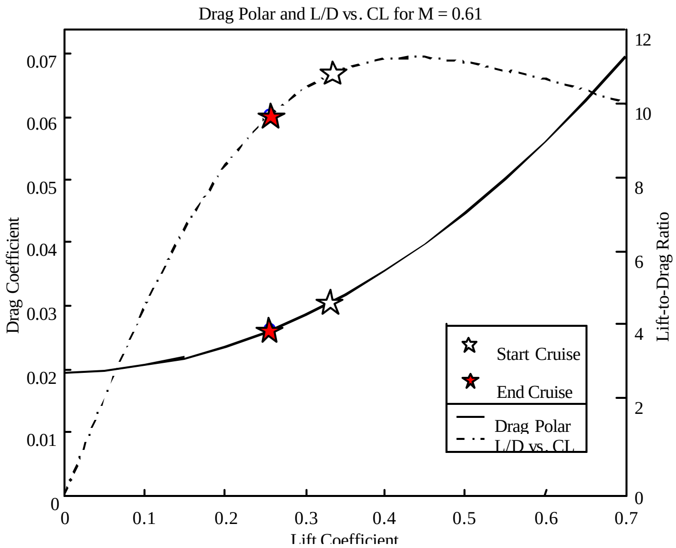

Figure 13- Cruise Drag Polar

STABILITY AND CONTROL

The stability and control characteristics must comply with the Part 25 Federal Aviation Regulations (FAR 25) for the commercial version and MIL-8785C for the military version [2]. These regulations place restrictions on the allowable range of frequencies and damping ratios for the airplane. Roll control and engine out control are also regulated. All stability and control calculations were made using the Advanced Aircraft Analysis (AAA) software which is based on the methods described in Ref. 32 and 33.

Using the AAA software the frequencies, damping ratios, and time constants were computed and compared against the applicable certification requirements. For the many cases when FAR 25 does not provide quantitative requirements, the MIL-F-8785C specifications were used [33]. Table 7 summarizes the frequencies, damping ratios, and time constants for landing and cruise, which complied with all FAR 25 and MIL requirements.

Table 7- Frequencies and Damping Ratios

	Landing Configuration (0 ft, 55 knots, 33860 lbs)	**Cruise Configuration** (37000 ft, 350 knots, 41000 lbs)
Short Period	$W_{n_{SP}}$ = 2.2 rad/sec Z_{SP} = 0.35 (~)	$W_{n_{SP}}$ = 4.61 rad/sec Z_{SP} = 0.74 (~)
Phugoid	W_{n_P} = 0.031 rad/sec Z_P = 0.041 (~)	W_{n_P} = 0.134 rad/sec Z_P = 0.05 (~)
Spiral Const.	T_s = 150.5 sec	T_s = 94.6 sec
Roll Const.	T_r = 1.02 sec	T_r = 0.82 sec
Dutch Roll	W_{n_D} = 1.08 rad/sec Z_D = 0.21 (~)	W_{n_D} = 2.63 rad/sec Z_D = 0.0803 (~)

The minimum control speed is the minimum speed at which the yawing moment due to an inoperative engine can be balanced by the vertical tail without stalling. FAR 25 requires that the minimum control speed be less than or equal to 1.2 times the stall speed in the landing configuration [33]. MIL-F-8785C requires the minimum control speed to be less than or equal to the highest of: (a) 1.1 times the stall speed, or (b) the stall speed plus 10 knots. The minimum control speed computation took into account the thrust loss of an inoperative engine and the windmilling drag. The Cardinal exactly meets the FAR requirements and exceeds the minimum MIL requirement.

PERFORMANCE ANALYSIS

Many of the design requirements for the Cardinal involve minimum performance requirements; for example, range, cruise speed, and takeoff/landing ground roll requirements. The RFP requires that the Cardinal have a maximum takeoff ground roll of 300 feet and a maximum landing ground roll of 400 ft. There are many statistical and approximate methods available for estimating takeoff and landing distances, either through statistical correlation with existing aircraft or simplifications of the equations of motion [22]. Due to the stringent takeoff and landing distance requirements for the Cardinal, the statistical methods are not applicable.

Using integral equations for the takeoff and landing distances [22] (modified to account for the vertical component of thrust in the case of the tilt-wing) a simple Euler integration was used to compute the ground rolls. For the variation of thrust with speed for turbofan engines, the performance code implemented a simple correlation between Mach number and the ratio of actual to static thrust [20]. The variation of thrust with speed and rotor angle for the tilt-wing aircraft was computed from data in Ref. 25. FAR regulations do not allow for any engine-dependent means of slowing down during landing (e.g. thrust reversers) to be used for certification [22]; the analysis for the Cardinal assumes no use of such devices.

Because the lift coefficient of a wing with blown flaps is a function of throttle setting, with the thrust being a function of speed and drag coefficient, the stall speeds in both the takeoff and landing configurations were determined iteratively. For the tilt-wing configuration, a force balance was done at each step in the integration to determine whether the plane had taken off. Landing speeds for the tilt-wing were computed by iterating to find a stable unaccelerated descent profile with a flight path angle of no more than -7°. Once the touchdown speed was established, the same method of integration was used to determine the landing ground roll.

A summary of the takeoff and landing ground rolls as a function of weight is shown in Figure 14 for the final

Cardinal design. The maximum takeoff weight of the Cardinal is 46,761 lb -- Figure 14 shows that at this weight the takeoff ground roll is 289 ft. The landing ground roll constraint was imposed at the maximum landing weight which was assumed to be 85% of the maximum takeoff weight (39,747 lb), with a resulting ground roll of 273 ft.

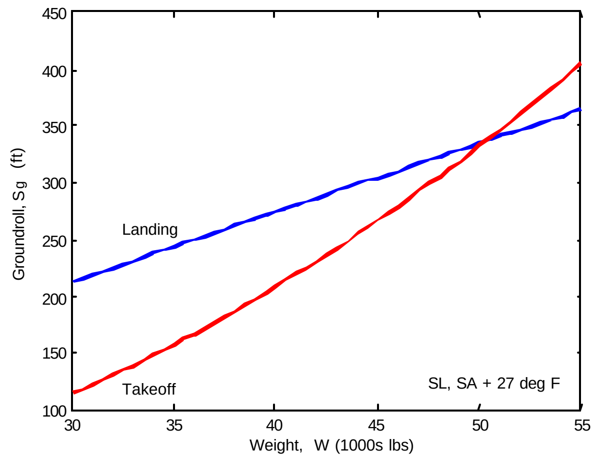

Figure 14- Takeoff and Landing Ground Rolls

Using the method outlined in Ref. 22 the climb rate was computed from drag, weight, and propulsion data. The AEO climb performance for various altitudes and Mach numbers is summarized in Figure 15.

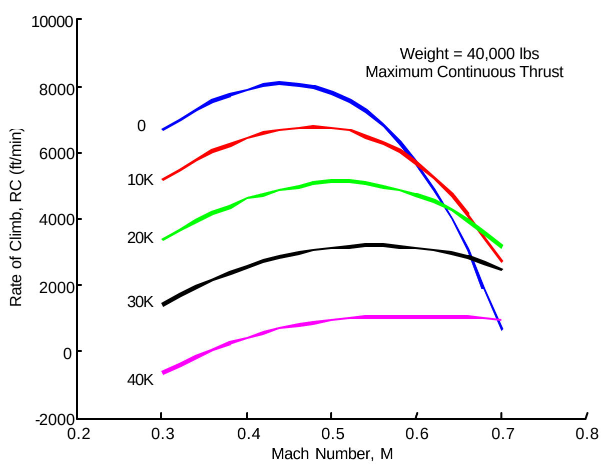

Figure 15- AEO Climb Rate

The FAR 25 climb performance requirements set minimum allowable climb gradients (CGR) for the aircraft in different configurations and speeds with OEI. This analysis included the effects of windmilling drag on the stopped engine and the additional rudder drag for trim. The climb gradients were computed for the various flight phases and summarized in Table 8. Because the FAR requirements are more stringent than the USN requirements, satisfying the FAR requirement means that the USN requirements are also met.

Table 8- FAR Climb Gradients

Flight Phase	***FAR Minimum CGR [22]***	***Cardinal***
First Segment Climb	0.5	0.53
Second Segment Climb	3.0	3.19
Third Segment Climb	1.7	2.35
Go-around (Approach)	2.7	3.19
Go-around (Landing)	3.2	3.80

Range was computed by numerical integration of the specific range from begin cruise weight to end cruise weight. The specific range, or range factor, is defined as the number of nautical miles which can be flown per pound of fuel. This value was computed for a ange of airplane weights, speeds, and altitudes. Figure 16 contains a plot of the specific range for the Cardinal over a range of weights at an altitude of 37,000 feet.

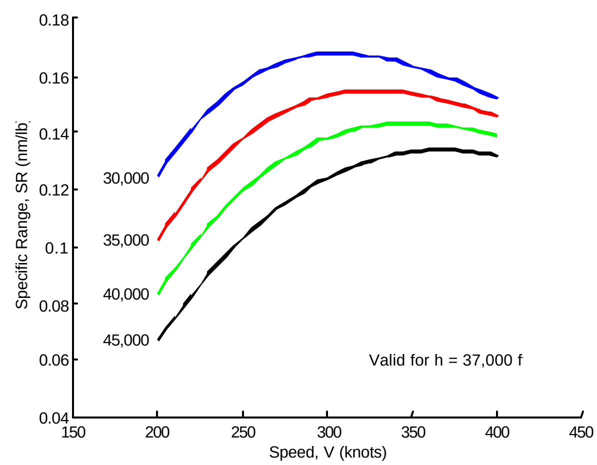

Figure 16- Specific Range

The range specified does not allow a range credit for descent, and requires adequate remaining fuel reserves after landing. For the case of USN cargo and transport aircraft, which was the critical version of the Cardinal for sizing purposes, the fuel reserve requirement is the greater of (a) 10% of mission fuel (including one approach, a wave-off, a go-around, a second approach, and trap) or (b) fuel equal to 30 minutes of loiter at sea-level speeds plus 5% of mission fuel [22]. The end cruise weight was iterated to provide adequate reserves, and the resulting range was computed from the known beginning and ending cruise weights.

A payload-range diagram was constructed to show the effects of various combinations of payload and fuel loading. Figure 17 shows that at the design payload of 10,000 lbs, the military version of the Cardinal has a range of 1,500 nm. The ferry range, representing the maximum range of the aircraft, was calculated to be 2,968 nm.

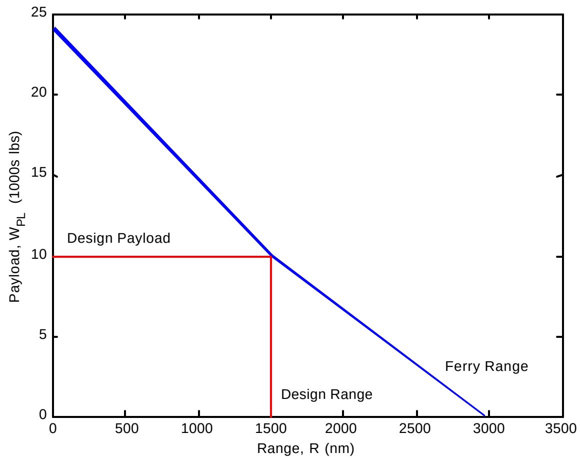

Figure 17- Payload Range

Table 9 summarizes the range for various configurations of the Cardinal. The first listing for the commercial version represents the range with the design payload and maximum volumetric fuel, while the second listing corresponds to the configuration with a 1500 nm range and a design payload of 24 passengers & baggage.

Table 9- Range of Commercial and Military Versions

Version	*Takeoff Weight (lbs)*	*Payload Weight (lbs)*	*Range (nm)*
Military	46,761	10,000	1500
Commercial	43,114	4,920	1988
Commercial	42,608	4,920	1500

COST ESTIMATION

The basic approach to cost estimation consists of a simple cost breakdown - estimating the cost for several airplane program phases, and then summing the estimates to compute life-cycle cost [32]. Included in this analysis were: Research, Development, Test, and Engineering (RDTE), Acquisition, Operating, Disposal, and ultimately Life Cycle Cost (LCC).

The Cardinal aircraft was designed with both commercial and military configurations. In the cost analysis, the number of airplanes played a significant role - many cost numbers, particularly operating cost and life-cycle cost, depend heavily on the production run. For the analysis discussed herein, a production run of 750 airplanes, of one version (commercial or military), was assumed. For actual operation of this aircraft, the production run will be 750 airplanes. However, they will not all be of the same version. To simplify the design, and make it possible to account for any number of commercial vs. military versions, the cost calculations were done assuming all one configuration.

The RDTE phases span the initial part of the airplane program. The RDTE phases begin with mission definition and conceptual design, move through trade studies and preliminary design, and conclude with detailed design and flight test. Acquisition consists of airplane manufacturing and delivery to the customer. The total cost of acquisition is estimated as the sum of the manufacturer's cost plus the manufacturer's profit. Program operating cost is the cost associated with operation of the airplane. This cost accounts for the largest fraction of the life-cycle cost. Operating cost consists of two parts: Direct Operating Cost, and Indirect Operating Cost. The operating cost is based on statistical data gathered for many existing aircraft [32]. The estimate for this major cost factor takes into account many parameters associated with aircraft operations such as mission range, number of years of operation, and number of airplanes acquired by the customer. Figures 18 and 19 summarize the operating and life cycle costs

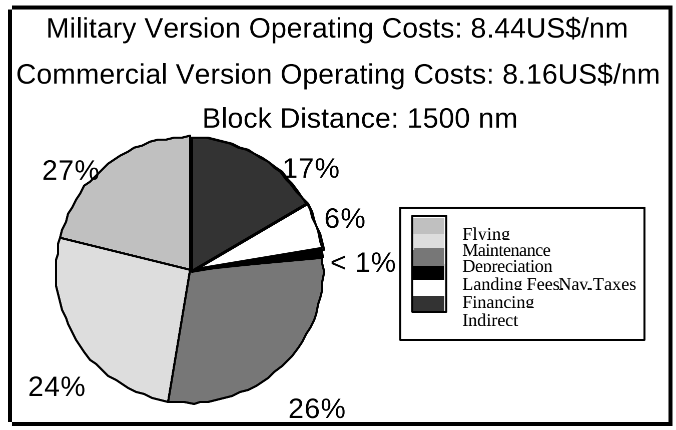

Figure 18- Operating Cost Breakdown

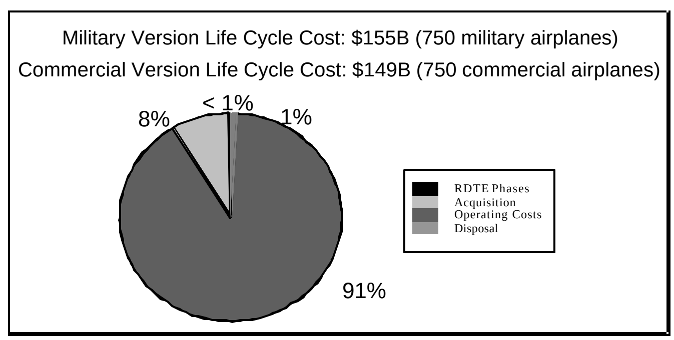

Figure 19- Life Cycle Cost Breakdown

DESIGN OPTIMIZATION

Due the complexity of the design process for this aircraft, an independent team handled each of the major design categories. These "subsystem analyses" were then combined for collaborative optimization. Prior to writing the optimization code, a literature review was conducted to find methods for introducing collaborative optimization into the aircraft preliminary design process. While many optimization methods exist, tailoring those to preliminary aircraft design is some thing of an art-the Cardinal team built on the expertise of several aircraft design optimization experts to better define the scope of the optimization code [7,14,16,17,18,19,21,28,35].

The goal of this optimization was to make the best airplane design. For the Cardinal, several design variables, Table 10, were chosen to describe the best design. Each of these design variables describes airplane geometry, performance, or cost metrics which, when viewed together, describe the Cardinal airplane. At the start of this project, the team chose to investigate several different airplane designs: two SSTOL aircraft (a tilt-wing and a fixed-wing), and one VTOL aircraft (also using the tilt-wing configuration). All subsystem analyses were conducted for each of these aircraft, leading to initial designs that were ready for optimization.

Of central importance to a successful optimization is selection of the overall flow of information. Prior to optimization, each subsystem was analyzed in terms of the design variables. Each subsystem function used some or all of the design variables to compute parameters relevant to that subsystem. These outputs were then used by other subsystems as inputs. The subsystem analyses, when combined in a sequence, yielded values for all design variables and constraints. The optimization code then used this information to iterate on the design until reaching an optimal solution that satisfied all constraints.

Table 10- Design Variables

	Variables
Mission Profile	cruise altitude, cruise speed, range
Wing Geometry	S_{ref}, span, taper ratio, thickness-to-chord ratio, sweep angle, wing location
Empennage Geometry	S_{ref}, span, taper ratio, thickness-to-chord ratio, sweep angle, tail location
Landing Gear Geometry	$distance_{nose\text{-}to\text{-}nose\ gear}$, $distance_{nose\text{-}to\text{-}main\ gear}$, lateral position of main gear
Propulsion	installed thrust/power, engine model (sfc, T_{avail} vs. speed, T_{avail} vs. altitude)
Weights	W_{TO}, $W_{max\ zero\ fuel}$, center-of-gravity locations

Figure 20 shows a flow chart laid out to simplify the optimization procedure for the Cardinal. The chart shows only feedforward - a concerted effort was made to eliminate feedback which would require iteration at the subsystem level, rather than overall design iteration at the systems level. The left-hand side shows the design variables. These parameters are the actual inputs to the optimizer. For the first iteration initial guesses are made for each design variable.

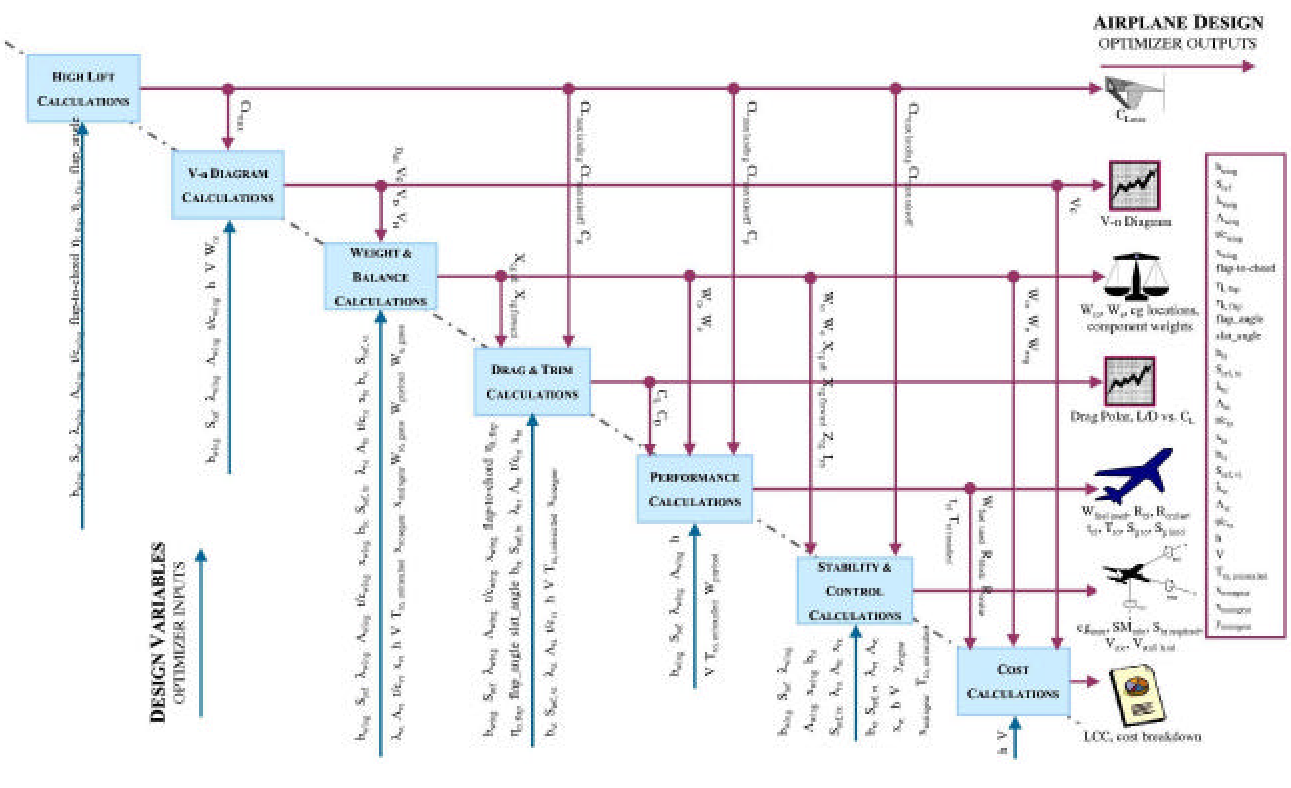

Figure 20- Optimization Flowchart

The purpose of constrained optimization is to transform a complex problem into much simpler subproblems that can be solved using iteration. Typically, the constrained problem is written as an unconstrained problem with penalty functions for constraints at, near, or beyond their limits. The constrained problem is then converged upon when the limit of a sequence of parameterized unconstrained optimizations is reached. This work used a Sequential Quadratic Programming (SQP) method [13]. This nonlinear method was implemented in an optimization code written using the Matlab Optimization Toolbox [34].

Restrictions on the decision variables were written as constraints, mathematical expressions relating the decision variable and its bound with inequalities and/or equations. The constraints, summarized in Table 11, were derived from several different areas. Some came directly from the Request for Proposal (RFP), others came from basic engineering guidelines for aircraft design, and still others came from Federal Aviation Regulations (FARs).

Table 11- Optimization Constraints

Constraint	,	***Bound***
Volume		60 ft x 29 ft x 18.5 ft
Takeoff ground roll		300 ft
Landing ground roll		400 ft
Cruise Range		1500 nm
Center-of-gravity excursion		25% mac
Static Margin		5 % mac
Takeoff Rotation, S_{ht}		$S_{ht,\ required\ for\ rotation}$
Tipover Angle		18 degrees
Turnover Angle		54 degrees
Fuselage Clearance Angle		10 degrees
Weight on Nose		8%
Minimum control speed		$1.2*V_{stall,\ landing}$

On the right-hand side of Figure 20 there is a block for the "airplane design." This block consists of optimized design variables that meet all constraints and subsystem outputs (like charts, graphs, etc.) which are not captured solely with input design variables. The data presented for the Cardinal design throughout this paper represents the final results from the optimization. This data was generated using the outputs from the optimizer as inputs to the post-optimality running of the subsystem analyses.

The objective function for the optimization was a minimization of Life-Cycle Cost (LCC). The three baseline designs were studied in both the military and commercial configurations, then optimized with respect to LCC. Design points generated by the subsystem analyses were given as inputs to the optimizer. For all cases, the optimizer ran successfully (iteration numbers ranged from 196 to 324) and produced the "optimal design" for each configuration. After careful consideration of the cost metrics used to select the best design, the SSTOL fixed-wing configuration shown in Figure 21 was selected. Table 12 summarizes the results for both a vertical and short takeoff tilt-wing, and a fixed wing USB version, all for the military design requirements.

Table 12- Design Comparison for Military Version

	Vertical Takeoff Tiltwing	***Short Takeoff Tiltwing***	***Short Takeoff Fixed Wing***
DOC	\$9.06/nm	\$7.82/nm	\$7.03/nm
IOC	\$1.81/nm	\$1.56/nm	\$1.41/nm
Fuel Price	\$1.20/gal	\$1.20/gal	\$1.20/gal
Engine Price (per engine)	\$1.09 M	\$0.81 M	\$0.52 M
AEP	\$20.8 M	\$18.0 M	\$17.1 M
AMP	\$19.7 M	\$17.3 M	\$16.7 M
LCC	**\$200.6 B**	**\$172.1 B**	**\$154.7 B**

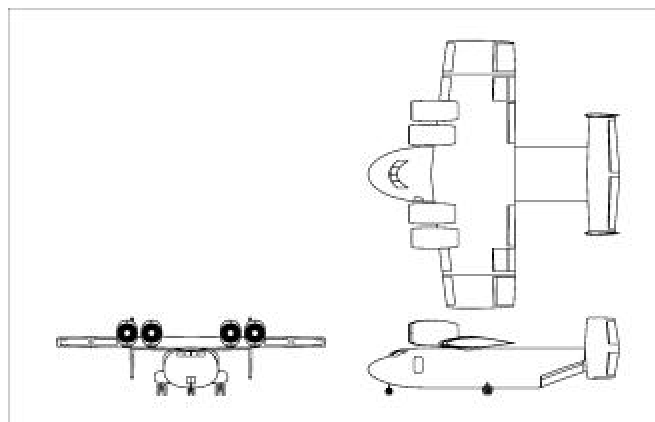

Figure 21- Three-View of Final Cardinal Design

Although the constraints for the Cardinal design were fixed by the RFP, the team felt it useful to show that by relaxing those parameters very slightly, the design would become lighter, less costly, and more efficient. The takeoff and landing distance requirements were the most difficult constraints to meet. The Cardinal optimal design was heavily influenced by the takeoff and landing distances - both were a major design driver. To analyze how significantly the takeoff and landing ground rolls impacted LCC, the constraints were relaxed by 100 ft. The LCC resulting from this constraint relaxation was \$130 B. For the optimal design with the original constraints, the LCC was \$154 B. A mere 100 ft of runway reduced the LCC by almost \$25 B. Figure 22 shows how LCC depends on takeoff ground roll (the most difficult of the two constraints to meet).

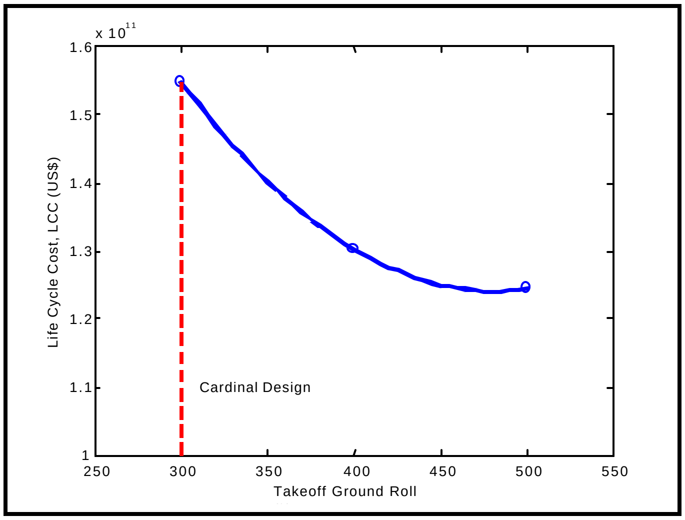

Figure 22- Variation of Life Cycle Cost with Takeoff Ground Roll Constraint

CONCLUSION

The Cardinal fills the gap for a Super Short Takeoff and Landing aircraft capable of operating from river "barges" and providing center-city to center-city travel. The need of the U.S. Navy for a Carrier On-board Delivery (COD) aircraft to replace the C-2 Greyhound is also met.

Upper surface blowing (USB) and a tilt-wing configuration were considered to achieve the takeoff and landing ground roll requirements. To assess which method was most cost effective to use a fixed-wing configuration with USB and a tilt-wing configuration were designed. Wing and high lift design, propulsion selection and performance characterization, structural layout and design, drag polar buildups, stability and performance analysis, and cost estimation were performed for both designs. Collaborative optimization was then used to minimize Life Cycle Cost (LCC) for the fixed-wing design and a tilt-wing design. A fixed-wing design with USB was selected for its lower LCC.

Performance of the final version of the Cardinal with a fixed-wing and USB includes:

- Takeoff ground roll of 289 ft
- Landing ground roll of 273 ft
- 1500 nm range at 350 knot cruise speed
- 24 passenger payload for commercial version
- 10,000 lb payload for military version
- Capable of carrying two GE F110 engines
- Spot factor of 60 ft by 29 ft for military version

To understand how the design requirements affected the costs, several design studies were conducted. The cost associated with vertical takeoff using a tilt-wing aircraft was estimated to cost 16% more than the fixed-wing design with short takeoff and landing capabilities. Sensitivity analysis showed that increasing the takeoff ground roll requirement by 100-200 ft would decrease life cycle cost by 15-20%.

ACKNOWLEDGMENTS

It was the pleasure of the Cardinal team to meet with many people at the NASA Ames Research Center over the course of this project. Dr. Yung Yu, Dr. Jack Franklin, and Larry Young of the National Rotorcraft Technology Center and Dr. John Davis and Rick Peyran of the U.S. Army Aeroflightdynamics Directorate offered extraordinary guidance during the trade studies between initial design configurations. The team would like to especially thank Dr. Michael Scully and John Preston, also of the U.S. Army Aeroflightdynamics Directorate for access to their incredible design library.

Dennis Riddle, former Branch Chief of Powered-Lift Flight at Ames, was a source of amazing knowledge about the QSRA. Mr. Riddle provided a wealth of flight test data from the QSRA, which aided in validation of many of the Cardinal's subsystem analyses.

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CONTACT

This work was originally submitted in response to the Request for Proposal (RFP) issued by the American Institute of Aeronautics and Astronautics for the 1998/1999 AIAA Foundation Graduate Team Aircraft Design Competition. For the complete, unedited version of the study, please contact Professor Juan J. Alonso (jjalonso@stanford.edu) or Professor Ilan Kroo (kroo@stanford.edu) of the Department of Aeronautics and Astronautics at Stanford University.