“The Cormorant”

A Multi-Mission Amphibian (MMA)

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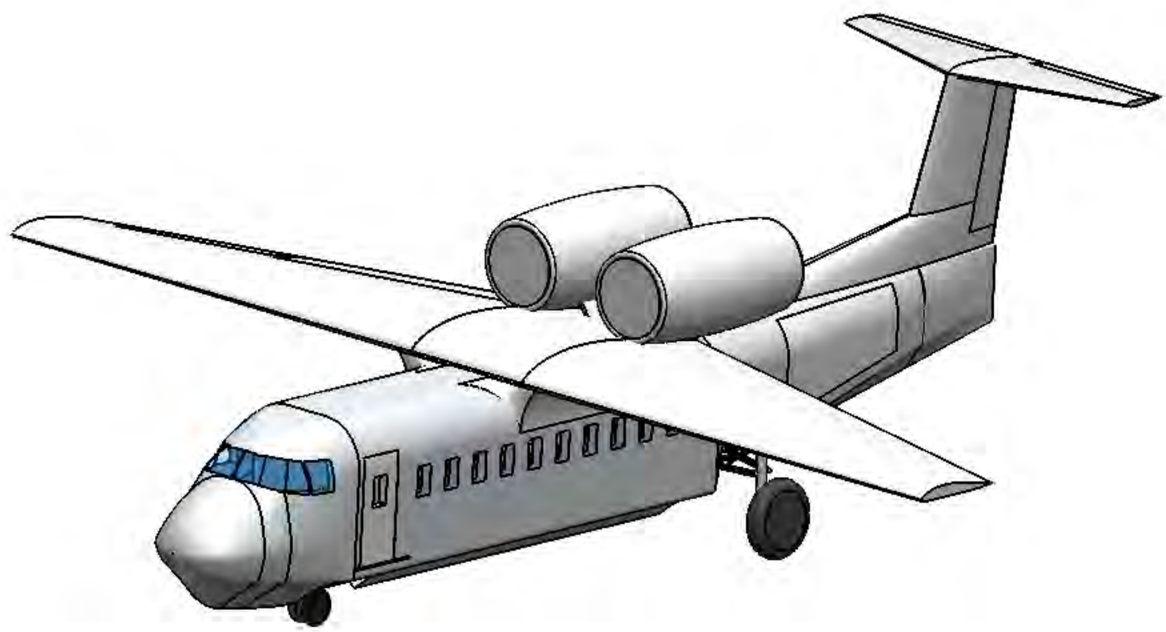
This is a proposal for a Multi-Mission Amphibian (MMA) aircraft for the 2017 Graduate Individual Aircraft Design Competition. A transport-category aircraft was designed to fulfill a versatile array of mission requirements encompassing both passenger and cargo transport over short- to medium-range distances and landing capbility on both water and a variety of runway materials. The proposed aircraft is optimized for flight at extremely low altitudes, where it can take advantage of a significant reduction in induced drag resulting from the so-called “ground effect.” This allows for a compact and robust airframe design which is well-suited to operation in geographically remote areas and constricted waterways. The aircraft described in this report would allow for economical expansion of air travel networks while minimizing the resulting strain on overcrowded airport infrastructure.



I. Introduction

Despite the vast proliferation of air transportation over the past half-century,many regions of the world still remain under-serviced, rendered largely inaccessible due to inhospitable terrain and a lack of large airport infrastructure. As more nations undergo rapid industrialization such as China, India, and many other Asian states have experienced, this lack of air access has becoming an increasingly urgent problem. New global markets mean an increased demand for air travel between expanding urban centers; currently, all of the ten most-traveled airline routes in the world connect cities in southeast Asia.[1] In addition, there is a strong argument to be made that many of these nations have a greater need for air travel than is reflected by overcrowded airports and congested airspace; many well-populated island chains and archipelagos are isolated by the inability of traditional air transport craft to reach them. As such, there is a clear need for small aircraft capable of transporting passengers and cargo short to intermediate distances through traditionally inaccessible terrain. Considering how many isolated regions consist of islands and archipelagos, amphibious capability is a highly desirable trait for any candidate airframe.

II. Design Requirements

As outlined in the Request for Proposals (RFP), the proposed multi-mission amphibian must satisfy a variety of requirements:

Aircraft Requirements

1. Passenger capacity of between 20 and 49 passengers
   (a) Passenger mass of 88 kg
   (b) Per-passenger baggage mass of 17 kg and volume of 0.113 cubic meters
   (c) Minimum seat pitch of 71 cm
2. Flight crew of 2 pilots with 1 cabin crew member.
3. Cruise speed of at least 200 knots
4. Certifiable under 14 CFR Part 25
5. Capable of VFR and IFR flight
6. Capable of flight in known icing conditions
7. Capable of takeoff and landing from finished and unfinished surfaces
   (a) Dirt
   (b) Grass
   (c) Metal mat
   (d) Gravel
   (e) Asphalt
   (f) Concrete
8. Capable of takeoff and landing from fresh- and saltwater

Mission Requirements

1. Maximum-density passenger mission
   (a) 1000 nmi range
   (b) Demonstrated takeoff and landing performance over a 50' obstacle to a dry, paved runway (assuming ISA + 18^o F day at sea level)
   (c) Demonstrated takeoff and landing distances on water (assuming ISA + 18^o F day at sea level)
2. Maximum-economy passenger mission
   (a) 200 nmi range
   (b) Single-class passenger configuration
   (c) Fuel burn per passenger at least 20% better than an existing aircraft
3. Water-based STOL mission
   (a) 250 nmi range
   (b) 20 passengers
   (c) Maximum takeoff distance of 1,900' over a 50' obstacle (assuming ISA + 18^o F day)
   (d) Demonstrated takeoff and landing performance at 5000' MSL altitude
   (e) Ability to takeoff and land in Sea State 3 conditions

4. Land-based STOL mission
   (a) 250 nmi range
   (b) 20 passengers
   (c) Maximum takeoff distance of 1,500' over a 50' obstacle (assuming ISA + 18^o F day)
   (d) Demonstrated takeoff and landing performance at 5000' MSL altitude (assuming ISA + 18^o F day)
   (e) Demonstrated takeoff and landing performance at sea level for finished and unfinished (assuming ISA + 18^o F day) runway surfaces
      i. Dirt
      ii. Grass
      iii. Metal mat
      iv. Gravel
      v. Asphalt
      vi. Concrete
5. Cargo Mission
   (a) 500 nmi range
   (b) 5,000 lb payload
   (c) Demonstrated takeoff and landing performance over a 50' obstacle to a dry, paved runway (assuming ISA + 18^o F day at sea level)
   (d) Demonstrated takeoff and landing distances on water (assuming ISA + 18^o F day at sea level)
   (e) Turn-around time of 60 minutes or less

III. Design Philosophy

Whenever possible in the creation of this conceptual design, emphasis was placed on three priorities: 1) Use of proven technology and materials; 2) Ease of operation in off-airport environments in the developing world; and 3) I swear there was something else.... anyway.

Considering the difficulty of completing a detailed conceptual design of a new airframe with a one-man design team, the approach taken was to outline a functional baseline vehicle capable of meeting all specified requirements, rather than attempting to design an aircraft optimized for any particular set of parameters. In a real-world design environment, this complete vehicle concept could serve as a solid nucleus for in-depth trade studies targeting a more refined design.

IV. Vehicle Concepts

The concept of designing an aircraft for prolonged flight in ground effect (a so-called "ground effect vehicle" or "wing-in-ground-effect (WIG) vehicle") arose early on as a promising design possibility. While few large-scale ground effect vehicles have flown to date, the concept has obvious merit for an amphibious vehicle designed to travel significant distances over water.

With the inclusion of ground effect vehicles, a total of four vehicle configurations were considered at the conceptual stage: 1) A large floatplane; 2) A high-wing regional jet designed as a seaplane; 3) A mid-size ground effect vehicle with a "conventional" seaplane layout; and 4) An inverted delta wing ground effect vehicle as pioneered by Alexander Lippisch.[2]

A. Large Floatplane

A large floatplane design presents several appealing characteristics. For one, it relies entirely on proven technology; many amphibious aircraft such as the Cessna Caravan and the DeHavilland Twin Otter have seen widespread use around the world as cargo and passenger transports. Developing a floatplane would require minimal investment in new materials and techniques, so development, production and maintenance

costs would all be low. A typical floatplane also offers flexibility for IFR and VFR flight as it does not have any particular limits on altitudes or routes which can be flown.
However, the traditional floatplane design also prevents significant disadvantages. One of the most troubling is the immense extra drag produced by large floats during flight; this curtails both speed and fuel efficiency. Float design also limits the scalability of the design as making floats for larger aircraft becomes progressively less and less feasible - no aircraft larger than the venerable Douglas DC-3 have been fitted with floats,[3] which despite its long and storied history is not an especially efficient transport aircraft by modern standards. Thus, a floatplane design is almost certainly limited to the large general aviation-size craft currently in production. Floatplanes also suffer as amphibians as their floats make them wholly unsuited for bush operation out of unpaved fields.

B. Traditional Seaplane

Beyond the upper size limit presented by floats, amphibious and aquatic aircraft have generally been designed as flying boats. The flying boat design offers several advantages over a floatplane; namely, it does away with the drag produced by floats, it allows for larger and more space-efficient design, and when fitted with retractable wheels becomes a more capable amphibian. The Consolidated PBY Catalina is an excellent example of a versatile, amphibious flying-boat design, with a boat hull and large, retractable wheels which allowed for operation off of a variety of unfinished fields in the Pacific theatre of World War II

The flying boat design, however, is not without its disadvantages; designing an aircraft fuselage capable of withstanding slamming loads during water operations is non-trivial, and structural weight of seaplanes increases as a result. Compared to a floatplane, takeoff distances for seaplanes are longer (although the comparison is skewed by the size difference between typical floatplanes and typical flying boats). In the water, access to cargo, passenger compartments, and maintenance panels is also an issue as by definition, part of the airframe is submerged.

C. Ground-Effect Seaplane

A ground-effect seaplane features many of the same qualities as a traditional seaplane, but with a few additional advantages. Flying in ground effect allows higher aerodynamic efficiency due to a reduction in induced drag; this allows smaller, stubbier, more highly-loaded wings. In addition, an aircraft designed to fly at lower altitudes can be simpler as cabin pressurization is no longer a concern; this saves the weight of a pressurization system and decreases the effect of structural fatigue. A stubbier, lower aspect ratio wing is also easier to build, allowing for a more robust overall airframe.

Naturally, there are downsides to the ground-effect design as well; while efficiency is high close to the ground, climbing to avoid terrain or weather decreases performance dramatically. While a ground-effect aircraft is still capable of performing instrument procedures, it does so at lower efficiency. The small wings also increase takeoff distances, and a relative lack of expertise in ground-effect vehicles is likely to increase development costs.

D. Inverted Delta

A unique class of ground-effect vehicles was pioneered by the German engineer Alexander Lippisch from the 1940s through the 1960s. Lippisch favored a design heavily optimized for ground-effect flight, resulting in vehicles bearing little resemblance to traditional aircraft. Lippisch's final ground-effect design, the X-114, featured floats integrated into the tips of an inverted delta wing, with a straight leading edge and a swept trailing edge. The wing was build with significant anhedral to allow the floats to contact the water, suspending the cabin above the water's surface. Directional stability was provided by a T-tail horizontal stabilizer mounted on an abnormally long vertical fin to account for the intricacies of maintaining longitudinal stability in ground effect. Lippisch's designs, in theory, offer a highly compact vehicle which would be ideal for accessing remote parts of Southeast Asia with limited air infrastructure; they also offer theoretically high fuel efficiency and structural efficiency. However, they are a highly unproven technology, and would require a comparatively large outlay for research and development, as well as significant investment in tooling and production for their unconventional shapes. It is also uncertain how well such a vehicle would be able to deal with modern instrument procedures, nor how easy it would be to maintain and operate in remote regions.

Lastly, it is unclear how scalable the design is and whether or not a vehicle capable of carrying more than a few passengers or a small amount of cargo is even feasible.

V. Design Down-Selection

The four vehicle concepts were evaluated for a series of attributes; each design was ranked from 1-4 (or 1-3 in the event of a tie) for each quality, with 1 indicating that a particular design was the best choice for a characteristic, and 4 that it was the worst. The qualities chosen are listed below, followed by an explanation of each and the design rankings.

		Concepts			
		Large Floatplane	Conventional Seaplane	Ground Effect Seaplane	Inverted Delta
Requirements	Amphibiousness	3	1	1	2
	IFR Capability	1	1	2	3
	Fuel Economy	4	3	1	2
	STOL Capability	1	2	3	4
	Bush Capability	4	2	1	3
	Cargo Versatility	2	1	1	3
	Cabin Space	2	1	1	3
	Testedness	1	1	2	3
	Complexity	1	3	2	4
	Durability	3	2	1	4
	Serviceability	1	2	2	3
	TOTAL SCORE	2.1	1.7	1.5	3.1

A. Amphibiousness

As stipulated in the RFP, a high degree of amphibiousness is a requirement for this vehicle. An ideally amphibious vehicle should be able to operate equally well on water or on hard surfaces, with a minimum of design compromises. Within the scope of this design, the seaplane/flying boat configuration offers the most amphibious layout, as in addition to being fully water-capable with its boat hull, there is a high degree of flexibility in the design of its landing gear, allowing for large, robust wheels for land operations. Conversely, the floatplane design ranks worst of the three designs, as its cumbersome floats make landing gear design difficult; the wheels of amphibious floatplanes are generally designed to mount to the floats, resulting in a highly suboptimal landing gear from a weight and versatility perspective. The inverted delta design is somewhere in between, as to date none have been built with amphibious capability, but it is not too difficult to imagine how a retractable undercarriage could be married to such an airframe.

B. IFR Capability

In order to integrate new aircraft into the international airspace system, it is imperative that the airframe is capable of instrument flight. In this category, the traditional seaplane configurations - floatplane and flying boat - have a clear advantage; where as ground-effect aircraft are optimized for very low-altitude flight, more conventional seaplane can easily fly across a broader altitude envelope, allowing them to adequately fly published instrument flight approach, arrival, and departure procedures. A ground-effect flying boat configuration is also capable of instrument flight, although at a markedly lower efficiency than its more conventional brethren. The same is true of the inverse delta design, although given the very limited flight data there are also questions about the maneuverability and stability of such a design outside of ground effect.

C. Fuel Economy

Fuel efficiency has been identified as a critical performance parameter for this aircraft as enabling greater access to traditionally isolated portions of he world with lower per-seat emissions is the primary objective of this design. The traditional floatplane layout suffers greatly here as the enormous floats required for water operations produce a disproportionately large amount of drag. A flying boat can be expected to perform better, although in normal operation a ground-effect aircraft of either a conventional seaplane or inverted delta design should perform significantly better.

D. STOL Capability

The ability to take off and land within a short distance is another desirable characteristic for the multi-mission amphibian. A traditional floatplane has an advantage here; due to its relatively low displacement, water drag and takeoff distances are lower. For a flying boat design, water takeoffs will be longer due to the large, high-drag boat hull, but hard-surfaced takeoff distances will be similar. For both ground effect designs, takeoff distances will likely be slightly longer due to the higher wing loading and relatively high displacement.

E. Bush Capability

As specified in the RFP, the ability to operate from remote, unpaved fields will be critical in allowing this aircraft to reach populations in remote areas. The final design must be able to operate off of gravel, grass, metal mat, and dirt runways, requiring rugged suspension geometry and large wheels. This is a major flaw of the floatplane design, which can only accommodate fairly small wheels on its large floats; in contrast, a flying-boat design has a spacious hull capable of stowing large wheels and shocks. The Consolidated PBY Catalina is an excellent example of an amphibious seaplane with significant bush-flying ability. Ground-effect aircraft are well-suited to bush flying due to their smaller wingspans; however, the inverted delta design suffers as its shape is not well-suited to the robust, large landing gear required for bush operation.

F. Cargo Versatility

In order for the proposed amphibian to fulfil multiple missions, it has to make an effective cargo transport. Key characteristics for an effective cargo transport are a large, easy-to-load cargo bay, and overall cargo capacity Seaplane/flying boat designs have high overall capacities, but are somewhat difficult to load due to the partial submersion of the fuselage. A floatplane has limited cargo space due to constaints on the overall size of the vehicle and the more rounded shape of the fuselage, but is easy to load and unload due to its relatively high water clearance. The inverted delta has limited cargo capacity due to its small fuselage; it is not immediately clear how much internal space such a design would have.

G. Cabin Space

Cabin space is analogous to cargo versatility; in general, the floatplane suffers from having a narrow fuselage and small overall size, whereas a flying boat has large amounts of space. This is particularly important for passenger transport, where the more rectangular cross-section of the flying boat's fuselage allows for higher ceilings and more space for overhead storage. As with cargo transport, the size and shape of the inverted delta design do not make it well-equipped for passenger transport.

H. Testedness

Any new aircraft design benefits when it relies on proven technology and practices; industry familiarity with a design concept reduces development costs and makes the aircraft more appealing to operators. Among the four design concepts, the floatplane is by far the most proven, with dozens of successful designs having flown throughout history and several flying today, such as the Kodiak Quest, Cessna Caravan, Twin Otter, and others. Conventional seaplanes are also fairly well-proven, although only a few designs currently see regular use; the CL-415 and BE-200 are both relevant examples of successful transport-class flying boats. Ground effect aircraft are inherently unproven as only a few examples have been built; notably the Soviet "ekranoplane" aircraft of the 1960s. However, the ground effect seaplane concept is preferable to he inverted delta as it takes fundamentally the same form as typical aircraft, just with different proportions; this is in stark contrast to the highly unusual structures and aerodynamics of the Lippisch design.

I. Complexity

As a general rule, a less complex aircraft is preferable from both a design and an operation standpoint. A simpler design will often be lighter and cheaper, as well as easier to operate. Of the four candidate configurations, the simplest is probably the traditional floatplane - the main structures and components are all modular, and a smaller aircraft can be operated at lower altitudes without the need for cabin pressurization. The ground-effect seaplane shares this latter benefit; being designed to fly at low altitude, it does not require pressurization or oxygen systems on board; its more compact profile and smaller wing also simplifies structural design compared to a higher aspect-ratio design. The more traditional seaplane would probably require a pressurization system to fly at conventional altitudes, and the high loads created by water operations would complicate the structural design of a typical high-aspect ratio wing. The inverted delta design is likely to be highly complex, requiring innovative structures and packing, as well as a complex controls to stabilize the closely-integrated system while flying in ground effect.

J. Durability

Any aircraft must be durable enough to survive a long service life with as little maintenance as possible; this is doubly true for commercially-operated vehicles. Due again to its uniquely complex structure which places high landing loads near the wingtips and suffers especially from slamming loads (due to its flat bottom), it seems as though the inverted delta design will see a high degree of wear, resulting in increased maintenance costs and a higher risk of structural fatigue. Floatplanes are also liable to see high landing loads which are concentrated at the float attachment points, decreasing durability. Seaplanes fare relatively better, as the hull can more easily be designed to minimize slamming loads and distribute them across a larger area. Since it is designed to fly at extremely low altitudes, a ground effect seaplane is especially durable - its engines spend less time operating at full-throttle, and it does not have to tolerate repeated pressure cycles in the cabin walls.

K. Serviceability

Another key aspect of a successful design is the ease with which it can be maintained - easier maintenance means lower costs for operators and consumers alike. In this category, the traditional flotplane surely comes out on top - it is a traditional airframe with modular design, and its high clearance should make it easy to inspect and access on both water and land. The flying boat designs should be comparable - they both suffer somewhat from the problem of being partially submerged at rest, making it more difficult to access certain parts of the airframe (and impossible to reach some, such as the landing gear doors) while on water. The inverted delta design is likely to be very difficult to maintain as its compact, highly-integrated design offers minimal access to important assemblies such as the flight controls, engines, and structures.

The average ranking score for each configuration is repeated below: Based on this scoring system, the

Concept	Averaged Ranking
Floatplane	2.1
Flying Boat	1.7
Ground-Effect Flying Boat	**1.5**
Inverse Delta	3.1

ground-effect flying boat configuration is the most promising design. It benefits from many of the same advantages as a more conventional flying boat design, but with lower fuel consumption and a simpler, more robust airframe. The floatplane and inverse delta designs can be discounted - the former is not scalable or versatile enough for amphibious bush operation, while the latter relies heavily on unproven technology and aerodynamics which are not currently well-understood. Based on this analysis, a flying boat design optimized for ground-effect flight is the preferred concept for this vehicle.

VI. Engineering Models

A. Gross Mass

One of the most critical elements of any aircraft design is the estimated weight; at the early design stages this is little more than an educated guess but as the aircraft develops, this becomes an increasingly precise number as systems are fully-designed. For the purposes of this study, a rough gross liftoff mass was estimated based on historical data from previous aircraft designs. For each aircraft, an equivalent number of passengers was estimated based on payload capacity and a standard passenger mass of 115 kg; the masses were plotted against the equivalent passenger number and power-law curves were fit to both land-based aircraft and water-capable aircraft. It is worth noting that while a reasonable curvefit can easily be attained for land-based aircraft (due to the plethora of designs and the existence of standard design practices), the relative scarcity and diversity of seaplane designs makes it very difficult to create a reliable, accurate curve. This problem is compounded by the fact that many seaplane designs date from the 1930s through the 1950s, when aircraft structures were significantly less efficient. Regardless, this was seen as by far the most practical approach for this study. The datapoints and curvefits for available historical data are shown below.

Table 1: Seaplane Takeoff and Payload Masses

Aircraft	Wingspan	Maximum Takeoff Mass (kg)	Payload (kg)	Passenger Equivalent
Martin P6M-2	31.2	86,183	13,608	113
Canadair CL-415	28.6	17,170	3,100	26
Dornier SeaStar	15.5	4,200	1,500	13
ShinMaywa U-2	33.1	43,000	3,800	32
Beriev A-40	41.6	86,000	10,000	83
Beriev Be-10	28.6	48,500	5,000	42
Beriev Be-200	32.8	37,900	7,500	63
Saunders-Roe A.1	14.0	7,273	1,000	8
Short Sunderland	34.4	26,323	2,268	19
Short Solent	34.4	35,381	5,095	42
Saunders-Roe Princess	66.9	156,501	24,560	205

Table 2: Land-based Aircraft Takeoff and Payload Masses

Aircraft	Wingspan	Maximum Takeoff Mass (kg)	Payload (kg)	Passenger Equivalent
Embraer E135	20.04	19000	4198	35
Embraer E140	20.04	20100	5284	44
Embraer E145	20.04	22000	5786	48
Embraer E170	26.00	35990	9100	76
Embraer E175	26.00	37500	10080	84
Embraer E190	28.72	47790	13080	109
Airbus A318	34.10	68000	15000	125
Airbus A319	34.10	75500	17700	148
Airbus A320	34.10	78000	19900	166
Airbus A321	34.10	93500	25300	211

Power-law curves for mass M and payload PL of the form $M = a * PL^b$ were fit for each set of data:

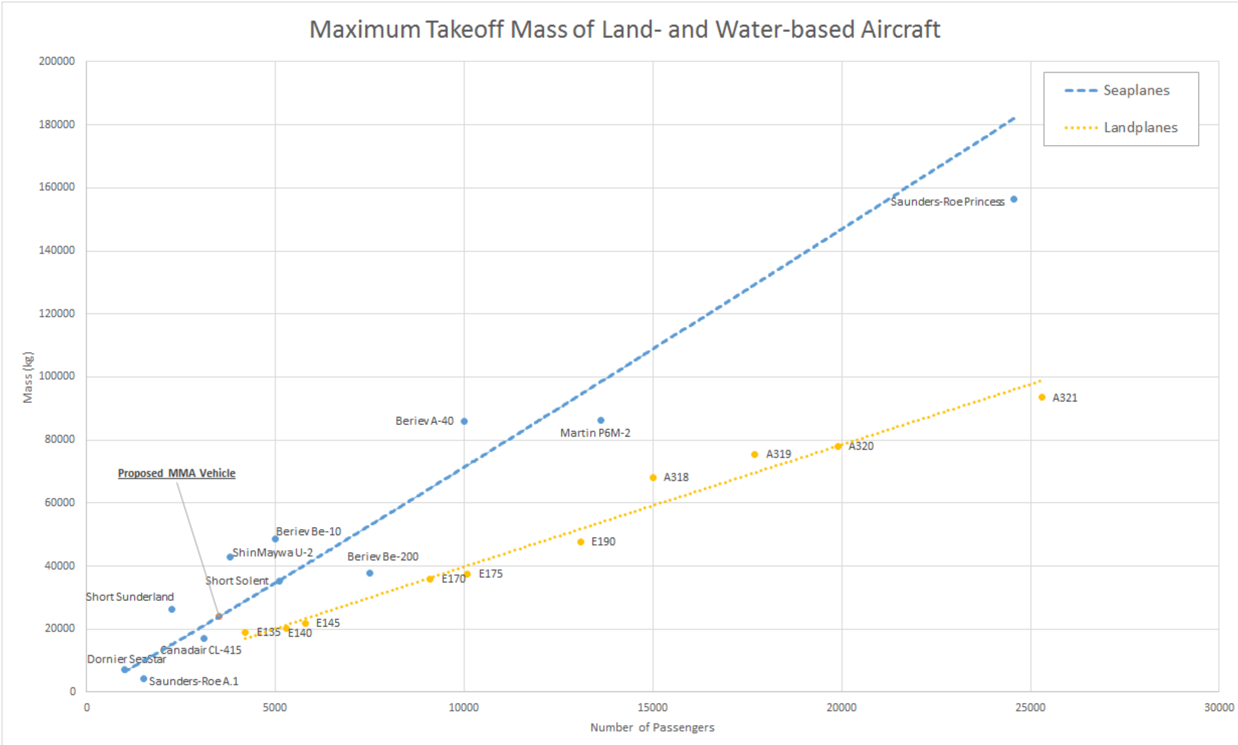


Figure 1: Masses of various sea- and land-based aircraft and power-law curvefits

Table 3: Power-law parameters for gross mass as a function of payload

Aircraft Type	a	b	r^2
Seaplanes	4.8855	1.0432	0.8577
Land-Based Aircraft	4.7929	0.9799	0.9819

For a regional transport-sized aircraft capable of carrying 27 passengers and 3 crewmembers (somewhat analogous to an Embraer E-jet or Canadair regional jet), the estimated maximum gross mass is 23,934 kg.

B. Range

Aircraft range was estimated using the familiar Breguet equation:

$$R = v_{cruise} \left(\frac{L}{D} \right) I_{sp} \ln \left(\frac{W_i}{W_f} \right) \tag{1}$$

This required the assumption of several parameters, notably specific impulse, aircraft mass ratio, and a zero-lift drag coefficient (for calculating induced drag and lift-to-drag ratio). As with the estimation of gross mass, a historical approach was used for each of these parameters. Specific Impulse (I_{sp}) was specified as 9164 s based on a candidate engine, the General Electric CF-34.[4] Mass ratio was heuristically estimated at 1.3 based on an analysis of similar aircraft types. The zero-lift drag coefficient was approximated using data from Roskam et. al's *Airplane Aerodynamics and Performance*,[5]reproduced below.

Table 4: Drag Data for Various Airplanes[5]

Aircraft	Wing Area (ft^2)	Aspect Ratio	Drag Polar
Cessna 150	160	7.0	$0.0327 + 0.0592C_L^2$
Cessna 172	174	7.5	$0.0281 + 0.0552C_L^2$
Cessna 180	174	7.5	$0.0246 + 0.0572C_L^2$
Cessna 182	174	7.5	$0.0293 + 0.0506C_L^2$
Cessna 185	174	7.5	$0.0207 + 0.0494C_L^2$
Cessna 310	175	7.3	$0.0263 + 0.0596C_L^2$
Douglas Skyrocket	183	6.7	$0.0163 + 0.0579C_L^2$
Saab 340	450	11.0	$0.0285 + 0.0362C_L^2$
Douglas DC-9	1,001	6.8	$0.0211 + 0.0450C_L^2$
Boeing 707	3,050	7.1	$0.0131 + 0.0650C_L^2$
Airbus A340	3,908	9.5	$0.0165 + 0.0435C_L^2$
Boeing 767	3,050	8.0	$0.0135 + 0.0592C_L^2$
Boeing C-17	3,800	7.2	$0.0175 + 0.0510C_L^2$
Learjet M-5	232	5.0	$0.0260 + 0.0078C_L^2$
Gulfstream II	800	6.0	$0.0230 + 0.0057C_L^2$

Based on these data, $C_{d,0}$ for a small transport-class aircraft was estimated to be not higher than 0.02.

C. Takeoff and Landing Performance

Takeoff and landing performances were calculated by estimating the coefficient of rolling resistance of the wheels with and without brakes (or, for water landings, an equivalent coefficient for the water resistance) and numerically integrating from a given landing speed to zero velocity, or from zero velocity to a given takeoff speed. This provided an estimate of the ground roll, which could be corrected to show the takeoff and landing distances over a 50 foot obstacle as stipulated in the RFP. The coefficients of rolling/water resistance are listed below:

Table 5: Coefficients of Resistance for Various Operating Surfaces

Surface	Coefficient of Resistance	Coefficient of Resistance (with brakes)
Asphalt	0.04	0.5[6]
Concrete	0.04	0.4[6]
Dirt	0.04	0.3[6]
Turf (soft)	0.07	0.4[6]
Turf (hard)	0.05	0.2[6]
Gravel	0.08	0.7[7]
Metal mat	0.045	0.5,[89]

D. Flight Performance

Flight performance was analyzed by stepping through a specified mission distance, calculating the lift, drag, and fuel burn of the aircraft at each point. Since this aircraft is designed to fly in ground effect, climb and descent performance is largely irrelevant. At each point in the cruise, the current aircraft weight was calculated based on estimate fuel burn; this was used to find the required lift and then the cruise speed was calculated as Carson's speed. The specific fuel consumption was used in conjunction with the thrust level to find the amount of fuel burned, which was in turn used to calculate aircraft weight for the next step; this cycle was repeated across the entire length of the journey.

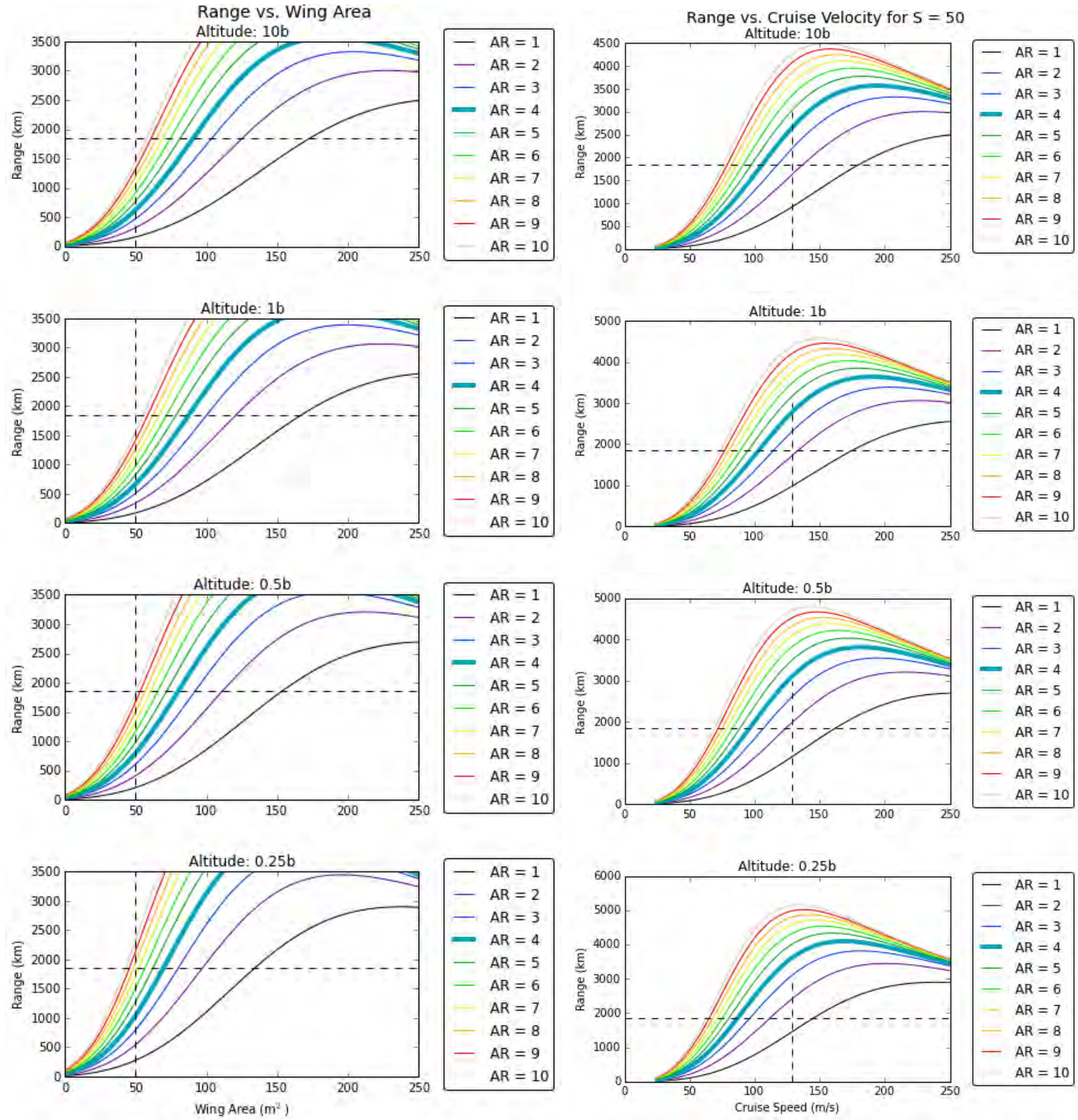
One important distinction of this analysis was an unconventional method of calculating induced drag. Since the aircraft is designed primarily for flight in ground effect, it is necessary to account for the resultatnt reduction in induced drag. This was done using a correction factor proposed by Wieselberger and popularized by Prandtl:[10]

$$\sigma = \frac{1 - 0.66 * h}{1.05 + 3.7 * h} \tag{2}$$

This factor allows for an accurate estimation of induced drag for any height h as a fraction of the aircraft wingspan, ranging from the surface to out-of-ground-effect flight.

VII. Trade Studies

Fundamental design parameters of the aircraft were chosen based on trade studies. In particular, the wing area, aspect ratio, and target cruise speed were varied to determine their effect on range. Analyses were conduced at several altitudes to gauge the significant of ground effect - cruise heights of $1/4b$, $1/2b$, $1b$, and $10b$ were considered. Aspect ratios of 1-10 were also examined; the intent of these studies were to explore the design space and to select baseline values for the aircraft to begin a more substantial analysis and design.



(a) Wing area study

(b) Cruise velocity study

Figure 2: Parametric design analysis and trends

Based on the trends visible in Figure 2, a wing area of 50 m^2 and an aspect ratio of 6 were chosen. These values exceed the minimum range requirements within ground effect and come close to satisfying them outside of ground effect as well. This indicates that the proposed aircraft will be able to complete its mission even if it has to climb out of ground effect to avoid terrain or obstacles.

VIII. Aircraft Description

The resulting aircraft has a relatively low aspect ratio wing in comparison to a typical transport aircraft in its class. This is desirable because in ground effect, wingtip vortex suppression ensures that induced drag is on par with that of a conventional aircraft flying at high altitude with a high aspect ratio wing. In theory, it would be possible to realize even higher aerodynamic efficiency (lower induced drag) by flying a high aspect ratio wing in ground effect, but a shorter and stubbier wing is more rigid and easier to build, in addition to being better-suited for bush operation off of narrow airstrips and waterways. The aircraft is designed with a boat hull, within which retractable tricycle landing gear are mounted. A cargo door behind the main cabin allows for the storage of luggage and cargo.

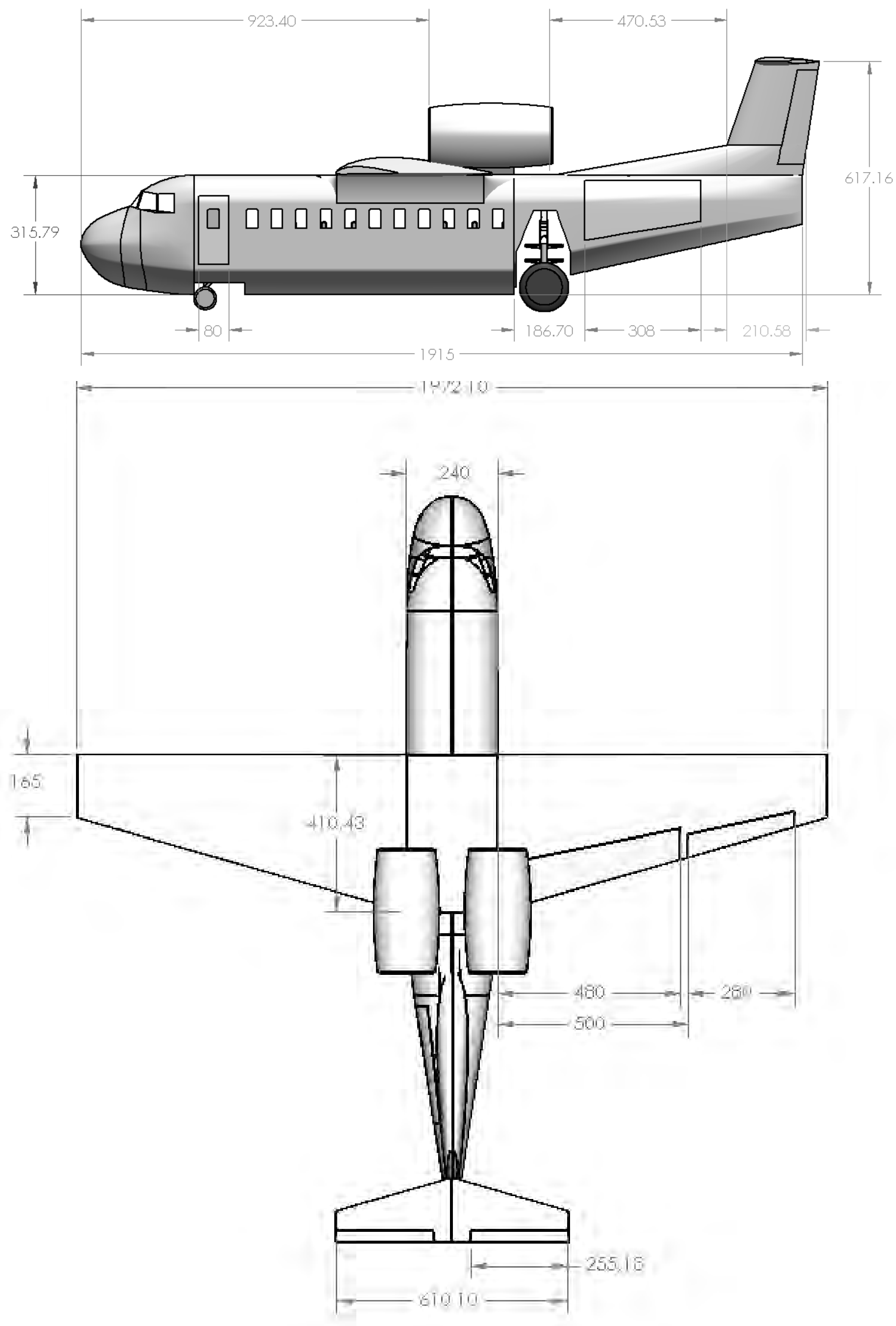


Figure 3: Aircraft exterior with landing gear extended (landing gear doors removed for clarity)

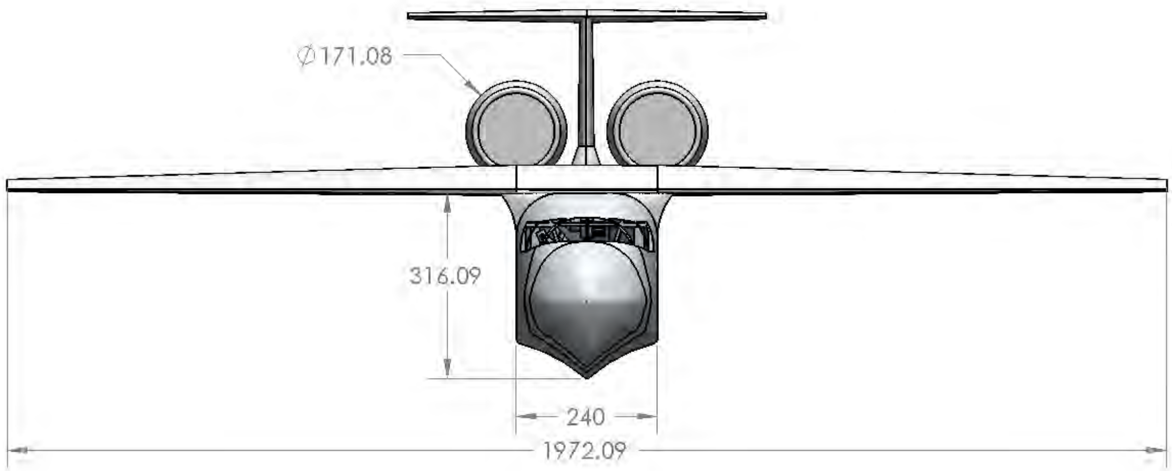


Figure 4: Front view without landing gear extended

A. Airframe

The airfoil selected for the wing is a NACA M-15 section; for the purposes of simplicity at the preliminary design stage, a constant profile was assumed across the entire wingspan. In reality, it is likely that a change in profile from root to tip would be desirable to enhance low-speed controllability and stall behaviour. However, this was beyond the scope of this project. The NACA M-15 was selected due to its high maximum lift coefficient ($C_{L,max}$); for a seaplane generating enough lift to rise up from the water is of paramount importance. Indeed, the NACA M-15 is comparable to the airfoil sections of many historic seaplanes, such as the NACA M-21 section used on the PBY Catalina or the Göttingen series used on several British flying boats of the 1930s (such as the Short Sunderland and Short Solent, among others). These thick airfoil sections produce higher form drag but allow for greater structural rigidity than a thinner, more efficient section, a significant advantage for a vehicle which will be subjected to the high dynamic loads of a water landing. Airfoil sections for the tail are the NACA 0012 profile; this was a somewhat arbitrary selection but the detailed analysis required for a more thorough justification was deemed superfluous at this stage of design. The wing planform is a forward-tapered trapezoid; at the relatively low speeds encountered by this aircraft, wing sweep appears to be unnecessary; a taper ratio of 0.4 increases aerodynamic efficiency to closely approximate an elliptical wing.[6] The forward tapering was selected as work by Lippisch and others suggests that a reversed delta wing provides enhanced longitudinal stability in the ground effect, and the reverse taper may approximate this behavior.

The proposed aircraft would be of conventional construction,i.e. a semi-monocoque aluminium structure. A variety of aluminium alloys could be employed, although 2024 is notable for its high strength-to-weight ratio. Aluminium 2024 is already commonly used in aerospace applications, so airframers would be well-equipped to handle construction of the proposed aircraft. A notional structural layout of the aircraft is shown below in Figure 5.

B. Propulsion

Propulsion for the proposed aircraft will be provided by two fuselage-mounted turbofan engines. Mounting the engines above the wings protects them from ocean spray and ingestion of water (during water landings) and particulates (during landings on unpaved surfaces). This also simplifies the design of the wing, as it no longer has to carry the weight of the engines. Two engines is a logical choice as it allows for redundancy, and is simpler than mounting three or four engines.

The selected engine is the CF34-8B from General Electric.[4] Two engines will provide a total installed

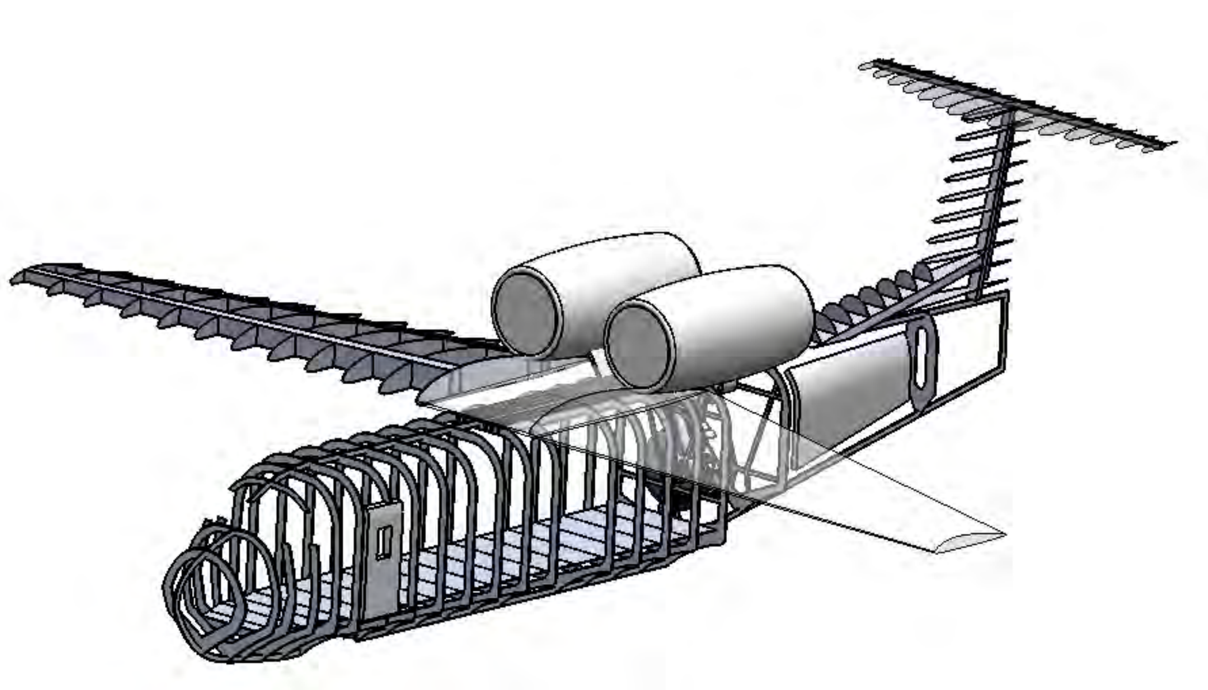


Figure 5: Notional structural layout

thrust of 82 kN. This is far in excess of the required cruise thrust, but a high installed thrust is necessary to ensure adequate STOL performance. Specific fuel consumption for the CF34-8B is 0.370 lbm/lbf-h (10.607 g/kN-s) at cruise, although flying at the low cruise altitudes specified for the proposed aircraft could allow even greater fuel efficiency.

C. Controls

Controls for the proposed seaplane will be conventional in nature, consisting of the familiar aileron/elevator/rudder in conjunction with wing flaps and spoilers. Spoilers will be necessary to create enough drag to ensure satisfactory short-field landing performance. Actuation for control surfaces will be provided by electro-hydrostatic actuators which will reduce the amount of required hydraulic plumbing and provide a more reliable control system. Dual actuators will be fitted to each control surface to ensure a fault-tolerant, redundant system capable of maintaining aircraft control even in the event of a system failure. All major flight control surfaces are hinged at 10% of their chord to reduce control forces and decrease the risk of aerodynamic flutter.

D. Ancillary Systems

In addition to the main flight controls, a variety of systems have to be considered for successful operation of a passenger aircraft, such as landing gear, cabin environmental controls, electrical power, and others. Landing gear design is a standard oleopneumatic design with four-bar retraction mechanisms which allow the wheels and struts to be stowed in the fuselage during water operations and in flight.

The geometry of the retractable main landing gear permits significant space along the center of the fuselage. This space will be used to mount an auxiliary power unit (APU) for use during ground operations - this is an especially useful feature for an aircraft operating outside of a typical airport environment where ground power units are available. A Honeywell 36-150 APU was selected for this design, as it is a representative choice for an aircraft in this transport category; as shown on the schematic view depicted in Figure **??**, the selected APU packages neatly at the top of the landing gear bay.

Behind the APU, an electrical hydraulic pump is mounted; this pump would be used to drive hydraulic pistons to raise and lower the gear; it could also be used to pressurize a conventional hydraulic system as a tertiary backup for the flight control system.

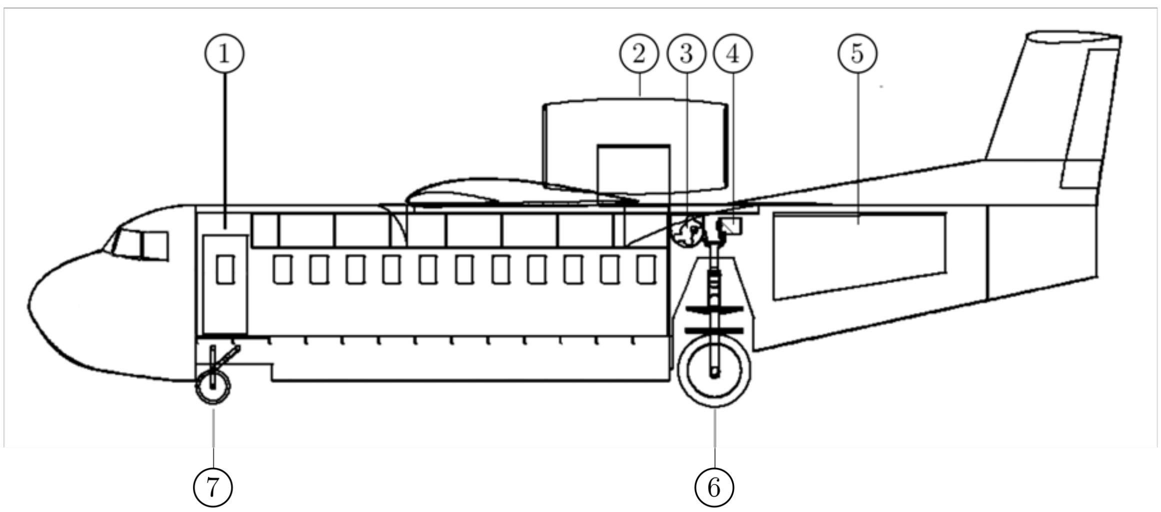
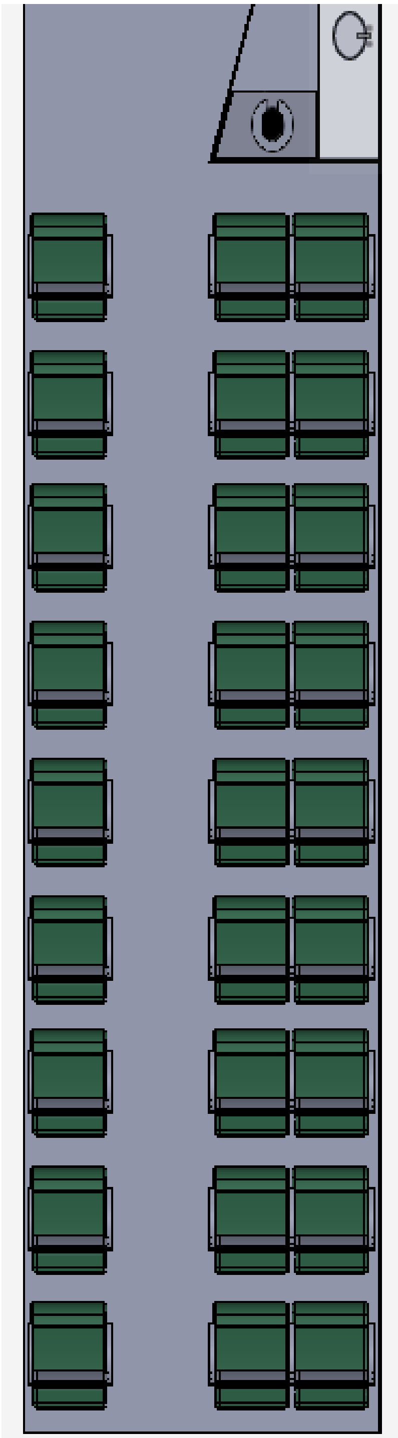


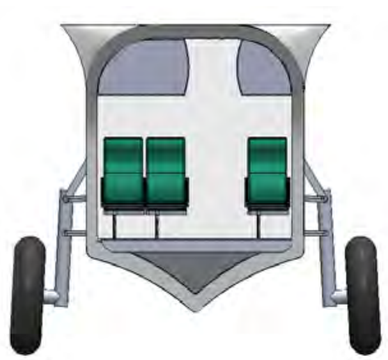
Figure 6: Schematic view of aircraft components showing 1) cabin door; 2) engines; 3) APU; 4) electric hydraulic pump; 5) cargo door; 6) main gear, and 7) nose gear

E. Cabin Configurations

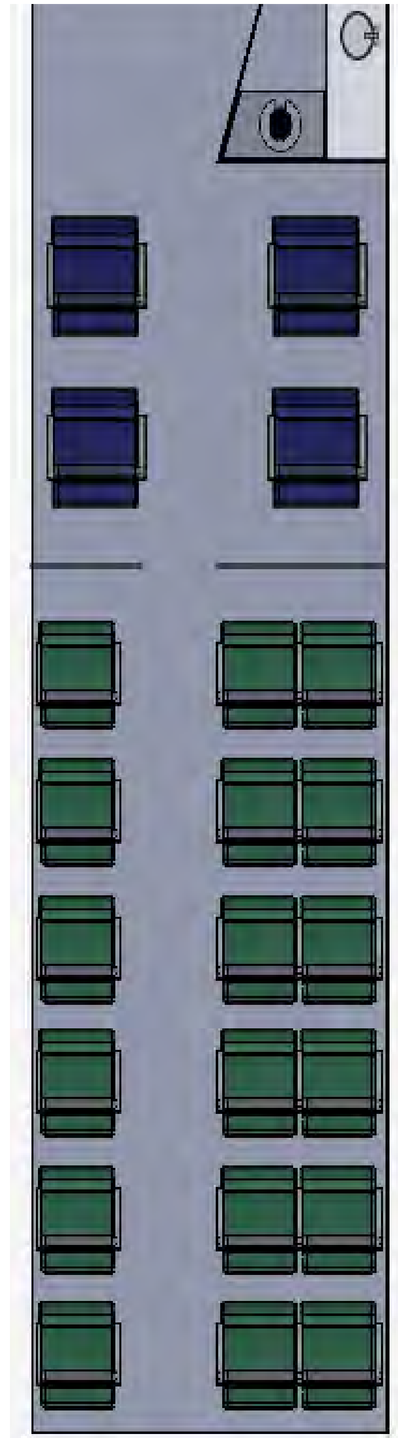
The aircraft cabin has been designed around a baseline single-class layout with 27 seats in 9 rows of 3. Seats are laid out in a 2-and-1 arrangement with an off-center aisle; a single lavatory is positioned at the front of the cabin. Seat pitch is set at 28 inches and overhead storage bins run the length of the cabin. Overhead storage provides adequate baggage space for passengers, at approximately 4.3 cubic feet per seat. Additional baggage or larger items can be accommodated in the aft cargo hold of the aircraft.



(a) Single-class interior layour



(b) Cabin cross-section



(c) Split-class interior layour

F. Weight Summary

A mass buildup was performed by estimating the overall masses of various components. Structural mass was obtained by using wetted-area approximations as found in;[6] system masses such as avionics and hydraulics were estimated based on.[13] Actual component masses were used for items that were specified, such as the APU and engines. The resulting table of masses is shown in Table 6.

Table 6: Mass Buildup

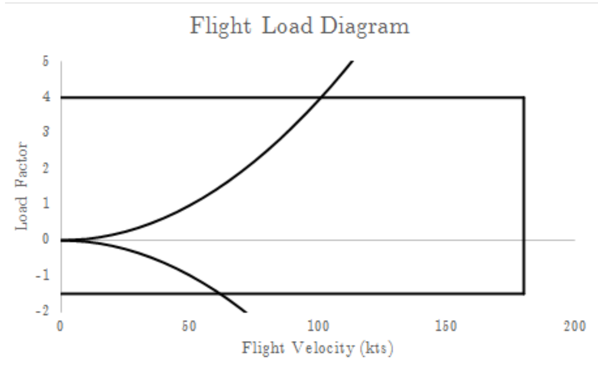
	Mass (kg)	Arm (m)	Moment (kg-m)
Fuselage	6779.6	9.389	63656
Fuselage Structure	1500	8.000	12000
Flight Crew	250	3.250	812.5
Seats	270	8.000	2160
Cockpit Seats	25	2.300	57.5
Avionics	500	1.300	650
Landing Gear	950	9.000	8550
Engines	2400	11.400	27360
Lavatory	100	3.500	350
APU	63.6	12.000	763.2
Hydraulics (torenbeek)	320	12.000	3840
Vertical Tail	159	17.800	2830
Horizontal Tail	242	17.700	4283
Wing	2450	8.164	20002
Anti-Icing	290	8.164	2368
Fuel	2500	8.164	20410
Overall Mass (Max Gross)	**22039**		

Several estimates for components such as the avionics and hydraulics are likely to be pessimistic due to advances in technology since Torenbeek's models were published. Even so, the sum of masses is 22039 kg, which leaves significant contingency for weight growth when compared to the initial estimated gross mass of 23934 kg.

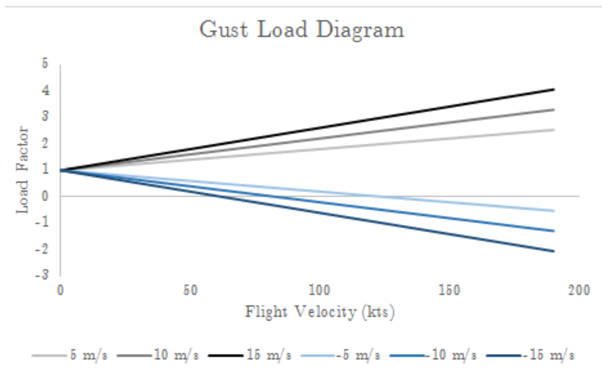
IX. Flight Characteristics

A. Flight Envelope

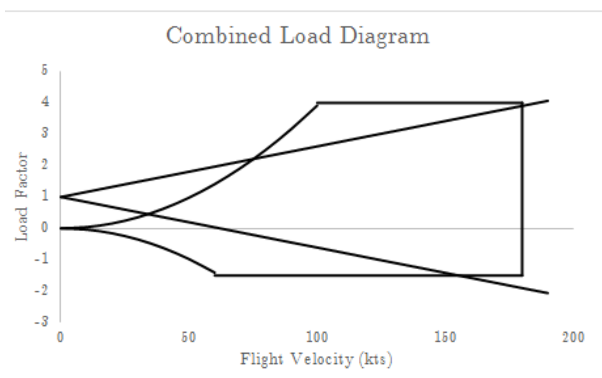
The operational limits of the aircraft were determined by applying load limits of +4/-1.5, which are reasonable for a transport-class aircraft.[6] Gust loads were evaluated at ± 5, 10, and 20 feet per second, but at the low altitudes required for ground-effect flight, these loads are found to be minimal compared with the overall aerodynamic loads on the airframe, as shown in Figure 8. Maximum dive speed v_d was set at 180 kts, using a factor of 1.4 over the proposed cruise speed.



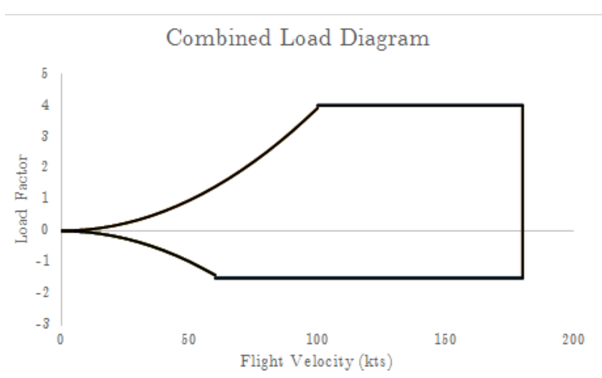
(a) Vehicle loading



(b) Gust loading



(c) Combined flight loading



(d) V-n diagram

Figure 8: Construction of a loading (v-n) diagram

B. Takeoff and Landing Performance

With the large engines and the relatively low waterline, the proposed aircraft should have excellent short-field takeoff capability. Estimated takeoff distance over a 50-foot obstacle at minimum weight is 484 m off of water and 480 m on asphalt. The twin engine configuration also allows for successful takeoff with a single engine loss. Taking off from a full stop with one engine, the estimated takeoff distance increases to 749 m for water and 767 m for asphalt. Performance for various unfinished runway surfaces is listed in Table 7.

Table 7: Takeoff Performance for Various Runway Surfaces

Surface	Takeoff distance at sea level (m)	Takeoff distance at 5000'MSL
Asphalt	484	540
Concrete	484	540
Dirt	484	540
Turf	489	545
Gravel	490	547
Metal mat	485	541
Water	480	587

Short-field landing performance is enhanced by the addition of thrust reversers and spoilers. Thrust reversal was assumed to provide 25% of the maximum installed thrust, and drag assumed to provide an 80% increase in drag. This provides a minimum landing distance of 332 m at minimum weight. Minimum landing distance for the aircraft on different surfaces is shown below in Table 8.

Table 8: Landing Performance for Various Runway Surfaces

Surface	Landing distance at sea level (m)	Landing distance at 5000'MSL (m)
Asphalt	332	540
Concrete	351	380
Dirt	375	408
Turf	407	445
Gravel	305	327
Metal mat	332	358
Water	525	581

C. Stability

For the proposed aircraft, initial estimates for the center of lift place it 9.03 m from the nose of the aircraft, or approximately 80% of the mean aerodynamic chord. At its basic operating mass (BOM), the aircraft's center of gravity should lie 0.580 m in front of the center of lift; at maximum gross, it will lie 0.639 m in front of the center of lift. Providing a static margin of 20% of the mean aerodynamic chord, this should ensure adequate static longitudinal stability. One potential concern for a ground-effect aircraft is a coupling between altitude and longitudinal stability caused by the variation in the lift profile of the horizontal stabilizer caused by the varying influence of ground effect at different heights above the surface. This has been successfully counteracted by a number of ground-effect vehicles in the past,[2] and with a modern design a dynamic stability system coupled to the flight controls should render this a non-issue.

D. Water Performance

Flotation and water performance were analyzed using a CAD model; displacement was calculated as a function of water height (measured from the keelson; this displacement was used to find the buoyancy force of the aircraft at rest in the water. The resting waterline was then found as the intersection between the displacement curve and the vehicle's gross weight. At maximum gross weight, the waterline lies 1.22 m above the keelson.

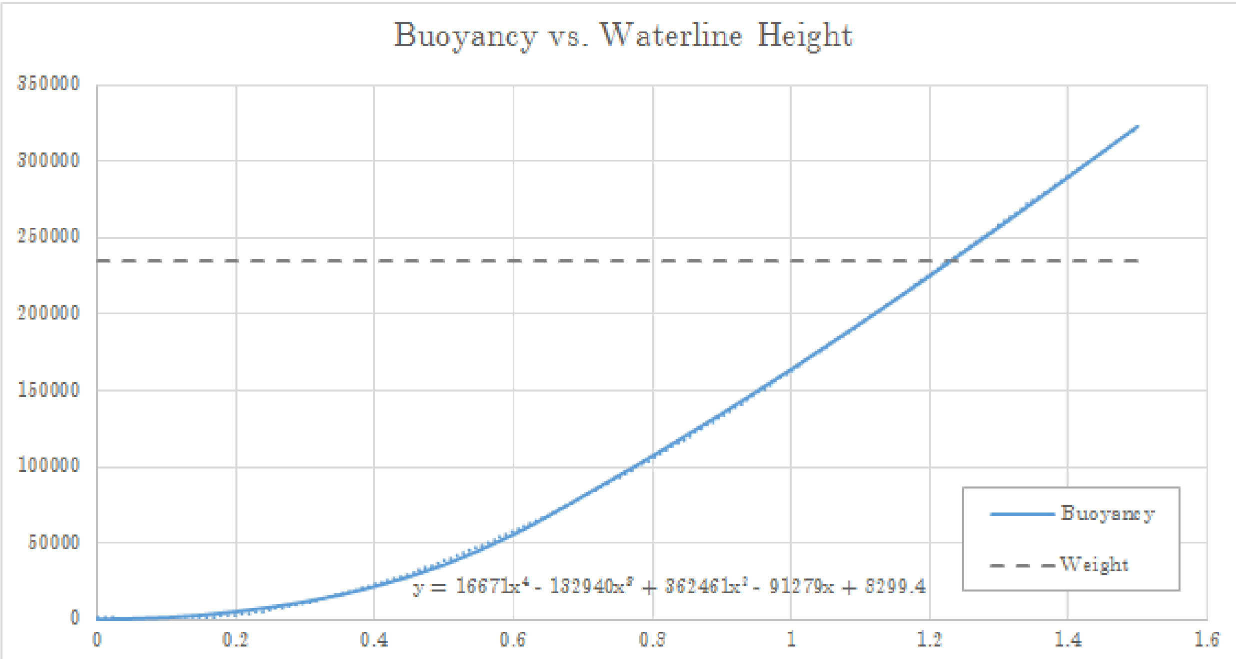


Figure 9: Resting buoyancy analysis

X. Mission Analyses

This amphibian is capable of satisfying a variety of missions: delivering passengers and cargo to regions otherwise without air access and infrastructure; facilitating commutes between coastal urban centers; and relieving strain on highly-congested airports. Even if only over-water flights are considered, there is a significant market for this ground-effect aircraft based on the number of high-density air routes in coastal areas and the number of islands and archipelagos without large airport infrastructure. This section analyzes aircraft performance for four sample missions: 1) A maximum-density passenger flight of 1000 nautical miles; 2) a cargo flight of 500 nautical miles; 3) a 250 nautical mile passener flight with STOL capability for water and hard runways; 4) a 20-passenger economy mission of 200 nautical miles.

A. Maximum-Density Passenger Mission

A primary design objective of this aircraft is for regional passenger transport. Many major urban centers around the world are currently under-served by existing airport infrastructure; in several rapidly-developing parts of the world, major airports are drastically over-crowded. Pacific Asia sees perhaps the worst of this, with airports such as Beijing and Hong Kong operating near or above 100% of their design capacities in 2012. The most egregiously over-burdened facility is probably SoekarnoHatta International in Jakarta, which in 2012 operated at over 250% design capacity.[11] As a representative route through this high-traffic and over-burdened region, the well-traveled Beijing-to-Shanghai route was analyzed. This is a distance of approximately 1000 nautical miles and is currently the fifth most-traveled air route in the world.[1]

Beijing - Shanghai Flight Analysis	
Route Distance	1852 km
Cruise altitude	4 m
Passengers	27
Basic Operating Mass	16012 kg
Cruise velocity	447 km/h
Flight time	249 min
Fuel burn	1918 kg
Fuel economy	4.6 L/seat/100 km
Liftoff mass	21036 kg
Landing mass	19117 kg
Required takeoff roll for water	412 m
Distance to clear a 15.24 m obstacle	679 m
Required takeoff roll for concrete	394 m
Distance to clear a 15.24 m obstacle	661 m
Required landing distance for concrete	228 m
Distance to clear a 15.24 m obstacle	402 m

B. STOL Missions

The STOL capabilities of this aircraft make it well-suited to missions requiring access to regions of the world which have traditionally been considered "backcountry". The vehicle could provide an economical transport from regional population centers to major airports, or even from isolated and remote communities to larger urban centers. This would allow for increased access to the global air transportation network without requiring massive infrastructure additions. For example, the proposed wing-in-ground-effect transport could provide rapid and economical transport between the capitals of island nations such as Indonesia, Malaysia, and the Philippines and the less-accessible settlements and towns on their respective archipelagos. Traversing stretches of the Indian ocean would allow the vehicle to cruise at an efficient altitude well within the ground effect region, with minimal fear of any sort of collision.

Jakarta Regional Shuttle Analysis	
Route Distance	463 km
Cruise altitude	4 m
Passengers	20
Basic Operating Mass	16012
Cruise velocity	429 km/h
Flight time	65 min
Fuel burn	461 kg
Fuel economy	5.9 L/seat/100 km
Liftoff mass	18773 kg
Landing mass	18312 kg
Required takeoff roll for water	323 m
Distance to clear a 15.24 m obstacle	576 m
Required takeoff roll for concrete	311 m
Distance to clear a 15.24 m obstacle	563 m
Required landing distance for concrete	215 m
Distance to clear a 15.24 m obstacle	389 m

C. Cargo Mission

The ability to fly to otherwise inaccessible parts of the world makes this multi-mission amphibian an excellent candidate for light cargo missions. For example, accessing remote scientific and industrial sites would be an ideal application for this vehicle as many such outposts are difficult or impossible to access except by air. One prime example which demonstrates the utility of this kind of mission is the plethora of remote mining facilities spread throughout the northern reaches of North America. In central Canada especially, many large mining facilities are situated in largely-flat tundra terrain, but separated from amjor urban centers and supply facilities by dozens or hundreds of miles. For example, between the Meadowbank Gold mine in Nunavut, Canada, is over 500 nmi from the nearest city with supplies - Yellowknife. This vehicle, with its rugged construction and STOL capability, would be an excellent aircraft for transporting cargo across the empty, flat landscape between Yellowknife and Meadowbank Gold Mine.

Yellowknife Cargo Flight Analysis	
Route Distance	926 km
Cruise altitude	4 m
Cargo	2267 kg
Cruise velocity	431 km/h
Flight time	129 min
Fuel burn	924 kg
Liftoff mass	19099 kg
Landing mass	18175 kg
Required takeoff roll for water2	335 m
Distance to clear a 15.24 m obstacle	590 m
Required takeoff roll for concrete	322 m
Distance to clear a 15.24 m obstacle	576 m
Required landing distance for concrete	212 m
Distance to clear a 15.24 m obstacle	387 m

D. Economy Mission

In addition to accessing remote regions of the world, the relative efficiency of the proposed aircraft makes it a compelling candidate for short-range commuting flights. For analysis of this proposition, the well-traveled route between Rio de Janeiro, and Sao Paulo, Brazil, was chosen. This route is currently the most-traveled air route in the world.[1] Both cities are coastal, so takeoff and landing could be performed on water or on paved runways; a water operation would potentially make it possible to reduce airport congestion while providing increased access to this sought-after route.

Rio de Janeiro - Sao Paulo Flight Analysis	
Route Distance	370 km
Cruise altitude	4 m
Passengers	27
Basic Operating Mass	16012
Cruise velocity	438 km/h
Flight time	51 min
Fuel burn	376 kg
Fuel economy	4.5 L/seat/100 km
Liftoff mass	19493 kg
Landing mass	19117 kg
Required takeoff roll for water	350 m
Distance to clear a 15.24 m obstacle	607 m
Required takeoff roll for concrete	336 m
Distance to clear a 15.24 m obstacle	593 m
Required landing distance for concrete	228 m
Distance to clear a 15.24 m obstacle	402 m

XI. Business Case

Since the proposed aircraft utilizes well-established technologies, materials, and construction methods, development and operating costs should be relatively low. Development costs have been estimated according to statistical correlations described in Hess and Romanoff's "Aircraft Airframe Cost Estimating Relationships".[12] These authors analyzed program costs for 11 aircraft dating from the 1960s to the 1980s and developed a series of cost-estimating relationships using empty weight and maximum speed as primary parameters. These relationships are shown below:

$$E = 0.0103(EW)^{0.777}(SP)^{0.894} \tag{3}$$
$$T = 0.0201(EW)^{0.777}(SP)^{0.696} \tag{4}$$
$$L = 0.1410(EW)^{0.820}(SP)^{0.484} \tag{5}$$
$$M = 0.2410(EW)^{0.921}(SP)^{0.621} \tag{6}$$
$$S = 0.0251(EW)^{0.630}(SP)^{1.30} \tag{7}$$
$$P = 2.5700(EW)^{0.798}(SP)^{0.736} \tag{8}$$

where EW and SP are the aircraft's empty weight and maximum speed, and $E, T, L, M, S,$ and P represent the engineering, tooling, labor, material, support, and total program costs to produce 100 aircraft, respectively. Based on these relationships, the total development cost for an initial production run of 100 aircraft would be 70m USD, including engineering and tooling. Fly-away cost for each of the first 100 aircraft would be 6.65m USD, which compares favorably with the fly-away cost of regional transport aircraft of equivalent role (for reference, the 37-seat Embraer ERJ-140 had an estimated cost at launch of 15.2m USD and the Q400 model of the venerable Dash-8 has an estimated unit price of 31.3m USD[14]).

XII. Conclusions

The ground-effect aircraft presented in this report offers significant advantages over conventional designs for the specified design missions. Offering full amphibious capability, this aircraft is capable of transporting passengers and cargo around many currently-underserved parts of the world such as pacific Asia, the tundra terrain of northern Canada and Russia, and a variety of coastal cities around the globe. Ground-effect aircraft offer significant operational advantages over their higher-altitude brethren - the minimal climb required decreases engine wear and stress on the airframe; low-altitude flight saves weight by negating the need for a pressurized cabin; drag reduction near the ground allows for a more compact footprint, further increasing the off-airport capability of the design; and finally, the aerodynamic advantages of flying within ground effect translate directly into lower fuel consumption - the maximum fuel economy on the sample missions outlined in this report is 4.5 L/seat/100 km, an improvement of 20-30% over the turboprop aircraft (such as those produced by Beechcraft,[15] Dornier,[16] or Pilatus[17]) which currently dominate on short-haul commuter routes.

The *Cormorant*, and the ground-effect technology which it represents, demonstrates a highly capable system capable of providing economical transport with minimal cost and emissions. The design offers enough versatility to allow VFR/IFR operation within traditional airport environments, while maintaining adequate power to enable significant capability in accessing unfinished back-country runways and waterways and climbing above terrain obstructions as necessary. Ground-effect aircraft, with their lower operating costs and more robust airframes, offer an ideal compromise between the high-performance transports that dominate at major airports and the antiquated bush planes which are more prevalent in the developing world. This middle ground of versatile, low-altitude, high-efficiency flight offers an unparalleled opportunity to expand the reach of air infrastructure to regions of the world which suffer from inaccessible terrain and/or overcrowded airports. Further development of ground-effect aircraft has the potential to drastically alter the landscape of air travel by enabling less-crowded terminals and more widespread access to air travel while minimizing monetary and environmental costs.

Acknowledgments

The author would like to thank Ms. Sydney Schnulo of NASA's Glenn Research Center for her assistance during their joint investigation of ground-effect vehicles during the summer of 2016. That precursory work inspired the design of the Cormorant*, albeit somewhat tangentially. The author would also like to thank the many members of the Propulsion Systems Analysis Branch at GRC for their encouragement, assistance, and general wisdom during the aforementioned project, and Ms. Margret Schaefer for contributing her ornithological expertise in the pursuit of an appropriately-avian vehicle name.*

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Appendix: Mission Analysis Code

```
import sys
import numpy as np
import matplotlib as mpl
from matplotlib import pyplot as plt
from scipy.sparse import linalg as sla
from scipy.interpolate import griddata
import scipy
import math
# Geoffrey's Parametric Ground-Effect Mission Analysis Spectacular, v.1.0


def Carsons_Speed(TvsV,vvals):
error = 97.0
vcruise = -1
Trequired = -1
for i in range(np.argmin(TvsV),len(TvsV)-1):
slope = (TvsV[i]-TvsV[i-1])/(vvals[i]-vvals[i-1])
tan_slope = TvsV[i]/vvals[i]
newerror = abs((slope-tan_slope)/tan_slope)*100
if newerror < error:
error = newerror
vcruise = vvals[i]
Trequired = TvsV[i]
return [vcruise, Trequired]

def Resistance_Coefficient(C_buoy, Cv):
if Cv <= 1.75:
Cr = 0.018075232*Cv**2 + 0.022392959*Cv-0.014043831
elif Cv <= 4.10:
Cr = -0.019059778*Cv**3 + 0.128434901*Cv**2 - 0.245265896*Cv + 0.195016622
else:
Cr = 0.011248761*Cv**2 - 0.093446996*Cv + 0.267868763
if Cr < 0:
Cr = 0
return Cr

def TakeoffEstimate(surface,obstacle):
global AR
global S
global Cd0
global Clmax
global e
global MR
global cruise
global g
global rho
global b
global h
global GLOM
global maxPL
global seat_mass
global luggage_mass
global passenger_mass
global sfc
```

```
global SFC
global Isp
global installed_thrust
global liftoff_mass

# Takeoff Analysis
numpts = 50
takeoff_run = 0

beam = 2.4 # m
static_submerged_frac = 0.25
static_displacement = liftoff_mass/(1000*g) # m^3
Cl = 2.0
vstall_TO = math.sqrt((liftoff_mass*g)/(0.5*rho*Cl*S))
weight = (liftoff_mass)*9.81
vrotate = 1.1*vstall_TO
v_tr = 1.15*vstall_TO
v_vals = np.linspace(0.01, vrotate, numpts)

h = 0.1
WBfactor =(1 - 0.66*h)/(1.05+3.7*h)

for i, v in enumerate(v_vals):
Cv = v/(g*beam)
#F_B = 1000*g*displacement
lift = 0.5*rho*v**2*S*Cl
if surface == 'water':
F_B = (weight-lift)
displacement = F_B/(1000*g)
fraction = displacement/static_displacement*static_submerged_frac
if fraction < 0:
fraction = 0
C_buoy = F_B/(1000*beam**3*g)
Cr = Resistance_Coefficient(C_buoy, Cv)
if F_B <= 0:
Cr = 0.0
#print "Cv & %1.3f     C_buoy & %1.3f     Cr & %1.3f\\\\\\\\" % (Cv, C_buoy, Cr)
resistance = 1000*beam**3*Cr
else:
if surface == 'dirt':
mu = 0.04 #Raymer
elif surface == 'water2':
mu = 0.1 #Raymer
elif surface == 'hardturf':
mu = 0.05 #Raymer
elif surface == 'softturf':
mu = 0.07 #Raymer
elif surface == 'concrete':
mu = 0.04 # NACA 583
elif surface == 'mat':
mu = 0.045 # Smith "evaluation of mo-mat 158 as light-duty landing mat"
elif surface == 'gravel':
mu = 0.08 #  Automotive Handbook, 4th ed., Robert Bosch GmbH, 1996, p. 330
elif surface == 'asphalt':
mu = 0.04 #Raymer
```

```
resistance = mu*(weight-lift)
if resistance < 0:
resistance = 0
Cdi = Cl**2/(math.pi*e*AR)*(1-WBfactor)
Cd = Cd0+Cdi
drag = 0.5*rho*v**2*Cd*S
netforce = installed_thrust-drag-resistance
acceleration = netforce/(weight/g)
if i > 0:
dV = v_vals[i]-v_vals[i-1]
dt = dV/acceleration
dS = (v_vals[i]**2-v_vals[i-1]**2)/(2*acceleration)
takeoff_run = takeoff_run + dS
#print dS
print "Required takeoff roll for " + surface + " & %3.0f m\\\\\\" % takeoff_run

R = v_tr**2/(0.2*g)
S_tr = math.sqrt(R**2-(R-obstacle)**2)

if obstacle == 0:
S_tr = 0
else:
print "Distance to clear a %2.2f m obstacle & %3.0f m\\\\\\" % (obstacle,(takeoff_run+S_tr))
return vrotate

def LandingEstimate(surface,obstacle):
global AR
global S
global Cd0
global Clmax
global e
global MR
global cruise
global g
global rho
global b
global h
global GLOM
global maxPL
global seat_mass
global luggage_mass
global passenger_mass
global sfc
global SFC
global Isp
global installed_thrust
global liftoff_mass
global landing_mass

numpts = 50
landing_distance = 0

beam = 2.4 # m
static_submerged_frac = 0.25
static_displacement = landing_mass/(1000*g) # m^3
```

```
Cl = 3.0
vstall_landing = math.sqrt((landing_mass*g)/(0.5*rho*Cl*S))
weight = (landing_mass)*g
v_vals = np.linspace(vstall_landing,0.01, numpts)

h = 0.1
WBfactor =(1 - 0.66*h)/(1.05+3.7*h)

for i, v in enumerate(v_vals):
Cv = v/(g*beam)
#F_B = 1000*g*displacement
lift = 0.5*rho*v**2*S*Cl
lift = lift*0.75 # spoilers
if surface == 'water':
F_B = (weight-lift)
displacement = F_B/(1000*g)
fraction = displacement/static_displacement*static_submerged_frac
if fraction < 0:
fraction = 0
C_buoy = F_B/(1000*beam**3*g)
Cr = Resistance_Coefficient(C_buoy, Cv)
if F_B <= 0:
Cr = 0.0
resistance = 1000*beam**3*Cr
else:
if surface == 'dirt':
mu = 0.3 #Raymer
elif surface == 'water2':
mu = 0.3 #Raymer
elif surface == 'hardturf':
mu = 0.4 #Raymer
elif surface == 'softturf':
mu = 0.2 #Raymer
elif surface == 'concrete':
mu = 0.4 # NACA 583
elif surface == 'mat':
mu = 0.5 # Smith "evaluation of mo-mat 158 as light-duty landing mat"
elif surface == 'gravel':
mu = 0.7 #  Automotive Handbook, 4th ed., Robert Bosch GmbH, 1996, p. 330
elif surface == 'asphalt':
mu = 0.5 #Raymer
resistance = mu*(weight-lift)
if resistance < 0:
resistance = 0
Cdi = Cl**2/(math.pi*e*AR)*(1-WBfactor)
Cd = Cd0+Cdi
drag = 0.5*rho*v**2*Cd*S
drag = drag*1.8 #spoilers
drag = drag + 0.25*installed_thrust #thrust reverser?!
if surface == 'water2':
netforce = -(drag+0.30*weight)
else:
netforce = -(drag+resistance)
acceleration = netforce/(weight/g)
if i > 0:
```

```
dV = v_vals[i]-v_vals[i-1]
dt = dV/acceleration
dS = (v_vals[i]**2-v_vals[i-1]**2)/(2*acceleration)
landing_distance = landing_distance + dS
#print "Velocity & %2.1f;   Distance & %2.1f\\\\\\" % (v, dS)
print "Required landing distance for " + surface + " & %3.0f m\\\\\\" % landing_distance
v_approach = 1.3* vstall_landing

S_tr = obstacle/math.tan(math.radians(5))
print "Distance to clear a %2.2f m obstacle & %3.0f m\\\\\\" % (obstacle,(landing_distance+S_tr))
#    return vrotate


def MissionAnalysis(flighttype,passengers,cargo,distance):
global AR
global S
global Cd0
global Clmax
global e
global MR
global cruise
global g
global rho
global b
global h
global GLOM
global maxPL
global seat_mass
global luggage_mass
global passenger_mass
global sfc
global SFC
global Isp
global installed_thrust
global liftoff_mass
global landing_mass

# Mission Parameters
distance = distance*1000

distancevals = np.linspace(0.01, distance, 100)
fuelburnvals = np.linspace(0.01, distance, 100)
vcruisevals = np.linspace(0.01, distance, 100)
print "\n-----MISSION ANALYSIS-----"
print "Route Distance & %4.0f km\\\\\\" % (distance/1000)
print "Cruise altitude & %2.0f m\\\\\\" % (h*b)
WBfactor =(1 - 0.66*h)/(1.05+3.7*h)
if WBfactor <=0:
WBfactor = 0

if flighttype == 'passenger':
payload = passengers*(seat_mass+luggage_mass+passenger_mass)
print "Passengers & %i\\\\\\" % (passengers)
BOM = GLOM/MR-maxPL+3*(passenger_mass+luggage_mass)
print "BOM & %f\\\\\\" % BOM
```

```
if flighttype == 'cargo':
payload = cargo
print "Cargo & %i kg\\\\\\" % (payload)
BOM = GLOM/MR-maxPL+2*(passenger_mass+luggage_mass)
error = 100
threshhold = 0.01
guessfuel = GLOM*(1-1/MR)
while error > threshhold :
TOM = BOM + payload + guessfuel
weight = TOM
fuelburn = 0
for j, dS in enumerate(distancevals):
# Cruise Performance
TvsVvals = np.zeros(200)
for i,v in enumerate(np.linspace(50,200,200)):
Cl = (weight*g)/(0.5*rho*v**2*S)
Cdi = Cl**2/(math.pi*e*AR)*(1-WBfactor)
Cd = Cd0+Cdi
D = 0.5*rho*v**2*S*Cd
TvsVvals[i] = D
min_thrust = np.min(TvsVvals)
best_speed = np.linspace(50,200,200)[np.argmin(TvsVvals)]
[vcruise, cruisethrust] = Carsons_Speed(TvsVvals,np.linspace(50,200,200))
vcruisevals[j]=vcruise
if j > 0:
dt = (distancevals[j]-distancevals[j-1])/vcruise
dfuel = SFC*dt*(cruisethrust/1000)/1000 # incremental fuel burned in kg
fuelburn = fuelburn + dfuel
weight = weight - dfuel
fuelburnvals[j] = dfuel

flighttime = distance/np.mean(vcruisevals)

error = abs(fuelburn-guessfuel)/guessfuel
if error > threshhold :
guessfuel = min(guessfuel,fuelburn) + (max(guessfuel,fuelburn)-min(guessfuel,fuelburn))/2
fuelvolume = fuelburn/840.0 # approximate volume of fuel burned in m^3
fuelvolume  = fuelvolume*1000 # converted to liters
liftoff_mass = (BOM+fuelburn+payload)
landing_mass = liftoff_mass-fuelburn

#print "BOM & %f    TOM:   %f\\\\\\" % (BOM, TOM)
print "Cruise velocity & %3.0f km/h\\\\\\" % (np.mean(vcruisevals)/1000*3600)
print "Flight time & %3.0f min\\\\\\" % (flighttime/60)
print 'Fuel required & %4.0f kg\\\\\\' % fuelburn
print 'Fuel burn & %2.3f kg/km\\\\\\' % (fuelburn/distance*1000)
if flighttype == 'passenger':
fuel_per_seat = fuelvolume/passengers # fuel use in liters/seat (55 is reasonable for 1000 nmi)
print 'Fuel used is %3.1f L/seat/100 km\\\\\\' % (fuel_per_seat*100/(distance/1000))
if flighttype == 'cargo':
print 'Fuel used is %3.1f L/kg/100 km\\\\\\' % (fuelburn*100/(payload*distance/1000))
print 'Liftoff mass & %6.0f kg\\\\\\' % liftoff_mass
print 'Landing mass & %6.0f kg\\\\\\' % landing_mass

vrotate = TakeoffEstimate('water',0)
```

```
#    vrotate = TakeoffEstimate('water2',15.24)
TakeoffEstimate('dirt',15.24)
TakeoffEstimate('softturf',15.24)
TakeoffEstimate('concrete',15.24)
TakeoffEstimate('mat',15.24)
TakeoffEstimate('asphalt',15.24)
TakeoffEstimate('gravel',15.24)


LandingEstimate('water',15.24)
LandingEstimate('dirt',15.24)
LandingEstimate('softturf',15.24)
LandingEstimate('concrete',15.24)
LandingEstimate('mat',15.24)
LandingEstimate('asphalt',15.24)
LandingEstimate('gravel',15.24)

print "Rotation speed & %3.0f km/h\\\\\\" % (vrotate/1000*3600)

# Aircraft Parameters
AR = 6.0
S = 50.0 # m^2
Cd0 = 0.02
Clmax = 3.0
e = 1.78*(1-0.045*AR**0.68)-0.64
MR = 1.25
cruise = 150.0
g = 9.81
rho = 1.18391 #ISA at MSL 78F
#rho = 1.01893 #ISA at 5000 MSL 78F
b = math.sqrt(S*AR)
h = .25
GLOM = 23934.0 #kg
maxPL = 3450;
seat_mass = 10. #kg
luggage_mass = 17. #kg
passenger_mass = 88 #kg

# Engines: 2x GE CF34-8C1
installed_thrust = 2*61340.976 # 2x GE CF34-1A
sfc = 0.370 #lb/(lbf-h) (GE CF34-1A)

SFC = sfc*0.453592/(4.48*3600*9.81)*10**7 # g/(kN-s)
Isp = 1/(SFC*g)*10**6


MissionAnalysis('cargo',0,2267.962,926)
#MissionAnalysis('passenger',27,0,370.4) #200 nmi "economic mission"
#MissionAnalysis('passenger',20,0,463) #250 nmi STOL mission
#MissionAnalysis('passenger',27,0,1852) #1000 nmi max density
```