STINGRÆ

Short
Takeoff
Integrated
Nacelle-less
Geometry for the
Reduction of
Acoustics and
Emissions

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Abstract

This document details the design of the STINGRÆ aircraft, the solution to the 2007-2008 NASA Aeronautics Research Directorate University Competition Request for Proposal (RFP). The main requirements of the aircraft specified by the RFP were:

- Operation on runways between 1,500 and 3,000 ft in length (STOL),
- Payload capacity between 25,000 and 50,000 lbs,
- Implementation of alternative fuels,
- Cruise between Mach 0.78 and 0.82, and
- Achieve significant reductions in noise and emissions compared to modern commercial aircraft.

The STINGRÆ meets all of these requirements through the innovative combination of the following technologies:

- Fully blended aircraft geometry,
- Digital throttling,
- Upper surface blowing,
- Wingtip turbine synergistic energy recuperation, and
- "Kneeling" landing gear.

Regarding the design of the STINGRÆ, the following conclusions were drawn:

1. The STINGRAE is on the order of 30% more fuel efficient than the Boeing 737-800.
2. The combination of fully blended aircraft geometry and the use of digital throttling effectively reduce noise and emissions while increasing overall efficiency.
3. STOL capability can be realized through the use of upper surface blowing.
4. Wingtip turbines can be used to replace the auxiliary power unit by recuperating useful energy from the trailing vortices of an aircraft.
5. The use of Fischer-Tropsch synthetic fuel offers a realistic alternative to fossil fuels, and could lessen American dependence of foreign oil.

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1 Introduction: The Need for Higher Performance and Efficiency

The aviation industry must create aircraft that meet several needs in order to remain competitive in the future. With fuel costs steadily rising, there is a drive to reduce total fuel consumption and overall industrial environmental impact as well as to find alternative fuel sources to supplement the industry in the future. This environmental effort drives the need to reduce overall noise and emissions associated with the aircraft industry. There is also a demand to make use of the smaller runways which make of 40-50% of all airport runways. These smaller runways only account for about 4% of all airport traffic, mainly because the larger commercial jet-liners cannot operate on the short field length [1]. The NASA RFP for the 2007-2008 New Aeronautics Competition targets these industry desires with hopes of creating a new, more efficient and economic aircraft for the future.

2 The 2007-2008 NASA RFP

2.1 RFP Design Drivers

The 2007-2008 NASA Request for Proposal (RFP) directly reflects the current needs within the aviation industry to increase performance efficiency, while reducing negative environmental and acoustical impact. The specifications requested by NASA were to design "a futuristic DC-3" type STOL aircraft with the following capabilities:

- Take off and land within a balanced field length of no more than 3,000ft
- Cruise between Mach 0.78 and 0.82
- Carry payloads ranging from 25,000 to 50,000 lbs
- Significantly reduce noise and environmental pollution relative to current aircraft.

Other considerations included operations at general airports, "point to point" traveling, increased passenger safety, and the use of alternative fuels.

2.2 RFP Implications

Initial evaluation of the RFP determined that that the two major governing physical equations of the solution aircraft would be the following equations:

$$TOP = \frac{W/S}{(T/W)\sigma C_{L_{T.O.}}} \tag{1}$$

where:

- TOP is the take off parameter, a value which is linearly related to take off distance
- W/S is the wing loading of aircraft
- T/W is the thrust to weight ratio of the aircraft
- C_{LTO} is the maximum lift coefficient at take off
- And σ is the ratio of the density of the air at take-off to the density of air at sea level;

and,

$$R = \frac{V}{SFC}\left(\frac{L}{D}\right)\ln\left(\frac{W_{T.O.}}{W_L}\right) \tag{2}$$

where:

- R is the range of the aircraft
- V is the vehicle cruise velocity
- SFC is the specific fuel consumption of the propulsion system
- L/D is the lift to drag ratio of the aircraft
- $W_{T.O.}/W_L$ is the ratio of takeoff weight to landing weight.

All the values within these two equations must be well balanced to achieve an efficient solution to the NASA RFP. To minimize take off distance and the TOP the following properties are desired:

- high C_{Lmax}
- high T/W
- low W/S.

To maximize cruise efficiency, the following properties are desired:

- high L/D
- low SFC
- high W/S.

2.3 Additional Requirements

Because the NASA RFP did not specify a required range, which is a major design driver of any aircraft, the STINGRÆ Group set the solution vehicle range to 4000nmi. This value reflects research that suggests that it is much more cost efficient for long-range (8,000+nmi) intercontinental aircraft to travel over their design range in multiple shorter trips, rather than to flying intercontinental ranges non-stop. This is because a substantial amount of fuel is burned over the first 2,100 nm of the journey in order to carry the extra fuel for the remaining 5,900 nm [3]. Thus, a design range of 4000 nm offers the ability of an aircraft to have the efficiency of a medium range aircraft, while achieving intercontinental ranges over two flights, if desired. This ability is complimented by the STOL requirement, which will allow the solution aircraft to utilize many shorter runways which currently only account for a small percentage of total airport traffic. In addition to range, the STINGRÆ Group also self imposed assumed compliance with all major FAR guidelines.

2.4 Comparative Aircraft

For the design of a new aircraft concept, it is useful to establish a comparison with a current working system. The tube and wing aircraft design, particularly the next-generation Boeing 737-800 and the Boeing YC-14, offer a solid foundation of comparative aircraft research. The Boeing 737 is one of the most successful commercial transports in service today and could be considered the DC-3 of modern times. The 737 has roughly the same payload capacity as required by the NASA RFP, yet requires a runway much longer than 3000ft to operate. The Boeing YC-14 is a prototype aircraft which already fulfills the payload and STOL requirements stated in the NASA RFP, the transonic cruise speed requirement being the only exception. The YC-14 and 737-800 and they are shown in Figures 1 and 2 respectively.

3 The STINGRÆ Solution

Presented in this report as the solution to the NASA RFP is the Short Takeoff Integrated Nacelle-less Geometry for the Reduction of Acoustics and Emissions (STINGRÆ) craft. The STINGRÆ was designed to meet and exceed all of the requirements stated within the RFP. The physical deliverables of the STINGRÆ are:

- Balanced Field Length: 2800 ft
- Cruise Mach: 0.82
- Payload: 50,000 lbs (design case)
- Increased Efficiency: 30% more fuel efficient than Boeing 737-800 comparison system at present day technology levels

3.1 Ideology

The STINGRÆ concept eliminates the inefficiencies associated with engine over-design typical of modern aircraft. The STINGRÆ accomplishes this through the use of digital throttling and blended geometry. The STINGRÆ utilizes four (relatively) small turbofan engines completely buried within the aerodynamic body of the craft. The engines are sized primarily for the cruise condition, so that only two of the engines are needed to produce the required thrust to match the maximum drag experienced during cruise. At takeoff, all four of the engines operate at max throttle, where they are known to be most efficient [5]. When the STINGRÆ has reached cruise conditions, two of the four engines are shut down and their inlets are sealed off, allowing the two which remain in use to operate at higher throttles. This effectively achieves lower SFC values and increases overall efficiency. Because the engines are completely buried, engine-out wind milling drag which would result from nacelle mounted engines is avoided.

3.2 Features/Specifications

The innovative features which comprise the STINGRÆ are:

- completely blended geometry for drag and noise reduction
- 4 Digitally throttled engines sized for efficient cruise
- Upper Surface Blowing (USB) for high lift at take off.
- Fischer-Tropsch (FT) synthetic fuel use for reducing dependence on fossil fuels
- Wingtip Turbines (WTT) for synergistic power extraction
- Elimination of the need for an auxiliary power unit (APU) with Wingtip Turbines
- “Kneeling” Landing gear for rotation at take off
- Conversion to military variant and hydrogen fuelled variant possible.

characteristic	B737-800	STINGRÆ
Design Max Payload Weight (lbs)	44,000	50,000
Design Fuel Weight (lbs)	46,000	50,000
Empty Weight (lbs)	84,000	78,000
Max Takeoff Weight (lbs)	174,000	178,000
Max Thrust (lbs)	55,000	72,000
T_{max} / W_{max}	0.31	0.40
W_{max}/S_{wing} (lbs/ft^2)	130	135
Design Range @ Max Payload (nmi)	2,200	4,000
T.O. run @ max payload (ft)	8,000	2,370
Cruise Mach	0.785	0.82
Aspect Ratio	9.5	11.0
Length (ft)	130	91.6
Span (ft)	117	120
Wing Area S_{wing} (ft^2)	1,340	1,320
Seating Capacity	189	125

Table 1 B737-800 and STINGRÆ Comparison

Detailed specifications of the STINGRÆ base model are presented in Table 1 and CAD Figure 1.

3.3 Variants

3.3.1 STINGRÆ Passenger Model

The first model of this aircraft is that of a commercial airliner that is able to make cross-country flights while still being able to land at smaller regional airports. Because the aircraft is also acting in a smaller, regional airliner role some passenger comfort was compromised due the generally short flight time and to ensure the largest amount of passengers and cargo possible. The seating is arranged such that it falls into the high-density, economy class and there are currently no multi-class designs being considered.

The model used for the interior design was the Boeing 737-300/400 series commercial airliners. From those aircraft the seating size and pitch were taking and then a suitable layout was chosen to fit the ultra-wide body design of this aircraft. The cabin is designed to support three rows of seating with two aisles; the outside rows having two seats and the center row having three seats each with overhead storage. Each seat has a seventeen inch cushion with two inch armrests with the armrests being shared between seats and the maximum cabin height of seven feet occurs at the center of each aisle. The high-density classification comes from the smaller, thirty inch pitch between seats; this is again to have the largest number of passengers in the shorter cabin. The main cabin supports fifteen rows of seven-abreast seating followed then in the rear by four rows of five-abreast seating to accommodate the shrinking diameter of the tail cone. This allocation of seating allows for a total of 125 passengers. It should be noted that assuming an average passenger and luggage weight of 225 lbs [6], 125 passengers results in about a payload of 28,125 lbs , which is considerably less than the 50,000 lb design payload. Therefore, the STINGRÆ generally will be more cost effective as a cargo conversion.

Located further forward or aft in the nose and tail cones are the traditional airline amenities. In total the aircraft supports two lavatories located in the forward section of the cabin where two galleries are located at opposite ends with one being at the forward end and the other aft. There are folding seats for four total flight attendants with two at each end of the cabin. For boarding, the aircraft has two Type I Entry/Exit doors measuring 72 by 34 inches located in the front of the cabin although only one will be in use during non-emergency events. In the case of emergency passengers will exit through either of the front doors or alternatively through another emergency exit through the tail cone. The tail cone exit is designed in such a away to comply with current FAR egress requirements.

3.3.2 STINGRÆ Freight Model

This aircraft was designed with versatility in mind therefore the cargo-carrying variant of this is very similar to the passenger model with the exception that it contains no seating and requires the addition of large loading doors on the top of the pressure shell. The main cabin floor and ceiling are in the same locations and all entry/exits remain fully functional. For capacity the aircraft can carry hold fifteen full-size LD3 cargo containers on the main deck while maintaining the same amount of hold storage for other items. Due to the shape, size and position of the aircrafts inner wings the main cargo in must be slid into the aircraft entering via a large ramp at the rear of the pressure shell. No other exterior modifications are required and all seat mounting locations are retained so if desired the aircraft can serve a hybrid role transporting both a number of passengers and bulk cargo.

3.3.3 STINGRÆ Type M

The STINGRÆ Type M is the military variant of the STINGRÆ base model. The Type M version exhibits a lowered floor from the base model, which allows the STINGRÆ to carry the largest High Mobility Multipurpose Wheeled Vehicle (HMMWV) version, and all smaller HMMWV variants currently in use by the United States Armed Forces [7], as shown in CAD Figure 2. The Type M was also designed so it can carry 1 STRYKER vehicle in addition to 1 HMMWV. Besides the altered floor, the Type M model has no other deviations from the base cargo model, allowing for cheaper production and acquisition costs.

3.3.4 STINGRÆ Type H

The STINGRÆ base model was designed so that the four identical (4x1) FT fueled turbofans may be replaced by a two identical (2x1) liquid hydrogen fueled turbofan engines, should the infrastructure for liquid hydrogen exist by 2058. The Type H offers virtually no CO_2 emissions, and only small NO_x emissions. Although hydrogen is very clean it is nearly 11 times less dense than current kerosene, and therefore the design range of the Type - H is reduced to 1,500 nm from the 4,000 nm ranged base version.

4 STINGRÆ Mission

The STINGRÆ was primarily designed for mid-range transport missions. Similar to modern commercial transports, the STINGRÆ highlights the following segments described in Figure 3:

- Take off in accordance with FARs
- Cruise 4000 nm to destination
- Loiter 40 minutes until cleared to land
- Land
- Climb back to loiter conditions (assuming an emergency or missed approach)
- Loiter 40 more minutes until cleared for second attempt
- Land

The STINGRÆ mission varies slightly depending on the fuel type. The commercial and military versions use the FT Synthetic fuel while the Type-H “point-to-point” model is powered by hydrogen fuel. Both variants are capable of short takeoff and landing on a balanced field length below 3,000 ft and maintain the same forty minute loiter time during descent. For the FT Synthetic versions, the maximum payload range is limited to approximately 4,000 nm while the hydrogen variant can only span roughly 1,500 nm with the 50,000 lb payload.

5 STINGRÆ Design Weight

The design weight of the STINGRÆ was calculated using the traditional iterative weight fraction method described by Raymer [5] and modified weight estimation equations obtained from FLOPS [8]. The empty weight resulting from these two estimation methods are shown in Table 2. With the empty weight estimated, a mission program was created which used the following values as inputs to create the thumbprint plot shown in Figure 4.

Componet	Weight (lbs)
Structural Weight	55600
Fuselage	11700
Inner Wing/Body	19300
Outer Wing	15600
V-Tail	800
Main Landing Gear	6200
Nose Landing Gear	1200
Engine Supports	800
Propulsion Weight	16040
Engines (x4)	12000
Thrust Ducting	2500
Starter Weight	400
Engine Controls	140
Fuel Systems	1000
Sytems and Equipment	6400
Surface Controls	600
WWT	1100
Instruments	800
Electrical Systems	2100
Air Conditioning	1800
Total Empty Weight	78,040
Max Design Payload	50,000
Fuel at Max Design Payload	50,000
Max Gross Weight	178,040

Table 2 STINGRAE Weight Beakdown

- Empty weight = 78,000 lbs
- Cruise Mach = 0.82
- $C_{LT.O.}$ = 4.0
- e = 0.80
- $C_{L,cruise}$ = 0.46
- Range = 4000 nm
- Payload Weight = 50,000 lbs
- Takeoff Distance = 3000 ft
- Loiter Time = 30.0 min.
- Wing sweep = 34 degrees
- Aspect Ratio = 11

Other restrictions taken into account in the thumbprint plot are:

- maximum wing loading required to keep the aircraft in the air
- the digital throttling consideration which requires that two engines must be able to provide more thrust than the maximum drag experienced by the aircraft
- The FAR [9] restrictions regarding second segment climb and top of climb are both superseded and fulfilled by the digital throttling requirement.

The thumbprint plot in Figure 4 shows that the major parameters of the STINGRÆ are optimized for the take off and cruise requirements as:

- Fuel Weight = 50,000 lbs
- Total Weight = 178,000 lbs
- T/W = 0.40
- W/S = 136 lbs/ft^2
- Wing Area, S = 1,320 ft^2
- Max Thrust, Sea Level = 72,000 lbs
- Max Thrust, Cruise (digitally throttled) = 9,500 lbs

The solid blue line in the thumbprint plot represents the minimum thrust to weight which results from using 4 engines at take off, any two of which will overcome the total drag experienced by STINGRÆ in cruise. The vertical black line represents the minimum wing loading required for cruise. With the total aircraft weight and wing loading determined from the thumbprint plot, aerodynamic analysis on the STINGRÆ was then performed.

6 Aerodynamic Performance

6.1 Preliminary Research and Airfoil Selection

Preliminary research found that the NACA 6 series and Whitcomb Supercritical airfoils as the best airfoil candidates for the inner and outer wing of the STINGRÆ respectively. Both of these airfoils are known to perform well when flying in the transonic realm [10]. TSFOIL2.exe [11] , a 2-d transonic airfoil analysis code was used to investigate the performance of different types of airfoils in these two categories. This analysis ultimately led to the selection of the NACA 64(3)-618 and the SC(2)-0714 airfoils to model the inner and outer wing sections of the STINGRÆ . These airfoils are shown in Figure 5. Using the data obtained from TSFOIL2.exe, the critical Mach number of each type of airfoil was determined using the method described by Anderson [12]. The NACA 64(3)-618 and SC(2)-0714 airfoils were found to reach local supersonic flow between 0.55-0.65 and 0.65-0.80 respectively. These values were found to be in agreement with those presented by Mason [10].

6.2 Transonic Wing Design

With the data and critical Mach numbers obtained for the selected airfoils, the Korn equation was used to determine the optimal amount of sweep for the inner and outer sections of the wing. The Korn equation is as follows:

$$M_{dd} = \frac{k_{\Lambda}}{cos\Lambda} - \frac{t/c}{cos^2\Lambda} - \frac{C_l}{cos^3\Lambda} \tag{3}$$

where

- t/c is the thickness to chord ratio of the airfoil
- C_L is the 2-d lift coefficient, and,
- Λ is wing sweep.

The Korn equation was plotted allowing M_{dd} and Λ to vary. The resulting Korn equation plots are shown in Figure 6. These plots show that the Mach divergence drag number is delayed the longest at optimum values of sweep for the inner and outer wings of 45 and 34.4 degrees respectively, at a cruise Mach number of 0.82. This is in good agreement with current BWB designs, which utilize more sweep in the inner wing sections than the outer sections [13].

6.3 3-D VLM Model

Having selected the inner and outer wing airfoils and their respective sweep angles, a 3-d model of the STINGRÆ's planform area was created using the TORNADO[14] Vortex Lattice Method. TORNADO is an inviscid and incompressible, vortex lattice code. Being inviscid, TORNADO cannot model skin friction and form drag, and can only produce reliable data up to M=0.7 using a Prendtl-Glauert correction. Although TORNADO is inviscid and incompressible, it was still useful in modeling lift, induced drag, and other body forces over a range of angles of attack at various flight conditions. The Tornado STINGRÆ planform model is shown in Figure 7.

6.4 Transonic Cruise Drag Analysis

Because TORNADO is inviscid and incompressible, the transonic laminar and turbulent skin friction program FRICTION.m [25] was utilized to estimate skin friction drag in the transonic regime. FRICTION.m calculates skin friction by a similar method to those described by Raymer [5] using form factors. The STINGRÆ was modeled in FRICTION.m as 5 parts as follows:

- Nose cone (3-d body of revolution)
- Inner Wing (3-2 body of revolution)
- Outer Wing (2-d planar)
- V-Tail (2-d planar)
- WTT Winglets (2-d planar)

$S_{ref} = 1{,}320\ ft^2$ M = 0.82 alt = 30,000 ft

component	S_{wet} (ft^2)	L_{ref} (ft)	t/c	FF_{3d}	FF_{2d}	Re/L	$C_{df_{fric}}$	$C_{df_{form}}$
nosecone	663.722	18.58	0.699	21.55	n/a	2336520	.0006834	0.0002162
main body/wing	5130	45	0.18	0.0451	n/a	2336520	.0062858	0.0009760
outer wing (x2)	1855	14	.14	n/a	0.0451322	2336520	.0006290	0.0002620
V-tail	1270	19	0.12	n/a	0.041218	2336520	.0005890	0.0001652
winglets (x6)	18	2	.10	n/a	0.0386	2336520	.0000263	0.0000700
							C_{D0} total:	0.00984
							C_{D_i}	0.00877
							$C_{D_{wave}}$	0.0027
							C_D total:	0.02131
							D total:	8182.90 lbs

Table 3 STINGAE Cruise Drag Summary

The resulting data is shown in Table 3, showing the contributions to total drag coefficient from each component of the STINGRÆ. Once C_{d0} was obtained, the total drag which consisted of:

- Skin friction and form drag C_{d0}
- Lift Induced Drag C_{di}
- Mach/Wave drag $C_{d,Mach}$

Which were calculated by the methods described by Raymer [5] and is shown in Table 3.

6.5 High-Lift Modeling

The STINGRÆ will utilize both traditional and non-traditional methods of generating high lift at take off and landing. The contribution from the "clean wing" geometry is known to contribute about 1.0 to the max lift coefficient. High lift devices such as slats are known to contribute about 0.4 to the total lift coefficient. Flaps are known to contribute at most about 1.5 to the lift coefficient. This brings the total lift coefficient to just under 3.0 utilizing standard high lift devices. Figure 8 shows a generic 2-d lift curve obtained from the method described by Keen [15]. This figure shows that a single engine providing USB can generate substantial 2-d lift coefficients, which translate into slightly lower 3-d lift coefficients. At high angles of attack, a USB engine can generate contributions to total lift coefficient on the order of 2.0. Upper surface blowing is discussed in more detail in the Enabling Technologies section of this report.

7 Propulsion Performance

7.1 Engine Considerations

7.7.1 Introduction

A variety of engine types and technologies were researched in the development of this aircraft concept. Because of the futuristic nature of the concept many interesting propulsion technologies could be pursued. Because of the nature of the concept it was decided to focus on two main types of engines: the traditional turbofan jet engine and the more obscure turboprop-fan jet engine. Among the types of engines not considered were the turbojet engine due to its relative inefficiency and noise and the turboprop engine due to its altitude and speed limitations. The next sections will explain, in more depth, the research given into the considered propulsion types.

7.1.2 Turbofan Engine

Naturally, the first propulsion type considered was the turbofan engine. Turbofans have been used, in essence, since the beginning of commercial air travel and offer among the most reliable and efficient engines available today. Over the last fifty years there has been a large increase in turbofan technology. New materials allow for higher combustion chamber temperatures and higher thrusts while three-dimensionally designed fan, compressor and turbine blades allow for greater mass air flow rates and over all efficiency. With the abundant use of turbofan engines in commercial aviation today a large resource of information was available for research.

As one of the world's largest jet engine manufacturers General Electric (GE) was a natural choice for a source of information about current and past turbofan engines. The CF34 variant engines developed by GE over the past thirty years are currently the most implemented turbofan engines in the world. The chart below gives some of the general specifications of the GE CF34-8/10 series turbofan engines.

Property	Quantity
T/O Thrust (lb_f)	14,500 – 18,820
Cruise Thrust (lb_f)	4,000 – 5,000
Max. D (in.)	52 - 57
Max. L (in.)	90 – 128.5
W (lb_f)	2,480 - 3800
BPR	5.0 – 5.3
OPR	26.3 – 28.5
T/O SFC (lb/hr/lb)	0.37 – 0.39
Cruise SFC (lb/hr/lb)	0.65 – 0.68

Table 4 Table properties for the GE CF34-8/10 series turbofan engine

Upon further research into engines of similar sizes it was found that the values given in the about table are consistent with most modern small turbofan engines. Because the

aircraft concept is design to operate in 2058 the above specific fuel consumptions were considered to be too high given the current state of the world's energy sources (see Fuel Research Chapter for more information).
Again looking towards GE research was directed towards larger turbofan engines such as the GE90 series and the newly announced GE-NX series turbofan engines. Both of these engines utilize state-of-the-art airfoil and combustor designs and are among the largest, most powerful and most efficient engines in production today. These advancements in much larger turbofans gives hope that as technology and manufacturing capabilities increase in the future that similar advancements will be made in the smaller turbofan engine industry.

7.1.3 Turboprop-Fan

The prop-fan system offers many desirable performance characteristics. Because the bypass ratios of the prop-fan are on the order of 20-35, the prop-fan system accelerates a larger mass of air, to a slower overall speed than that of turbofans, effectively achieving greater efficiency. This platform is known to achieve SFCs which are on the order of 15 % lower SFC than that of the turbofan [21]. Also, the propeller of the prop-fan is designed specifically for transonic operation. Although prop-fans are highly efficient, they are not as powerful as turbofans, are known to have acoustical issues associated with the supersonic propeller tip speeds when traveling in the transonic realm. Public perception of the prop-fan is also an important issue, as propellers are generally thought of as being obsolete. Also, the very large diameter propellers characteristic of prop-fan systems would not be easily integrated into a blended geometry. For these negative reasons, the prop-fan was not adopted.

7.1.4 Decision

The design of the aircraft's propulsion system presented a challenge due to the given efficiency, noise and pollution requirements. Because of these it was decided to remain with the initial concept of using turbofan engines to power the aircraft. As stated in the Propulsion Research Chapter, turbofan engines are generally more efficient and quieter then other jet-type engines while still providing adequate amounts of thrust to meet our design needs. The following sections will summarize the placement; the sizing and selection of the propulsion system as well discuss the provisions made for the integration with powered, high-lift devices.

7.2 Configuration

First consideration for this design was the number and arrangement of engines to use. Immediately it was decided that four small turbofan engines would be the minimum required for this aircraft (see Digital Throttling Section). The question was then whether the design consists of four engines or a like design (4x1) or two sets of two engines in like design (2x2). Both options allow for the same amount of total thrust and total weight and both offer similar advantages with digital thrusting. However, the 2x2 option present several problems. The first is that even though enough thrust is provided at takeoff the two smaller engines may not be able to provide adequate thrust during cruise whereas the two larger may provide too much and be less efficient. The second disadvantage to the 2x2 system deals with cost. Put simply, it would be more costly to provide support and maintenance to two different types of engines than it would be to one. Because of these disadvantages it was decided that the 4x1 concept was the best option for this aircraft design.

7.3 Engine Sizing and Selection

Because this aircraft is being designed to be ready for service in the year 2058 it is hardly accurate to assume that the design will use an engine used in today's aircraft. However, only speculation can give rise as to what kind of turbofan will exist in fifty years so it is important to look at the performance of modern turbofan engines and how it has improved over the previous fifty years so a logical deduction can be made about the performance characteristics of a future turbofan engine.

Arguably the most important aspect of an aircraft engine is the amount of thrust the engine can provide. Traditionally the thrust at takeoff has been the determining factor in engine selection and this always resulted in engines, which although providing adequate thrust at takeoff, were severely over-designed for cruise conditions. However, as discussed in the Technology Decisions Chapter this design will be utilizing the concept of digital throttling and therefore the thrust required is strictly based upon cruise conditions most notably the drag encountered during cruise.

As discussed in a previous section the engines will be housed internally with the complete propulsion system taking up the entirety of the inner wing sections of the aircraft. The design states the inner wing will have a span of twelve feet and a length of sixty feet. While engine length is not unrestricted, the overall diameter of the engine must be chosen to give sufficient space within the inner wing to allow for the other engine systems such as fuel delivery and lubrication as well as insulation between the engines' mounting locations and the passenger cabin nearby. Given these constraints it was decided that an overall engine diameter of forty-eight to fifty-four inches would be the maximum allowed. This allows for four extra feet of space allotted for the items discussed above. Due to the shape of the airfoil used for the inner wing it was decided the maximum length of the engine should not exceed ten feet or 120 inches. Knowing the thrust required and general sizing constraints a modern engine with these properties could be analyzed. The engines were designed in a way such that two engines operating a near full output will provide more than 9,500 lb of thrust at altitude.

It was found that the required engines for this aircraft most resemble the GE CF34-8/10 series turbofan engines. It can be seen that this turbofan engine matches closely the desired properties outlines above. However, modern turbofan engines, while efficient from today's standards, may not be able to operate in the oil-depleted world fifty years from now. Using the engine program GasTurb the properties of the CF34 series engines were modified in a way to model the progression of engine technology over the next fifty years. The chart below summarizes some important specifics of the engines desired:

Property	Quantity
T/O Thrust (lb)	18,000
Cruise Thrust (lb)	4,800
Max. D (in.)	54
Max. L (in.)	110
W (lb)	3000
BPR	7.0
OPR	25.5
T/O SFC (lb/hr/lb)	0.26
Cruise SFC (lb/hr/lb)	0.55

Table 5 Table of some properties of the desired engine to be used

As can be seen in the table above a drastic reduction in engine specific fuel consumption is anticipated. Note also that the values in the table above assume a fuel type similar to current JP-4 jet fuel. With large engines such as the GE-90 exhibiting takeoff specific fuel consumptions as low as 0.52 lb/hr/lb it is not hard to assume that within fifty years this technology will have extended down into the smaller turbofan engines. The above data shows that with all four engines running at maximum power and the total vehicle weight of 178,000 lb results in a thrust-to-weight ratio of 0.4 at takeoff. This concludes the engine design aspect of the propulsion system. The next section will summarize the engine placement and integration within the airframe itself.

7.4 Engine Placement and Integration

The first requirement to meet for this concept was a reduction in noise from modern aircraft. Because of this requirement it was agreed that either a partially or completely blended engine system was needed. To reduce ram or appendage drag it was decided that a completely internal engine system was the most desirable. This would allow for the reduction of external engine noise as well as the reduction of drag that would usually be a result of nacelles. The size of the aircraft designed sans engines allows for much more cargo capacity than required by this competition. It was decided that the inner wing portions of the aircraft were not needed for cargo or passenger space so it was determined this space would be utilized solely for the integration of the propulsion system.

The design calls for completely internal-mounted engines with the intake being placed at the leading edge of the airfoil. The engines themselves are placed at ten percent of the chord length from the leading edge allowing for a six foot intake duct used to slow the incoming transonic air to subsonic speeds acceptable by the engines. The exhaust outlet from the engines involves a thrust diversion system that both allows for the incorporation of upper-surface blowing or dumping lift when not needed through what is essentially lower-surface blowing. The exhaust outlet consists of a split-pipe layout similar to "y-pipes" seen in exhausts of automobiles. However, instead of exiting on opposite sides the exhaust can exit either via outlets on the upper or lower surfaces placed at fifty percent of the chord length or thirty feet. To control which path is taken an internal flap diverts the exhaust to the upper, lower or a combination of both routes depending on the flight condition needed. When high lift is required the exhaust will be routed out the upper surface whereas when higher speeds are required the exhaust will be routed more out the bottom of the wing. More of this will be in the next discussing the aerodynamic aspects of the design.

7.5 Hydrogen Option

As mentioned earlier the possibility for the use of liquid hydrogen is available despite its low fuel volume. In order to allow for a zero-emission variant drastic changes to the engine layout and design had to be made. The first change that was required was the removal of two of the four total engines. Although with this the digital throttling aspect is loss the extra space gained from the removal of the outer most engines is required for the storage of fuel due to liquid hydrogen's low fuel volume. However, because two engines have been removed it was necessary to design yet another larger and more powerful engine type, to be fueled by liquid hydrogen, to allow the aircraft to fly. A thrust-to-weight ratio of 0.33 was decided for takeoff so that resulted in the necessity for two 30,000 lb_f engines. GasTurb was once again used and the chart below summarizes the final liquid hydrogen-powered turbofan design:

Property	Quantity
T/O Thrust (lb)	30,000
Cruise Thrust (lb)	8,600
Max. D (in.)	52
Max. L (in.)	110
W (lb)	3500
BPR	6.0
OPR	25.2
T/O SFC (lb/hr/lb)	0.1176
Cruise SFC (lb/hr/lb)	0.2188

Table 6: Table of some properties of the desired liquid hydrogen-powered engine

While the above engine is operating in a tradition sense in that it is severely overpowered for cruise (one engine alone could nearly power the aircraft) the improved specific fuel consumption from the use of hydrogen clearly offsets this despite the need for much larger fuel space. This engine and its coinciding concept is not the primary design of this project but rather a possible variant that could be used assuming an improved hydrogen-as-fuel infrastructure.

7.6 Digital Throttling Performance

Digital throttling is at the heart of the STINGRÆ's design. By shutting down two of the four engines once the cruise conditions have been met, the two that remain in operation are allowed to operate closer to their local maximum thrust which corresponds to their lowest possible SFC. The SFC vs. % Throttle curve for the STINGRÆ's engines are presented in Figure 9. Figure 9 confirms that turbofans are most efficient when operating near max throttle. The required throttle over the entire cruise segment of the

STINGRÆ's mission is shown in Figure 10. Because of digital throttling, the STINGRÆ operates between 0.85 and 0.75 max throttle which is much higher than if the STINGRÆ used all four engines during cruise.

Property	GE CF34-8/10 [26] Series	STINGRÆ Base Model and Type-M	STINGRÆ Type-H
$T_{T.O.}$ (lb_f)	14,500-18,820	18,000	30,000
T_{cruise} (lb_f)	4,000-5,000	4,800	8,600
Max Diameter (in)	52.0-57.0	54.0	52.0
Max Length (in)	90.0-128.5	110.0	110.0
Weight (lb_f)	2,480-3,800	3,000	3,500
BPR	5.0-5.3	7.0	6.0
OPR	26.3-28.5	25.5	25.2
$SFC_{T.O.}$ (lb/h/lb)	0.37-0.39	0.26	0.11
SFC_{cruise} (lb/h/lb)	0.65-0.68	0.55	0.22

Table 7 Summary of STINGRAE and Comparison Engine Properties

Finally, the SFC over the entire cruise range is presented in Figure 11. The STINGRÆ operates with an SFC under 0.58 over the entire cruise range, which is very efficient compared to modern aircraft that do not utilize digital throttling.

7.7 Fuel Choices

7.7.1 Synthetic Kerosene

A great amount of research and development has been given to the development of synthetic fuels; most notably the Fischer-Tropsch Synthetic Fuel often abbreviated FT Synthetic fuel. This fuel type was developed in Germany during the Second World War in response to the allied bombing of German oil fields. The process starts with the gasification of a source of carbon after which the remaining carbon dioxide and hydrogen gas are converted into very long hydro-carbon chains. These chains are then broken down and rearranged to give desirable fuel properties. This process is completely synthetic and even though it currently uses coal as the carbon source, any source of carbon can ideally be used such as biomass. This fuel is very similar to the current jet fuel used and can even be mixed with it to allow for a smoothing transition into complete synthetic fuel use. Because the synthesis process is closely monitored the fuel contains little to zero sulfur-based or nitrogen-based compounds and therefore emissions of those particulate as vastly decreased. However, this is a heavy carbon-based fuel and carbon dioxide emissions are still a concern. Because of these traits and the current successful use of FT Synthetic fuel in one engine of an Airbus A380 it was decided that this would be the preferred fuel choice for this design with potential provisions for the use of liquid hydrogen in the future.

7.7.2 Liquid Hydrogen

The alternative fuel considered, liquid hydrogen, has the best specific energy but also the lowest energy density due to its very low density. Because of this it requires about four times the volume of liquid hydrogen to provide the same amount of energy of current jet fuels. Liquid hydrogen is cryogenic and must be stored at temperatures of -253 degrees Celsius to remain in a liquid state. Hydrogen does however allow for the least amount of particulate emissions due the absence of other compounds in the fuel; zero sulfur-based and carbon-based compounds are emitted from burning hydrogen as a fuel. Although liquid hydrogen fuel provides the best energy per unit mass and has lowest particulate emissions, liquid hydrogen is not feasible at this time as a primary fuel source. However, this concept incorporates a liquid hydrogen-fueled variant that will have only two engines and provide a lesser operating distance (see Propulsion Chapter).

7.7.3 Biodiesel

For completeness it is necessary to discuss fuel options that were not pursued. This consideration was biodiesel. This fuel possesses many similar qualities as current jet fuel but has better lubrication properties than current jet fuels; this could result in prolonged life in certain applications. As with hydrogen this fuel also contains little to no sulfur therefore causing very little sulfur-based compounds to be emitted when burned. The biggest disadvantage to using biodiesel as a fuel is its freezing point which is far above the ambient temperature at cruise altitude. Another disadvantage to biodiesel is that in its nature as a predominately carbon-based fuel it actually emits more carbon-based compounds, such as carbon dioxide, than current jet fuel. Because of these last two reasons it was decided that biodiesel also was not a viable fuel option.

8 Mission Performance

In this section, the overall mission performance of the STINGRÆ is presented. The performance discussion in this section is limited to the design case of 50,000 lbs of payload and 50,000 lbs of fuel. The performance in each flight regime is described below.

8.1 Takeoff Performance

At take off, the STINGRÆ operates with the T/W of 0.4, a CLmax of 5.0, and a W/S of 135lbs/ft^2. The resulting take off performance as calculated from the take-off parameter (EQ1) is shown in Figure 12 with the corresponding data in Table 5. The STINGRÆ achieves takeoff in 2,370 ft requires a balanced field length of 2800 ft, which is below the maximum runway length required by NASA RFP.

8.2 Cruise Performance

Once the STINGRÆ has climbed to a cruise altitude of 30,000 ft, the cruise segment begins. Using a mission program to iterate the range equation, plots an L/D and total aircraft weight were created. These plots are shown in Figures 13 and 14 respectively.

C_{Lmax}	5.0
V_{stall} (ft/s)	150
$V_{T.O.}$ (ft/s)	165
Segment	Length (ft)
Acceleration	1200
Rotation	500
Clear 35 ft obstacle	570
Total Take Off Distance:	2370
Balanced Field Length:	2800

Table 8 Takeoff Distance Segments

Both plots show that digital throttling significantly increases efficiency and range. The lift to drag ratio of the STINGRÆ base model is initially 20.7. This value is much higher than current aircraft which have an L/D of about 18 [5]. As fuel is burned, total weight, lift, and drag all decrease, which causes the lift to drag ratio to drop to about 18.75 over the entire cruise range. Figure 14 shows the total weight of the STINGRÆ over the entire cruise range.

8.3 Loiter Performance

The STINGRÆ has enough fuel to cruise for 4000nmi and then loiter, if necessary for up to 80 minutes. Loiter occurs at maximum L/D, which is about 22.0 for the STINGRÆ.

The corresponding loiter Mach number is about 0.6, which minimized the drag due to compressibility effects.

8.4 Landing Performance

The STINGRÆ is able to land within the required 3000 ft landing field length. Landing performance and data are shown in Figures 15, 16 and Table 6 respectively. Assuming 10% maximum thrust from idling all four engines, and with the deployment of high lift devices, a lift coefficient of 3.5 is easily obtained during landing.

C_{Lmax}	3.5	3.5
Descent Angle	$-1.5°$	$-2.5°$
V_{stall} (ft/s)	153	170
$V_{approach}$ (ft/s)	200	220
Aprroach Distance	1,700	1,000
Segment Length (ft)		
Flair	150	300
Touchdown/Groundroll	2200	2500
Total Landing Distance:	2350	2800

Table 9 Landing Distance Segments

8.5 Range-Payload

The range-payload diagram for the STINGRÆ is shown in Figure 17. Observing the aircraft properties in Table 1 and the range-payload diagram, it is shown that the STINGRÆ carries 6,000 lbs more payload than the 737-800, 4,000 lbs more fuel, yet travels approximately 1,500 nm farther than the 737-800. Just analyzing the design range to design fuel weight ratio, R_{design}/W_{fuel} reveals that the STINGRAE travels .08 nm/lb_{fuel}, while the 737-800 travels .047 nm/lb_{fuel} assuming that the difference in payload is negligible, this shows that the STINGRÆ is on the order of 30% more fuel efficient than the 737-800 when considering only design range and design max fuel.

9 Structural Considerations

9.1 Wingbox Design

Analysis and sizing of a wing box for the structure of the aircraft was performed with the aid of PDCYL, an analytical program produced by NASA. Some assumptions were made in order to have the program size a single piece wing box for the outer wing, which ran through the body of the aircraft. It was assumed that the large, inner portion of the wing, which houses the engines, was not a part of the aircraft and that the structure in the smaller, outboard, portion of the wing carried all of the lifting forces on the aircraft. This assumption actually led to a slightly over-designed wing box, due to the fact that the inboard wing structure would probably alleviate some of the loading on the wing and thus make a lighter wing box possible. The spar spacing used was 15% of the chord for the first spar and 55% for the second spar. Moving the location of the second spar further back towards the trailing edge of the wing makes a lighter wing box possible; however towards the wingtips there is not enough space to fit the box inside the wing.

Four different materials were tested with the program to see which allowed for the lightest weight wing box. Carbon Fiber gave the lowest weight compared with titanium, aluminum, and carbon nanotubes. Using carbon fiber composite material led to a wing box weight of just 5,671 lbs and a maximum wingtip deflection of 2.12 feet.

9.2 Materials

An important aspect of the design of the aircraft is the materials selection process and structural layout. Due to the nature of the design, creating an aircraft which is intended for use in the year 2058, many cutting edge and revolutionary materials are likely to be available. Though many of the standard aerospace materials will be used, there are also some exciting new materials which may be incorporated into the design of the STINGRÆ.

Aircraft have traditionally been composed mainly of metals and metal alloys such as aluminum, titanium, steel, magnesium, etc. Aluminum has always been a very popular material for use in aircraft structures due to its abundance, ease of processing, and cost. Aluminum is also fairly corrosion resistant and has a fairly high strength to weight ratio. Recently, advances have been made in material processing which have been able to increase aluminum’s strength, ductility and corrosion resistance. Also, a new alloy, Aluminum-Lithium, has been developed which can offer as much weight savings as certain composite materials; however there have been concerns regarding low fracture toughness. Another material which has seen widespread use in the aerospace industry is titanium. Titanium has a better strength to weight ratio than aluminum, higher temperature resistance than steel, and better corrosion resistance as well. Titanium also costs more than aluminum however, and has historically been very difficult to form into desired shapes. A new method of forming titanium called Super Plastic Forming/Diffusion Bonding has been created which is excellent for producing complicated pieces from titanium alloys. Steel, which is an alloy of iron and carbon, is an extremely strong and ductile metal which has a very important, however limited, use in aircraft [16]. Steel is very inexpensive, abundant, and easy to form. Magnesium is another metal which is used rarely in aircraft, which offers extreme weight savings but is highly corrosive and flammable and needs a protective coating.

Another class of materials which has seen more and more usage in the aerospace industry in recent years is composites. A composite is a combination of a reinforcing material which is suspended in a matrix which bonds it together. The reinforcing material can be in particle form, what are called whiskers, or most common, fiber orientation which is essentially sheets of the reinforcing fabric. In general, composites have a very high strength to weight ratio, but only in the direction of the fabric, they are poor in compression, and have low corrosive and temperature tolerances. Another large concern with composites is the difficulty of detecting defects in the material. Fiberglass composites are extremely light but not usually strong enough for most structural aerospace applications. Carbon fiber has extremely good strength to weight properties and is fairly easy to form but is relatively very expensive. It also is very good for usage with titanium due to the fact that it does not corrode when used in direct contact. Aramid, or Kevlar, is another type of composite which can be used for relatively light loading, or in conjunction with carbon fiber to increase the carbon fiber's ductility.

The STINGRÆ will have an airframe which is composed mainly of carbon fiber as well as titanium alloy parts where the extra strength is necessary. The skin of the aircraft will be composed of Kevlar reinforced carbon fiber which will decrease weight while also eliminating rivets on the lifting surfaces, making them smoother. Potentially, carbon nanotube composites could be used in place of the carbon fiber which could drastically reduce the skin weight by decreasing skin thickness as well as density of the skin. Due to the upper surface blowing over the top of the inner wing of the aircraft a high temperature resistant, low weight metal such as titanium may be used to protect the skin from heat damage. The interior parts which are non-load bearing will be composed mainly of fiberglass as well as lightweight plastics. Steel will most likely need to be used for the landing gear due to the extremely high loading on those particular pieces.

9.3 STINGRÆ V-n Diagram

Figure 18 shows the V-n diagram for the STINGRAE aircraft. Important features of this diagram are the max loading factor, set at 3, which is typical for transport aircraft, and the negative max loading factor of 1.5. To create the max lift curve, CLmax was set at 5.0. This gave a stall speed of 150 fps and corner point at "high angle of attack AOA" of 261 fps. The cruise speed at 30,000 ft., adjusted for altitude by normalizing density, is 496 fps. The "Max q" point is representative of the maximum speed or dynamic pressure, estimated at 40% above the cruise velocity or 694 fps.

10 Stability and Control Considerations

10.1 Blended-Wing-Body Stability and Control

The Blended-Wing-Body concept presents many challenges regarding stability and control. In most BWB designs, the center of gravity (CG) is generally aft of the aerodynamic center, and therefore the design is inherently unstable. This instability requires active flight control laws and systems with high bandwidth and fidelity [13]. As result active control laws, the pilot does not directly control the deflections of the control surfaces. Because all of the control surfaces of the BWB are lumped together at the trailing edge, the moment arm resulting from an aft CG location is very small, and therefore greater forces and deflection angles are required to control the BWB during flight. Current BWB concepts attempt to lower the forces experienced by any single control surface by having on the order of 20 coupled and redundant control surfaces, none of which are dedicated to trim the aircraft. [17] These surfaces are called elevons, and can act as elevators, ailerons, and drag rudders; which produce pitch, roll, and yaw moments respectively. The BWB configuration is considered trimmed at the nominal cruise condition where the aerodynamic center of pressure coincides with the gravity and all control surfaces are faired [13, 18]. Current BWB designs utilize large winglets which act as vertical control surfaces and attempt to provide lateral-directional stability. Some of the stability problems associated with the BWB concept is reflected in the STINGRÆ.

10.2 STINGRÆ Stability and Control

The STINGRÆ has a negative static margin of 4 ft, that is, the CG of the STINGRÆ is located 4 ft behind the aerodynamic center. Because of this, the STINGRÆ, like the BWB, is inherently unstable. Unlike the BWB however, the STINGRÆ utilizes semi-traditional control surfaces. The primary control surfaces of the STINGRÆ are the outboard ailerons, V-tail rudders, and elevons located at the trailing edge of the inboard wing. These surfaces were sized by the method described by Raymer [5] and their dimensions are shown in CAD Figure 1. Of particular interest is the V-tail which the STINGRÆ utilizes mainly as a vertical control surface, and to some degree as horizontal control surfaces. Raymer[5] states that V-tails must be sized with the same total area required by traditional elevators and vertical rudders. The size of the STINGRÆ's V-tail, had it been the only aft control surface used, would be required to have a total 2-d area of 470 ft2 . The total 2-d area of the STINGRÆ's V-Tail is 420 ft^2, and is sized primarily to fulfill the role of acting as a vertical control surface. To compensate for the lack of horizontal control surface area, the STINGRÆ has two rear elevons with a combined 2-d area of 187.5 ft^2. Because the STINGRÆhas a very large V-tail which primarily acts a vertical surface, the STINGRÆ has moderate stability in the lateral-directional area, as opposed to the BWB. The inherent longitudinal instability of the STINGRÆ is less of a concern, as much of current stability research focuses in the longitudinal direction [18]. Also, modern fly-by-wire and fly-by-light control systems are known to be able to stabilize inherently unstable systems [18]. By 2058, control technology of unstable systems should be well developed and understood, and therefore STINGRÆ will utilize a robust control system to achieve stability in all flight regimes.

11 Noise Considerations

11.1 FAR Requirements

The Federal Aviation Administration requires all aircraft above 75,000 lbs to meet Stage III noise requirements in order to fly within the continental United States, as described in FAR 36 [9]. It is a very difficult problem to tackle which involves overcoming many technological and regulatory obstacles. Traditional tube and wing aircraft with 2020 technology levels would see an overall increase in operating cost, maximum takeoff weight, NO_x emissions, and fuel weight [19]. In order to reverse that trend and maintain cost-effectiveness, the STINGRÆ Group chose to attack this requirement by primarily integrating the airframe and engines into a BWB-inspired aircraft. Within this configuration, engine thrust loading, exhaust, and aerodynamic efficiency are all factors which can reduce engine noise but also affect overall performance.

11.2 Engine Noise

Engine noise is one of the major contributors to noise pollution. The STINGRÆ integrates the engines within a lifting body, shielding engine noise from outside observers. Inlet and outlets within the body frame provide the air needed to run the HBR engines, and the shielding is projected to achieve a noise reduction in the area of 6 EPNdB [19]. With the engines out of the free stream, air moves with minimal disturbance across the body and wing, ultimately saving fuel and thrust normally associated with nacelle and pylon drag. The noise reduction does not come without penalties, as HBR engines take enormous thrust hits during cruise due to low-speed exhaust [20]. The STINGRÆ compromised with this design feature by adding digitally throttled engines which are tailored primarily for the cruise condition. This allows them to operate at closer to their local maximum thrust at altitude level, thereby achieving higher exhaust velocities. These extra engines being carried during the cruise segment add to the total weight of the aircraft, but the reductions in required fuel, noise, and drag justify the use of digital throttling and establish the STINGRÆ as achieving significantly better efficiency compared to the modern aircraft of today.

11.3 Airframe Noise

Another noise consideration addressed was that associated with airframe drag. Disturbances in the free air flow cause noise, especially during landing and takeoff. The STINGRÆ Group chose airfoil profiles that delayed supersonic shocks and also incorporated USB to achieve high lift with minimal use of flaps. These combined technologies should significantly reduce noise over the complete mission and are based on current estimates and BWB studies [19].

12 Enabling Technologies

12.1 Fully Blended Geometry

The STINGRÆ effectively blends the body, wing, and engines into an aerodynamic shape. There are many beneficial reasons for achieving such a highly integrated geometry, as opposed to that of the traditional tube and wing design. Nacelle and pylon drag is known to contribute significantly to the total drag experienced by a tube and wing aircraft [6]. This drag, as with all components of drag, adversely affects the aerodynamic performance of the vehicle and creates noise. Aside from the benefits in reduction of noise and drag, the integrated geometry of the STINGRÆ was primarily created to allow for two of the engines to be shut off two achieve digital throttling as discussed below.

12.2 Digital Throttling

One of the main issues leading to the inefficiency of modern aircraft it that turbofan engines operate the most efficiently at maximum thrust. In modern aircraft maximum thrust is used only at takeoff and in emergency maneuvers. Because of this aircraft are not utilizing their engines' maximum efficiency potential for the majority of the aircraft's mission.

Digital Throttling is the deactivation of one or more engines during the cruise portion of the mission to increase the efficiency of the aircraft. This requires the remaining activated engines to operate at higher thrust levels therefore resulting in greater engine efficiencies. While this concept has not been accepted in modern aircraft it has already established itself as a means for better fuel economy in automobiles as major manufacturers such as General Motors and Daimler-Chrysler have adopted a similar idea in which up to four cylinder are turned off under light loads (cruise) in their large V8 engines in their trucks and SUVs. For this design the concept of digital throttling will be used to obtain the highest possible engine efficiency by matching the drag or thrust required with the amount of thrust available from two engines during cruise (see Propulsion Chapter). During takeoff all four engines will be operating at maximum thrust and therefore all engines will be operating at maximum efficiency. However, once cruise altitude has been reached, two of the engines will be deactivated. During cruise the maximum thrust required is equal to total drag of the aircraft. Even with two engines deactivated the remaining engines will be able to provide more than 9,500 lb total thrust at altitude which is still more available thrust than drag encountered. This will allow for higher operating engine efficiencies as well as conforming to any flight requirements imposed by FAR 25.

12.3 Upper Surface Blowing

The technique known as upper surface blowing (USB) has been known to be able to contribute very high lift coefficients to medium sized STOL aircraft [28]. In essence, USB is the act of using a powered device such as a compressor or an engine to re-energize the boundary layer of the fluid flowing across the upper surface of the wing. The flow is accelerated over the upper surface of the wing, which creates lower local pressure coefficients, and hence creates greater lift. The YC-14 is one aircraft which utilizes USB, and is known to have achieved real lift coefficients on the order of 7.5 at high angles of attack [15]. A generic graph showing the 2-d lift contribution from a single engine at various jet (thrust) coefficients and angles of attack is shown in figure 8 from Keen. The actual real 3-d lift coefficients resulting from USB will be less than the idealized 2-d coefficients. Lift contributions from clean geometry, flaps and slats is known to be on the order of no more than 3.0 [6], therefore the two USB engines on the YC-14 are able to increase the max lift coefficient of the aircraft on the order of 4.0 . This implies that each of the two engines on the YC-14 can realistically increase the lift coefficient of the YC-14 by 2.0. It is this experimental data that is the primary justification for the STINGRÆ being able to achieve a lift coefficient at take off of 5.0, which is considerably less than the maximum lift coefficient recorded in YC-14 data. Figure 19 shows the inner wing design of the STINGRÆ which allows for USB.

12.4 Augmenter Wing Consideration

Again for completeness concepts not included in the final design are discussed. A previous consideration for a powered-lift device was the augmenter wing system. Jet augmenter wings are a type of high-lift device in which hot exhaust gas from the aircrafts engines is exhausted between two flaps on the trailing edge of the wing. The high velocity exhaust can then be redirected by deflection of the flaps down, potentially up to an angle of 60 degrees. This deflection in essence acts as a thrust vectoring, where during takeoff, the engines can actually be producing upwards lift on the aircraft, thus shortening the takeoff distance necessary. The augmenter wings also increase lift over the wing because low energy air on the top of the wing surface is sucked through the small opening slit between the augmenter flap and the rear of the wing, thus reducing the adverse pressure gradient over the top of the wing slightly and improving flow attachment. Test cases on an unswept wing have shown a possible maximum lift coefficient of up to 6. The augmenter flaps also act in some way as a nozzle for the hot exhaust gasses, whereas a normal turbofan does not have a variable geometry nozzle. The two flaps can move independently and have been shown to be able to increase the maximum thrust of the engine by 1.3 times.

The major benefits to jet augmenter wings were clear: higher lift, higher thrust, and thus a shorter takeoff distance. The system was also conducive to having engines which are blended into the wing, since the exhaust is simply ported out of the trailing edge of the wing. A major problem associated with blending the engines into the wing however, is the amount of ducting which would be necessary. Potentially 30 feet of ducting between the exit of the turbofans and the trailing edge of the wing would have been necessary. The friction losses in that long distance were deemed to be too high to make the system effective and therefore this concept was dropped..

12.5 Wingtip-Turbine Energy Recuperation

It long been known that a significant portion of the total drag of an aircraft is the drag that is induced as a result of generating lift. The embodiment of the induced drag is the fluid phenomenon of the shed vortices resulting from high and low pressure fields interacting. It is further well known that much of the total strength of these shed vortices is located just behind the wingtips of an aircraft as it moves through the air. Within the past 20 years, there has been interest within the aviation industry regarding ideas of possible schemes which attempt to recuperate some energy from the trailing vortices which would otherwise be lost [23].

12.5.1 NASA WTT experiment

NASA investigated the concept of possible energy recuperation from the trailing vortices of an aircraft as described by Moore [24] of NASA Langley More states that the experimental setup tested by NASA consisted of retrofitting two wingtip turbines to a Piper PA-28 general aviation aircraft. The rate of rotation governed by a gearbox, and the shaft of the turbines were attached to a brushless motor. During takeoff, the brushless motor was used to drive a compressor which provided high lift in the form of boundary layer circulation control over the majority of the PA-28's wing. During cruise, the rate of rotation and the pitch angle of the wingtip turbines were varied. The results of the experiment are discussed below.

The NASA wingtip turbine experiment showed many promising beneficial and novel uses for wingtip turbine systems. NASA found that they were able to extract up to 5hp from the WTT system by varying the pitch angle and rate of rotation of the turbine blades during cruise. More power could be extracted, at the cost of increased vehicle drag. It was also found that the cruise drag of the vehicle could be reduced by up to 1.5 drag counts. During takeoff and landing, the wingtip turbine circulation control system was found to increase the lift coefficient of the Piper PA-28 aircraft up to a total value of 4.0 and 2.5 respectively. More also notes that the net effect of this type of high lift system was to allow for a reduction in required wing area from 174 ft2 to 105 ft2. The experimental setup and resulting data collected from the cruise conditions are shown in Figure 20[24] .

It should be noted that Moore states that ideally NASA was interested in whether this method of power recuperation could first be justified experimentally, and then expanded to include medium to large sized jet transport aircraft. Analyzing the data, produced from the NASA WTT cruise investigation, shows that 5 hp was extracted without drag penalty. Knowing the wing area of the of Piper PA-28 to be 172 ft2 , and assuming an Oswald efficiency factor of 0.8, allows the induced drag coefficient to be calculated as 0.0072 corresponding to an induced drag force of 181 N. When this value is multiplied by the metric equivalent of 140 mph, the resulting power of the total induced drag is calculated to be 11 kilowatts. When converted to horse power, this value is just over 15 hp. Because NASA was able to extract up to 5hp without drag penalty, this implies that roughly a third of the total power lost in the induced drag can be recuperated. A recuperation of one third of the power associated with the induced drag of an aircraft of the same weight as the STINGRÆ would result in a power extraction on the order of 1100hp. The NASA WTT experiment and the resulting analysis of the power associated with the induced drag of the PA-28 and of a medium sized jet transport serve as the basis for justification of the STINGRÆ eliminating the need for an auxiliary power unit during cruise.

12.6 "Kneeling" Landing Gear

Short takeoff aircraft traditionally use a high, very large horizontal tail for rotation in order to rapidly rotate and achieve the desired angle of attack to increase lift during takeoff. The STINGRÆ will use a different mechanism to rotate, namely the main rear landing gear struts will retract 7.5 feet to squat the rear of the aircraft. With the current spacing of the nose and main gear relative to the aircraft, as seen in the structures section of this paper, this squatting will give an angle of attack of 10 degrees.

The benefit of avoiding the addition of a high horizontal is great. The main sizing criterion behind high, horizontal tails is that they are designed primarily to produce rotation and achieve high angles of attack at take off. Therefore, STOL tails are oversized for the cruise condition, and create much drag in the cruise regime. By using the landing gear to achieve the necessary angle of attack at take off, this technique eliminates the need for a high horizontal tail. However, other longitudinal stability criteria must be met, as described in the Stability and Control Consideration section of this report.

13 Cost Estimation

One feature which made the DC-3 aircraft so popular was the production cost. To briefly estimate projected production costs for the STINGRÆ a method employed by Raymer [5] was used. The Research, Development, Test and Evaluation Costs are broken down as shown below:

Category	Cost
Engineering Cost	$5,058.6
Tooling Cost	$2,997.6
Manufacturing Cost	$10,748.1
Development Support Cost	$8.08
Flight Test Cost	$22.6
Materials Cost	$6,678.9
Cost of engine, prop and accessories (4)	$33.6
Cost of avionics & instruments	$0.25
Total Cost of the Program	$25,547.73*

*All cost in millions of year 2008 dollars

Table 10 Cost Estimation for STINGRAE

The table above shows the estimates for the total cost of the STINGRÆ for a fleet of 300 aircraft to be roughly $25 billion, approximately $83 million per aircraft. This estimate is reasonable considering the Boeing 737-800 is between $70 - $80 million and has been in production for a few years now.

14 Feasibility Discussion

The STINGRÆ not only meets all of the main requirements, but overall establishes some means to justify them. The use of current technology platforms and model validates some features of the STINGRÆ. Still, there are areas in the design such as detailed structural configuration and overall aircraft stability which have not been completely discussed within this report. So, while many of the technologies and areas of design are justified individually, in combination, there are still conflict areas which need to be reformed and resolved, as discussed later in this section.

There is significant evidence in the aforementioned areas of aerodynamics, propulsion, and high lift which make the claims of short takeoff and landing capability of the STINGRÆ realistically possible. The basis for short takeoff and landing depended primarily on the takeoff parameter equation discussed earlier. However, a more in depth takeoff analysis and aerodynamic modeling tools is required for further investigation. Throughout the design, multiple programs such as Tornado, TSFoil2, and Friction.m were used to model and calculate the aerodynamics of the design and consistently returned reliable results for drag, lift, and pressure coefficients, etc. The design team also accounted for factors which represented the high-lift devices used throughout the aircraft. These calculations, combined with the four 18,000 lb-thrust engines and refined weight analyses, serve as the foundation to realistically suggest that the STINGRÆ can takeoff and land in less than 3000ft.

Another design feature of concern is the internally shelled engines. This design feature is extremely practical in regards to minimizing the ambient noise outside of the aircraft since the engine noise is buffeted by the inner wing frame. Still, the ducting systems which make USB possible for the STINGRÆ have the potential to interfere with the main inner wing structures, making it difficult to gauge the true structural integrity of the design. This style of engine blending also makes maintenance an issue given that the engines are completely surrounded by walls and duct-work.

Other problems arise in determining the stability control laws and overall functionality. Although the proportionally sized V-Tail and horizontal control surfaces ideally can handle longitudinal instability with the aid of modern fly-by-wire or fly-by-light systems, controls laws would have to be created to account for the longitudinal instability of the STINGRÆ. Secondly, the hydrogen variant of the STINGRÆ has a limited range compared to the FT synthetic versions. The range requirements are not stated explicitly in the NASA RFP, but do determine the competitiveness and functionality in relation to real world utilization. The hydrogen variant can serve as an economic and environmentally friendly aircraft used for short point-to-point transport missions, while the commercial and military variants manage the longer transport trips.

15 Conclusions

The STINGRÆ designed for short takeoff and landing, transonic cruise, and low environmental impact, is the future of versatile aircraft. It meets the NASA RFP requirements for operation on 3000 ft runways with an innovative combination of established technologies. The STINGRÆ achievements are shown in Figure 21. The upper surface blowing and circulation control is maintained by both the engines and wing tip turbines, which also double as either a primary or secondary auxillary power unit within the aircraft. The STINGRÆ also accomplishes transonic cruise Mach 0.78-0.82, another NASA requirement. The cruise speed is possible because of a the specially designed engines which produce the thrust required at high efficiency, and also the supercritical wing profiles which reduce the onset of shockwaves and wave drag. Finally, the hybrid tube-and-wing-BWB design not only makes USB possible over most of the aircraft body, but also allows for internally mounted engines, a feature which has significant noise reduction properties. Overall, the STINGRÆ design addresses all of the necessary design requirements, and even accounts for future changes in the economy and resources by making a variant which does not depend on fossil fuels. Environmentally, the STINGÆ projects less negative effects as compared to modern aircraft, and further studies will determine if this design can truly go into production by the year 2058.

16 Epilogue

The STINGRÆ is an innovative concept comprised of a combination of well established and not-too-distant future technologies, created by a group of six Virginia Tech undergraduate students over the course of an academic year. Although the STINGRÆ is presented as an environmentally friendlier STOL solution aircraft for the challenges of the future, there are still several areas of major concern which need further analysis and investigation. These areas are outlined in the Feasibility Discussion chapter of this report. This uncertainty within the design, combined with the fact that the STINGRÆ is proposed to come into service in 2058, renders this report as the product of a broad, “quick-run” through the design process. The following sections outline the major weaknesses of the STINGRÆ design, as well as the major accomplishments and pitfalls of the STINGRÆ Group.

Aside from the major areas of uncertainty within having to do with stability, control, and structural concerns of the design, the following are major weaknesses of the STINGRÆ design:

1. No experimental data regarding actual noise and drag levels is offered to verify the concept.
2. The level of integration yields a high degree of design complexity.
3. The designed passenger capacity is less that current aircraft.
4. Windowless cabin and egress issues resulting from blended geometry are not fully solved.

Despite the weaknesses of the final STINGRÆ design, the following are considered major accomplishments of the STINGRÆ Group:

1. Proved that the combination of digital throttling and blended geometry can greatly increase efficiency of medium sized aircraft.
2. Created an innovative concept for future aircraft.
3. Established preliminary analysis in the areas of aerodynamics, performance, weight allocation, and propulsion.
4. Created the necessary Computer Aided Drawings to illustrate the concept visually.

Concerning the outcome of the overall design process, the STINGRÆ Group realizes the following mistakes and pitfalls experienced, as lessons learned:

1. The Group should have chosen a final concept by the end of the first semester, at the latest.
2. Realistic goals and deliverables concerning which problems/disciplines of the design would be addressed should have been established as early as possible once the final concept was chosen.
3. The expected structure of the final report to NASA and the level of detail required of the CAD should have been realized at the beginning of second semester.
4. The Group should have not returned from Winter and Spring Breaks empty-handed.

Appendix A: Figures

Figure 1: The Boeing YC-14 Prototype [2] which heavily utlizes USB.

Figure 2: The next-generation Boeing 737-800 [4]. This aircraft serves as the modern comparison aircraft for the STINGRÆ .

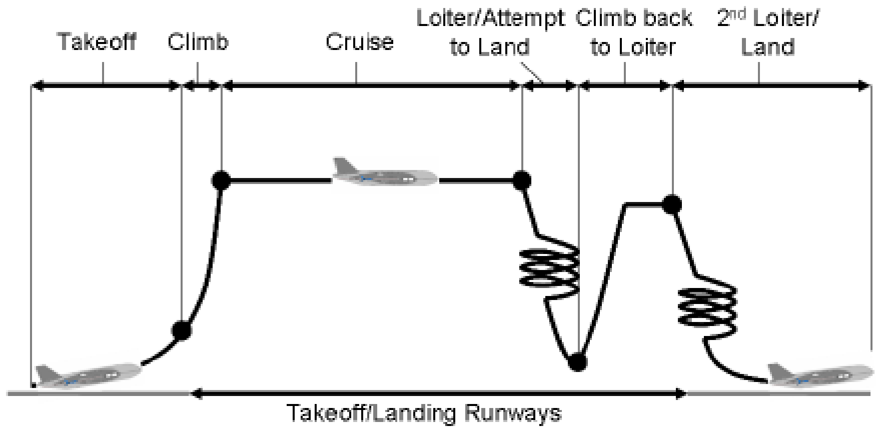


Figure 3: STINGRÆ Mission Profile

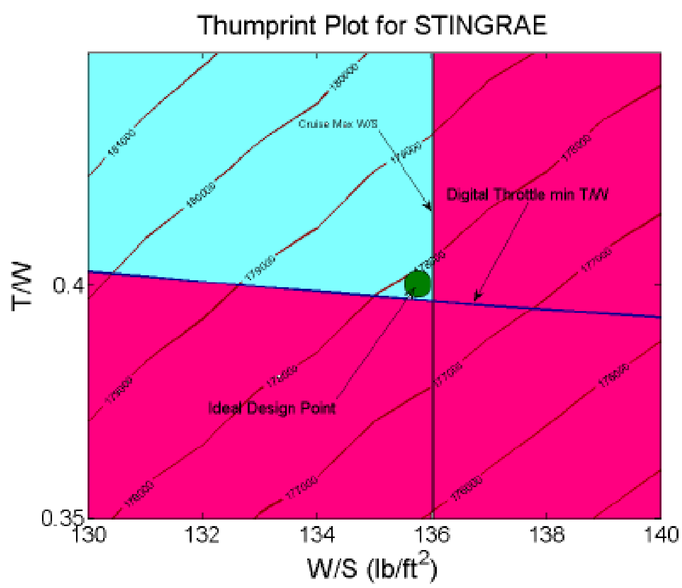


Figure 4: The STINGRÆ's Thumprint Plot shows that a T/W of .4 and a W/S of 136 lb/ft^2 at a MTOW of 178,000 lbs are the idealized design parameneters when the engines area sized for digital throttling.

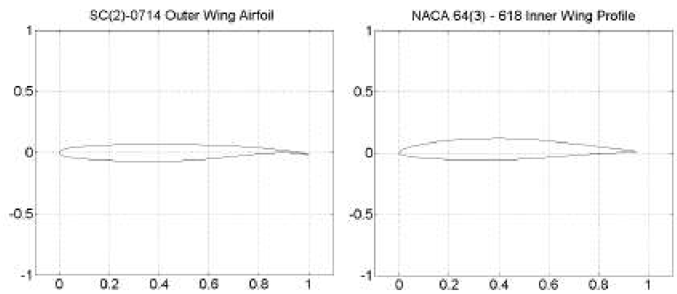


Figure 5: The airfoils selected to model the inner and outer wings of the STINGRÆ

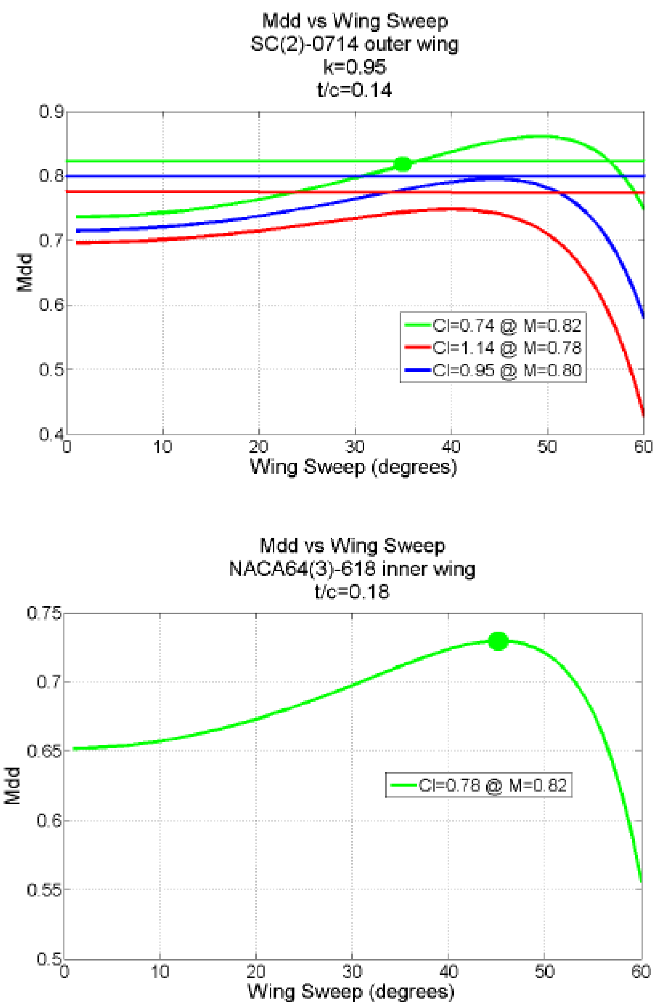


Figure 6: The optimal amount of sweep for the inner and outer wings was determined with the Korn equation to be 45° degrees and 34.4° , respectively .

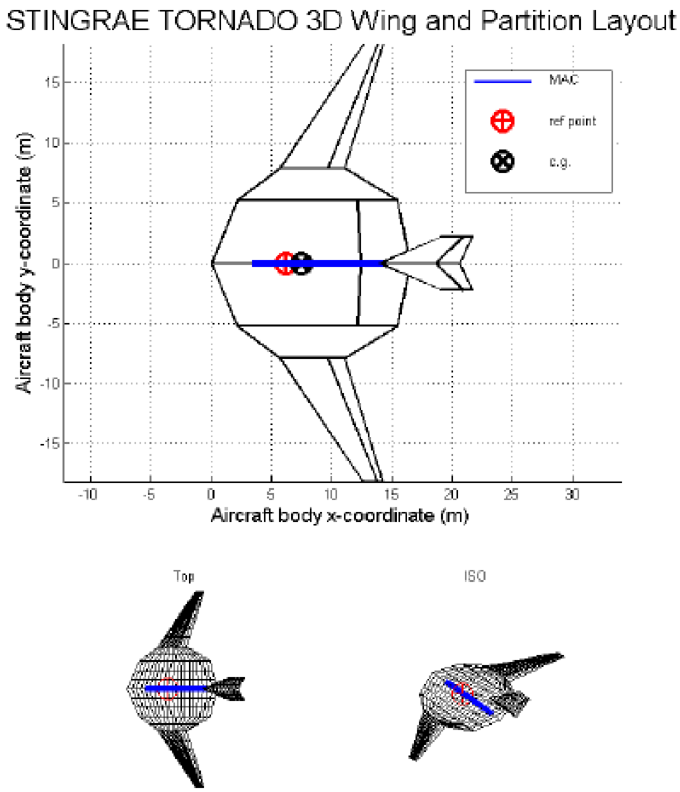


Figure 7: The STINGRÆ planform geometery model in TORNADO.

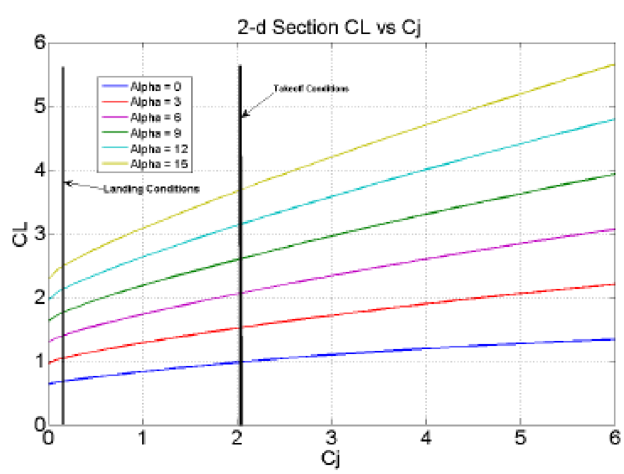


Figure 8: 2-d lift contributions from a single engine providing USB. Cj is the jet or thrust coefficient. The corresponding jet coefficeint vlaues at takeoff and landing are shown by the verticle lines.

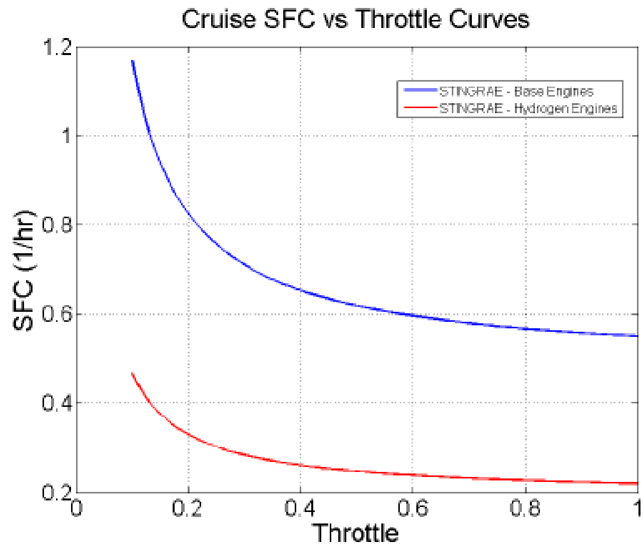


Figure 9: SFC is decreased as turbofans operate more towards local max throttle

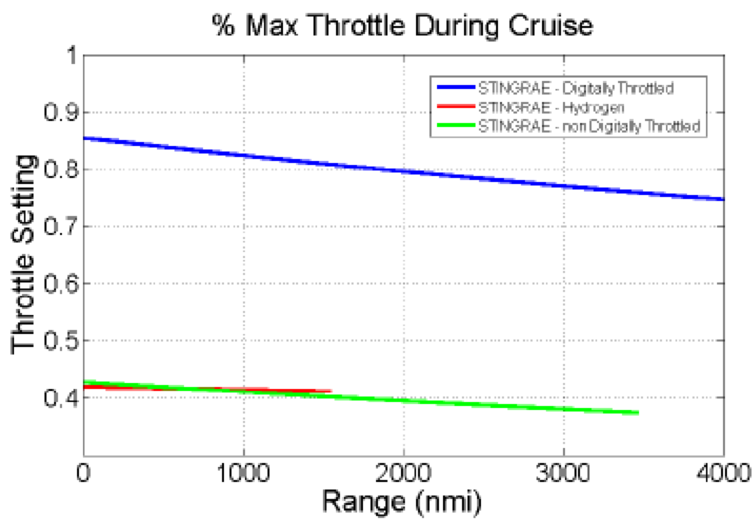


Figure 10: Throttle required during cruise.

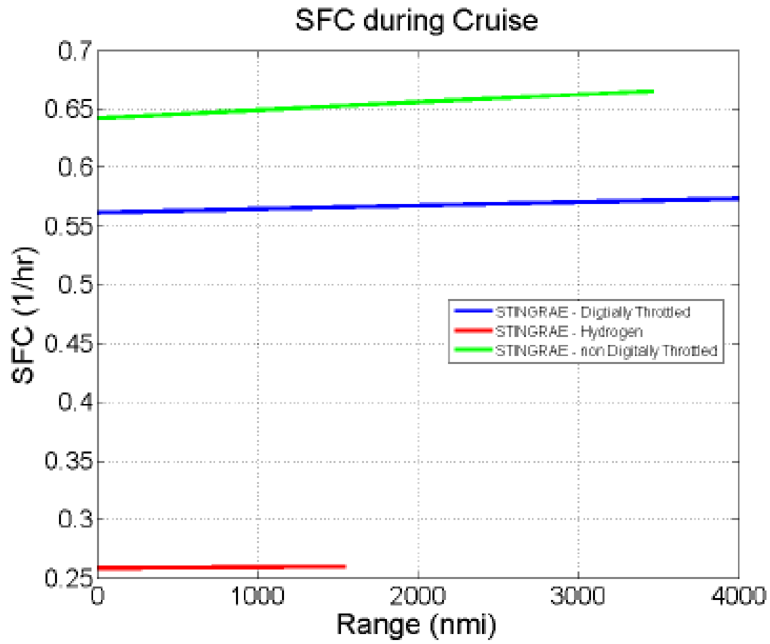


Figure 11: SFC values over the distance traveled.

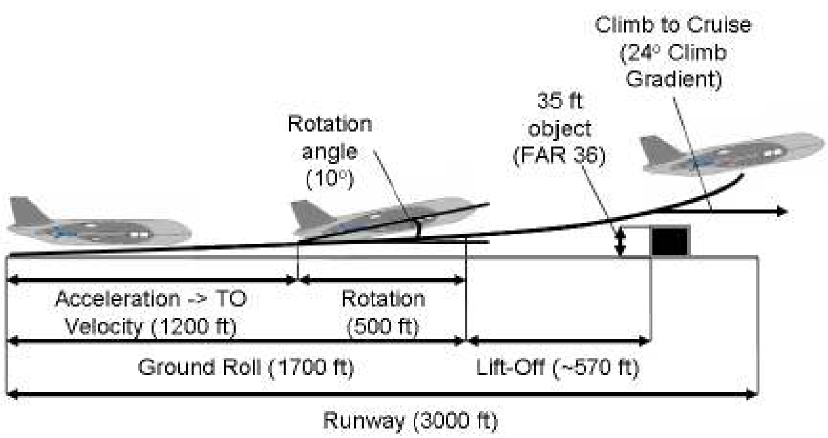


Figure 12: STINGRÆ Takeoff Performance

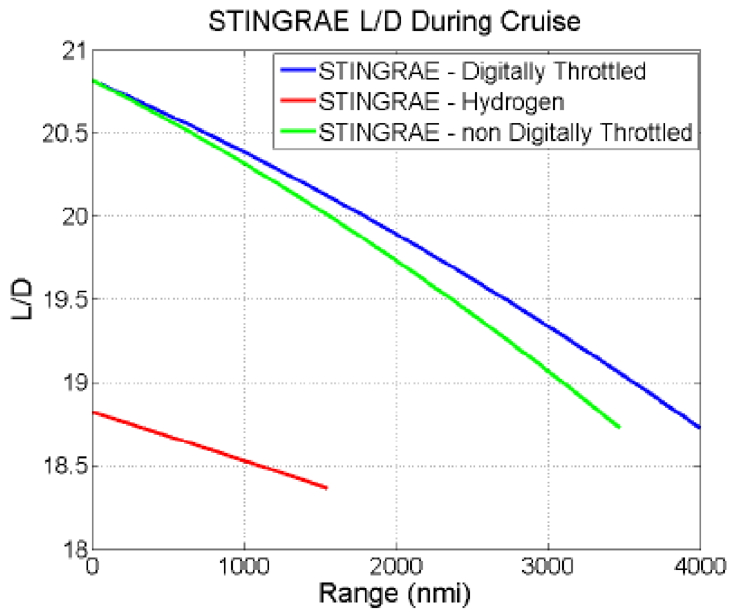


Figure 13: STINGRÆ L/D over the cruise range.

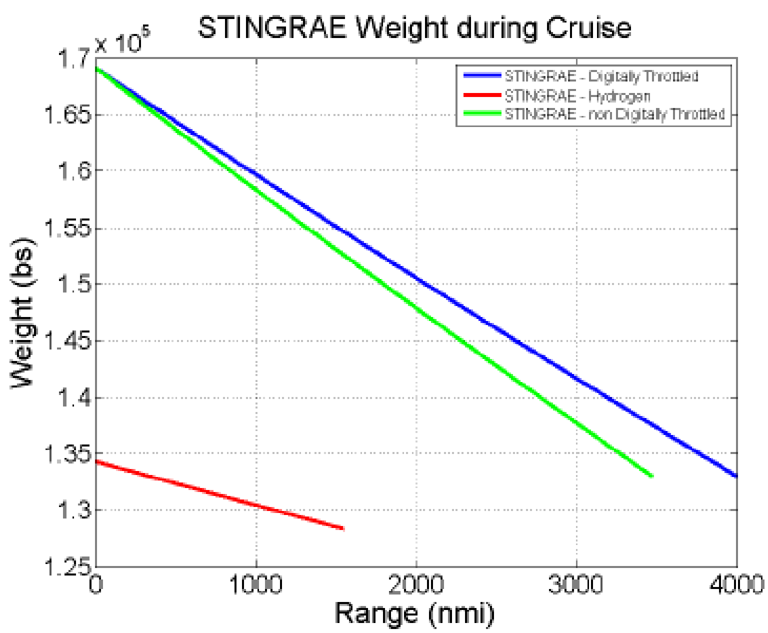


Figure 14: STINGRÆ Weight During Cruise

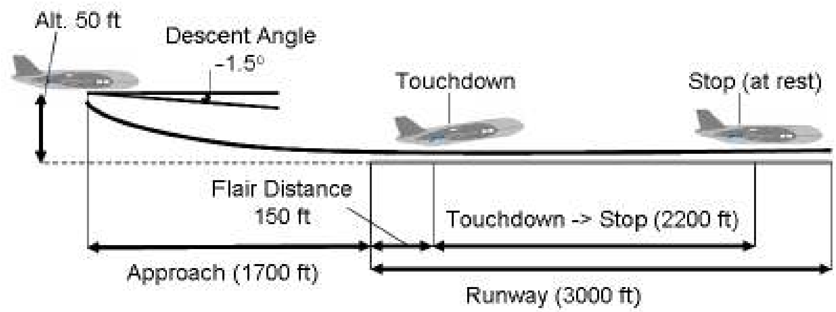


Figure 15: STINGRÆ landing Performance

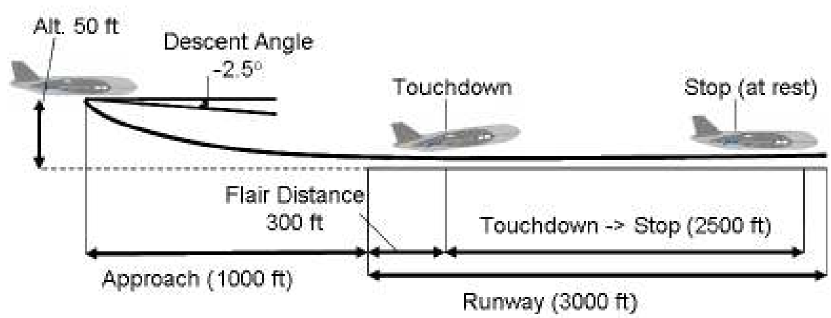


Figure 16: STINGRÆ alternate landing Performance

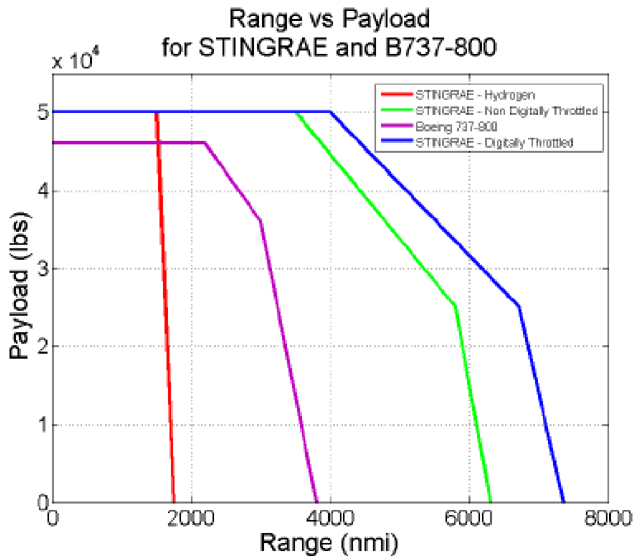


Figure 17: Range-Payload diagram for STINGRÆ and comparitive Boeing 737-800.

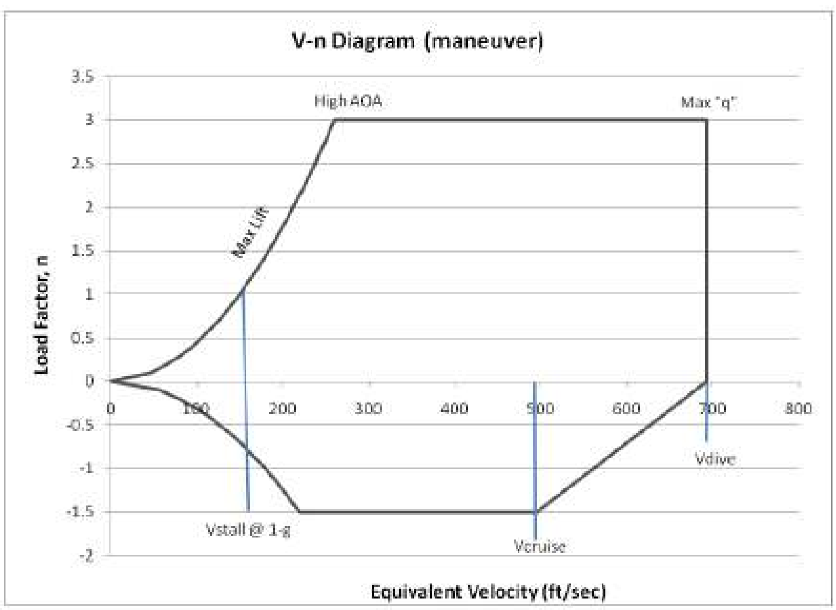


Figure 18: The V-n diagram for the STINGRÆ .

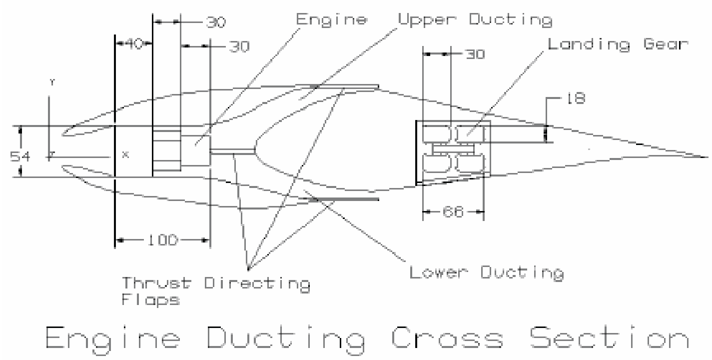


Figure 19: A crossection of the inner wing of the STINGRÆ showing the rewuired ducting for USB.

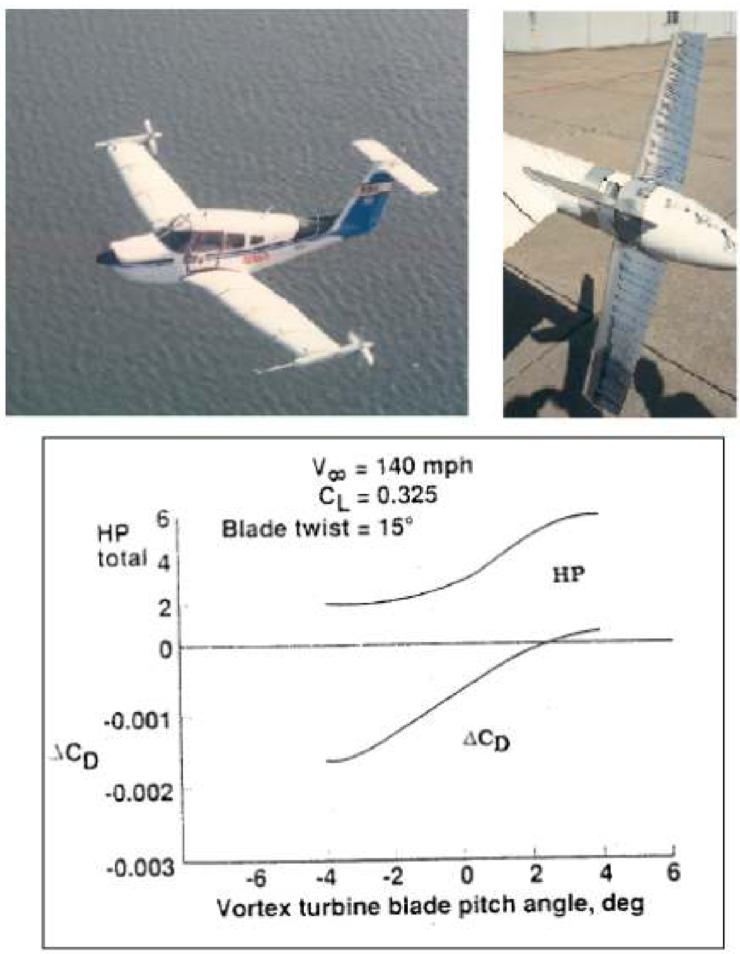
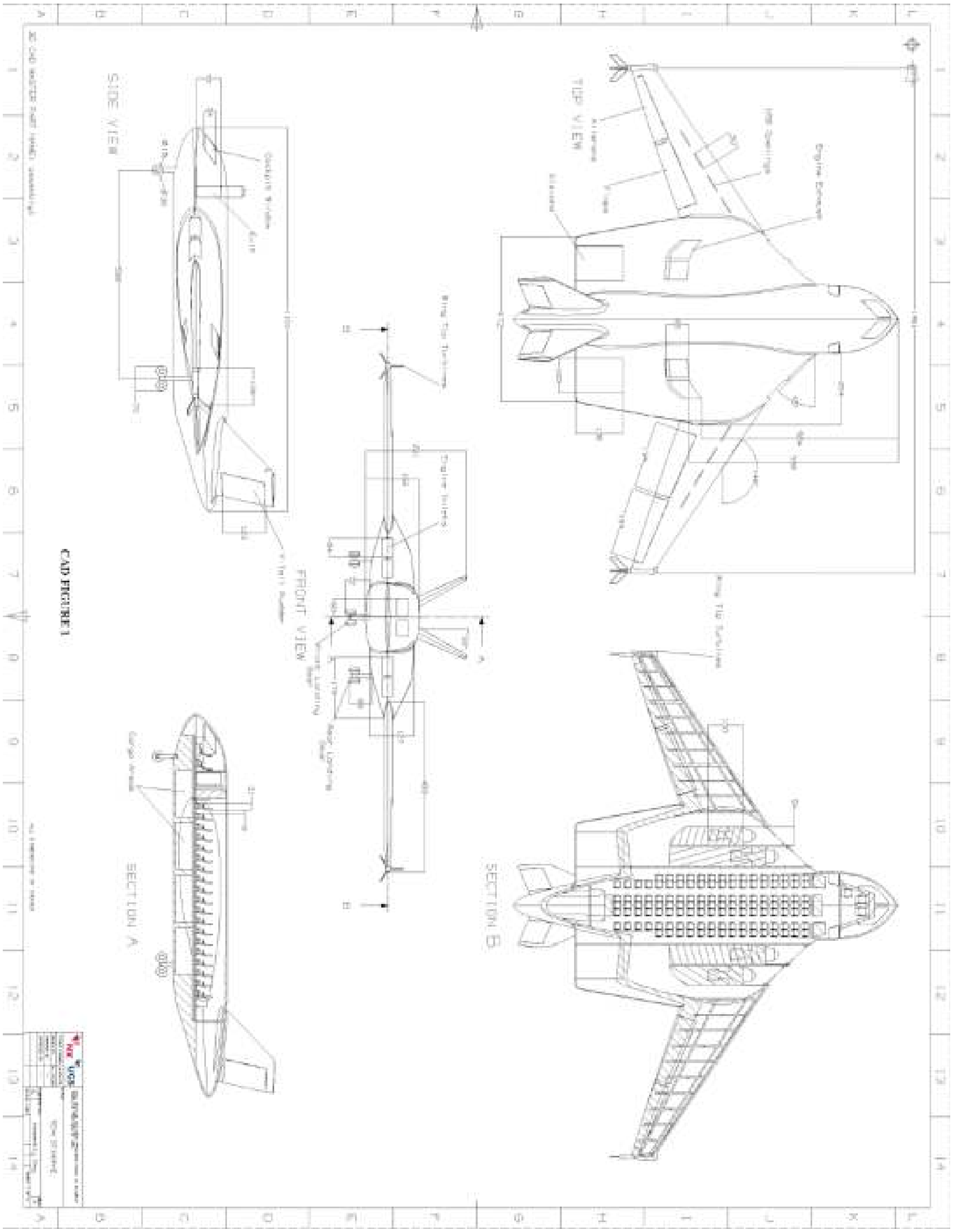


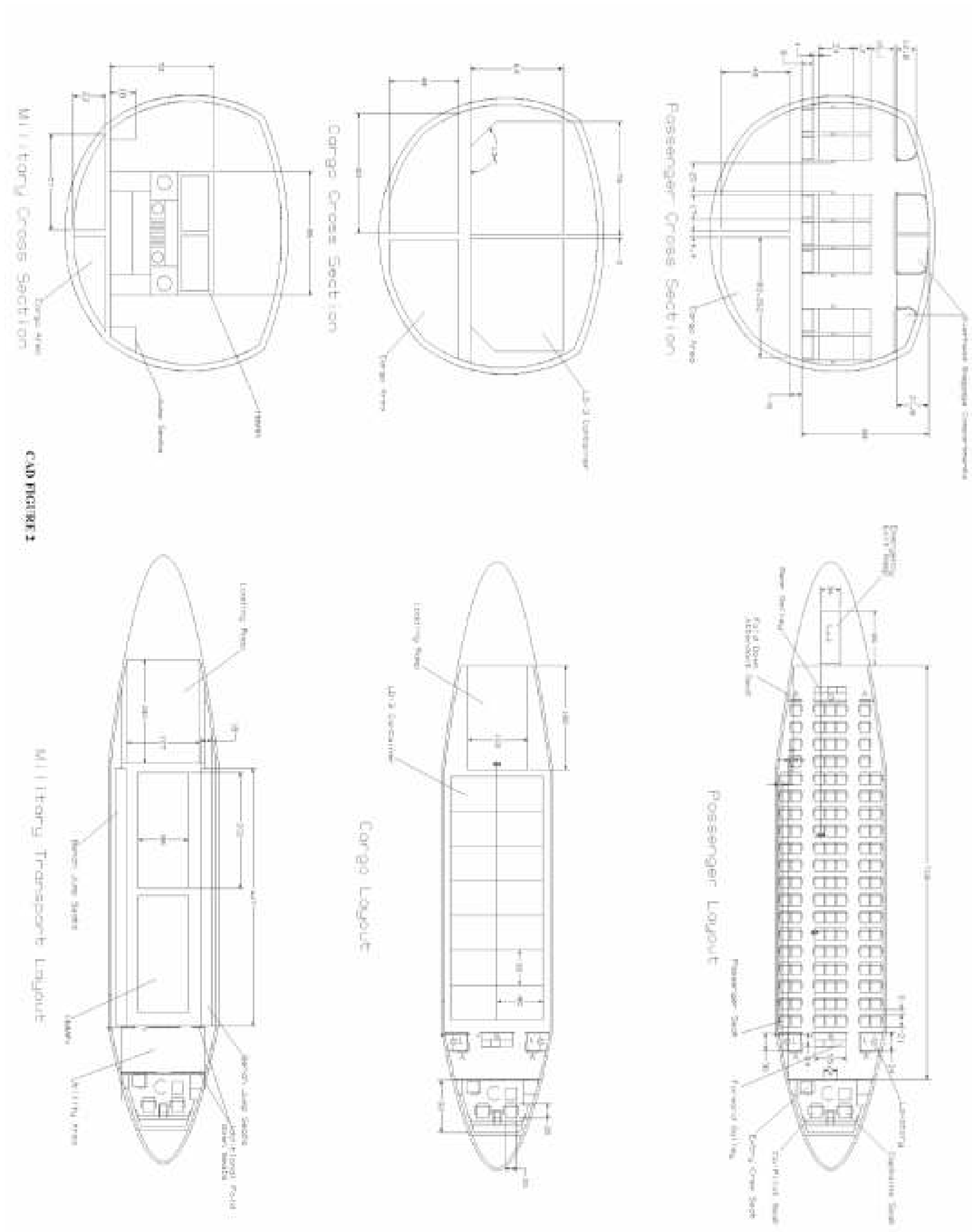
Figure 20: The NASA wingtip turbine experimental setup, and cruise data.

Requirements & Considerations	Met?	Section(s)
Primary Requirements		
Takeoff and Landing Balanced field Length = 3000 ft	YES	8.1, 8.4
Cruise between Mach 0.78 - 0.82	YES	7.2
Carry Payloads ranging from 25,000 to 50,000 lbs	YES	5, 8
Significant Noise Reduction	YES	11.1, 11.2, 11.3
Variable Uses for Future	YES	3.3
Secondary Considerations		
Operations at General Airports	YES	12.6
Increased Aircraft Efficiency	YES	3, 7.2, 8.5
Competitive Range compared to modern aircraft	YES	8.5
Alternative Fuel Use for less Environmental Impact	YES	3.3,

Figure 21: STINGRÆ RFP Requirement Conclusions.

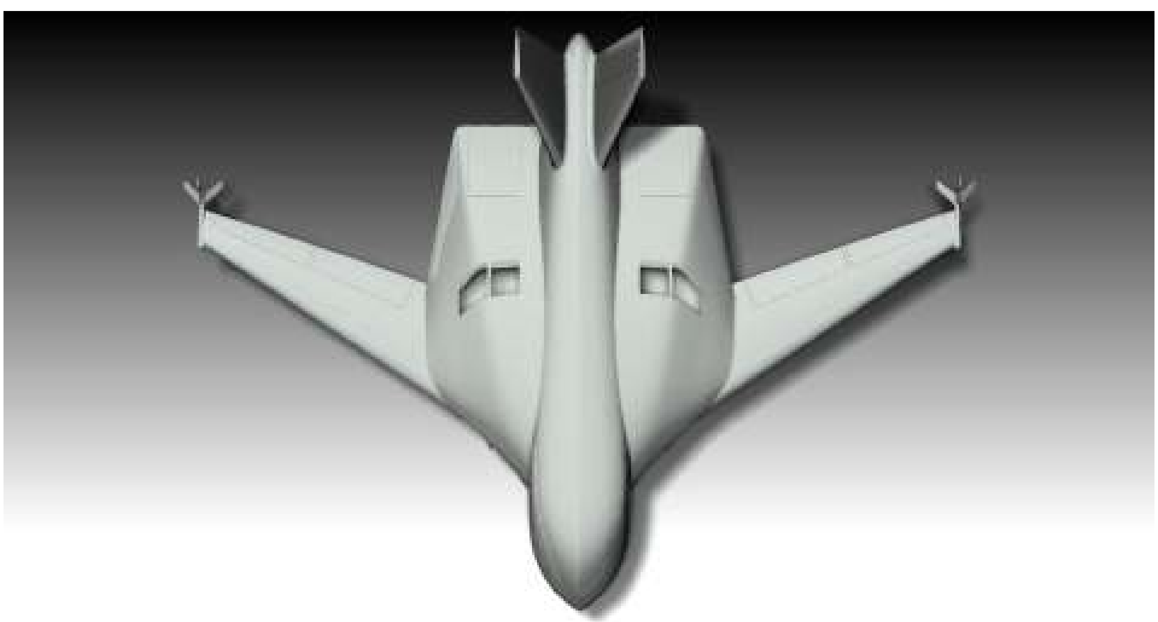
Appendix B: CAD Figures




Military Cross Section
Cargo Cross Section
Passenger Cross Section
Military Transport Layout
Cargo Layout
Passenger Layout

CAD FIGURE 2

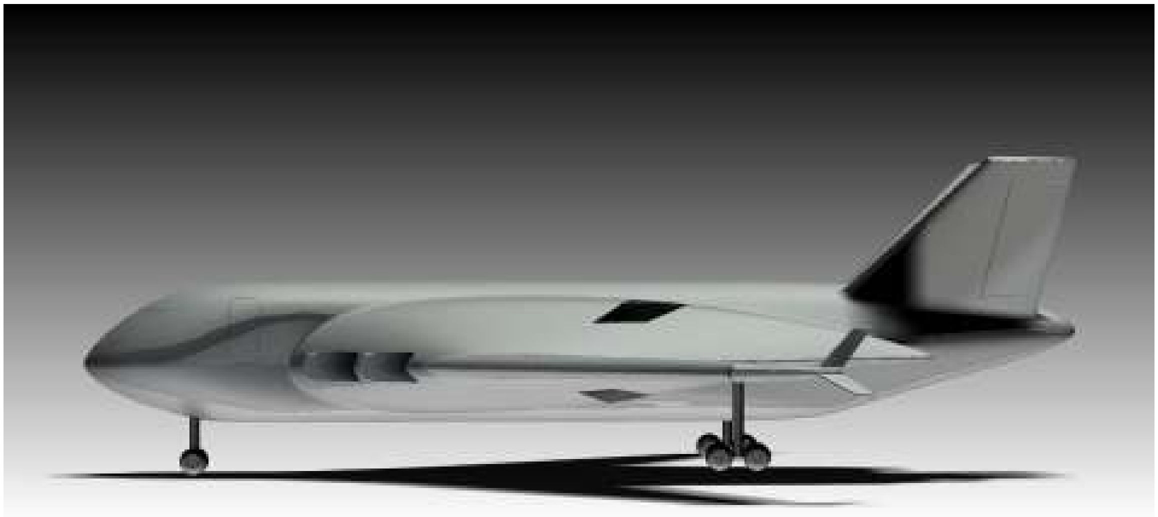
CAD Figure 3 Isometric View



CAD Figure 4 Top View

CAD Figure 5 Front View

CAD Figure 6 Back View



CAD Figure 7 Side View

Appendix C: References

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