Disruptive Propulsion Technology Makes Endo/Exoatmosphere Operating Commercial Aircraft Possible

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Applying emerging theoretical disruptive propulsion technologies to future commercial aircraft opens up bold new ways of thinking. Unproven propulsion systems with paradigm-shifting high thrust-to-power ratios enable endo/exoatmospheric flight trajectories to "fly anywhere in the world in about two hours." When a wide range of vehicle designs and flight trajectory scenarios were tested against disruptive propulsion technology performance metrics, the best-performing vehicle had a counterintuitive design. The vehicle was a mostly conventionally built commercial composite aircraft, which exhibited small, stubby folding wings, and a NASA-like elliptical cross-section fuselage for 180 passengers. The vehicle is roughly the size of a Boeing 737 MAX 9, possessing both vertical lift and horizontal thrusting propulsion. A Mach 5+ hypersonic aircraft approach was also evaluated in the trade space but considered unworkable for commericial air travel due to an unacceptable percent of vehicle mass required by the thermal protection system (TPS), a high airframe manufacturing price, and a lack of reusability and economic maintainability. However, a new endo/exoatmospheric (in atmosphere/vacuum of space) flight profile traded favorably. The aircraft maintains a near horizontal attitude throughout all flight regimes for passenger comfort, subject's passengers to only moderate g-forces, and flies mostly subsonic to local conditions while avoiding aeroheating and preventing the formation of sonic booms that will otherwise reach the ground. The vehicle takes off from conventional airports, ascends vertically to the minimum vacuum of space, and accelerates forward to high velocity to make range while maintaining constant altitude with vertical thrusting. The vehicle then reverses horizontal thrust to slow down prior to atmospheric reentry, performs a near vertical-powered descent, and lands vertically or enters a conventional aircraft landing pattern. This paper explores the possibilities introduced by new disruptive propulsion technology.

Acronyms

BMI = bismaleimide
BWR = back work ratio
CMC = ceramic matrix composite
CVD/CVI = chemical vapor deposition/chemical vapor infiltration
I_{sp} = specific impulse
ITB = inner turbine burner
LOX = liquid oxygen
MMC = metal matrix composite
MOTS = modified off-the-shelf
MP = momentum propulsion (impulse momentum)
NMP = non-momentum propulsion
RCC = reinforced carbon carbon
ROM = rough order magnitude
RP = relativistic propulsion
SFC = specific fuel consumption
SOTA = state-of-the-art
TPS = thermal protection system
TRL = technology readiness level
UAV = unmanned aerial vehicle

I. Introduction

The purpose of this paper is to explore the uses of disruptive propulsion technology in commercial aircraft designs. Disruptive propulsion is defined as the achievement of revolutionary specific fuel consumption (SFC) and specific impulse (I_{sp}) gains. The thrust generated by disruptive propulsion is far greater than state-of-the-art (SOTA) chemical propulsion systems, which use momentum propulsion (MP), also known as impulse momentum. Due to the finite performance limitations of MP, propulsion technology must utilize what this author coins' non-momentum propulsion (NMP), defined as propulsion not reliant on Newton's third law. In other words, NMP is any propulsion system, which can create thrust without accelerating mass that leaves the control volume. Surprisingly there are technically sound teams working in the field of NMP right now, looking to realize practical disruptive propulsion. The most recent notable is perhaps EM-Drive propulsion, where microwaves bouncing around in an asymmetric resonant cavity generate positive, measureable, and repeatable thrust. Despite NASA's careful and repeated certification of positive EM-Drive thrust, the idea of NMP is still very controversial and generally not accepted by the greater propulsion technical community.

The purpose of this paper is not to debate if NMP is scientifically valid or not, but rather explore the *possibilities* if it were real and how it could transform commercial air transportation. No matter what type of NMP is applied the potential effect is the same, allowing engineers to create new and exciting missions for commercial aircraft with the author's goals of: (1) standard coach airfare affordability to all passengers, (2) performance supporting "anywhere in the world in about two hours", and (3) 90% reduction in overall environmental impact over current commercial aircraft.

II. Procedure

A. Short List of NMP Concepts

Table 1 is a short list of NMP technologies, essentially propulsion that does not rely on Newton's third law of momentum propulsion (MP). Included in the table is a category the author further coins the term relativistic propulsion (RP), a broad catch all for propulsion concepts reliant on Einstein's relativistic theories. The table is not meant to be an exhaustive list or in any way validate the propulsion types, since the general propulsion community considers them all "implausible" at this time. Rather, the table is included for completeness and overall understanding of this technical area.

B. Identifying Power Sources to Drive NMP Thrusters

All NMP systems for commercial aircraft (and other applications) require a power source in one form or another to energize or otherwise drive the thruster component. For this study we limited power sources to SOTA and near term anticipated improvements of the art. Table 2 illustrates different power sources that could potentially drive NMP thrusters. Said table relies on available technical data but does include some engineering best estimate subjectivity in areas of modified-off-the shelf (MOTS) ratings applied to NMP.

The turboshaft engine can provide power to the NMP thruster two ways; through direct mechanical rotational shaft horsepower, or by electrical power via an electrical generator with its accompanying conversion efficiency knockdown. It is important to note turboshaft engines are limited only to endoatmosphere air breathing missions.

An oxidizer/fuel fueled combustion chamber driving a gas turbine approach frees the vehicle to fly both endoatmosphere and exoatmosphere (vacuum of space) missions, with the noted performance detriment of having to carry its own oxidizer. Performance calculations are based on using liquid oxygen and commercial Jet A-1 aircraft fuel, essentially a refined kerosene (n-Dodecane, $C_{12}H_{26}$). Conventional liquid oxygen (LOX)/kerosene rocket engines operate in a fuel rich off stoichiometric mix ratio, primarily to lower the adiabatic flame temperature of their combustion gasses, so they don't heat damage high temperature operating components. Because a conventional gas turbine gas inlet section found on turbofan engines operates thousands-of-degrees Fahrenheit cooler than gases coming from a rocket motor combustion chamber, there needs to be a way of cooling the gas with the minimum loss in efficiency. Adjusting the oxygen to fuel mix ratio either significantly above or below stoichiometric will cool the combustion gasses to match required gas turbine inlet temperature, but with significant performance loss.

A proposed innovation to boost efficiency is applying a kind of turbine afterburning called inner turbine burner (ITB) within or between turbine stages (sometimes using turbine blade oxygen rich cooling gasses), allowing the turbine section to not overheat and still achieve a near stoichiometric oxygen to fuel ratio. The ITB idea is not new, being previously proposed for conventional gas turbine engines. It's just being applied in a novel way. By way of example combustion gasses generated in the combustion chamber enter the first turbine section with a significantly fuel rich ratio (could also be oxidizer rich), adjusting temperature down to approximately 2,912°F, a reasonable turbine entry temperature. The first turbine section takes work out of the gas, lowering its temperature such that more oxidizer is later introduced and combusted to an acceptable raised temperature before entering the second turbine section. This process is repeated until a near net stoichiometric oxidizer to fuel ratio is met by the time combustion gasses reach the last turbine section.

NMP Name	Theory of Operation	State-of-the-Art
EM-Drive	Theory 1 - Microwave pressure bouncing in asymmetric cavity creates net thrust due to different opposing wall areas. Theory 2 – Relativistic propulsion	NASA Eagleworks Laboratories validates small positive <1 lbf thrust in repeated controlled tests[1]. Results generally not accepted by propulsion community
Cannae Drive	Similar to EM-Drive	NASA Eagleworks also testing this device
DiscThruster™	Based on rocket equation[2]. Maximizes pressure thrust component. Zeros out momentum thrust and recycles very low velocity sonic choking fluid in a closed loop system. No mass leaves system	22 hp gas engine driven DiscThruster disc prototype designed to produce tens-of-pounds of thrust is being built. No test data. No propulsion community review. Trademark[3] and US and Foreign patents pending[4]
Inertial	Rotating or reciprocating inertial masses counteracting against each other in Newtonian frame of reference	No valid test data. Generally abandoned
Relativistic Propulsion (RP)	Relies on Einstein's relativity theories generally related to creating thrust by reacting rest mass against a "heavier" moving apparent mass at the electromagnetic wave or particle level	EM-Drive may or may not produce thrust based on RP theory of operation

Table 1 ***Short List of Non-Momentum Propulsion Concepts***

It's important to understand the relative power output efficiency between a conventional turboshaft engine burning JP-1 and atmospheric air, and the proposed LOX and JP-1 combustion chamber driving just the turbine section (no compressor section required) equipped with a ITB. The assumption is a turboshaft or turbofan using ambient air is many times more efficient than a system that is required to carry its own onboard oxidizer as proposed. Three factors close the efficiency gap; back work ratio (BWR), stoichiometric ratio, and low oxygen fraction in ambient air. The BWR for a turboshaft engine is the percent of power generated by the turbine section required to drive the compressor, typically 40-80%. By way of example an 80% BWR means that only 20% of turbine work actually goes into shaft horsepower. The second factor is stoichiometric ratio. If the proposed LOX/JP-1 turbine engine can truly utilize an ITB, it more efficiently produces hot gas being fed into the turbine section. The third factor is the need for air breathing turboshaft engines to perform work and incur significant losses compressing a majority of nitrogen gas in order to obtain the approximate 21% oxygen content for combustion.

A combustion analysis calculator for the LOX/JP-1 turbine concept, determines a rough order magnitude (ROM) SFC estimate in pounds of propellant (oxidizer plus fuel) per horsepower x hour (lbm/hp-hr) units. This allows us to compare this concept against other more mature NMP thruster power sources, as well as a conventional air breathing turboshaft engine. Despite including the three factors discussed previously to close the efficiency gap with other potential power sources shown in Table 2, the LOX/JP-1 turbine concept's SFC is still too high, being rated low in the trade study. Its SFC is as much as an order of magnitude higher than other technical approaches, making it non-competitive as a power source for NMP thrusters.

Electro-chemical storage battery technology is steadily advancing, in particular lithium-ion chemistries. By some published accounts[5] battery technology, driven primarily by the needs of the electric car industry to extend range, increase specific power, battery cycle life, and reduce cost are making 8-10% incremental performance improvements every year.

A trade study focusing on two high performing lithium-ion chemistries are shown in Table 2. Lithium thionyl chloride ($Li/SOCl_2$) battery chemistry and other variations (usually referred to as "lithium sulfur" batteries) are probably the highest specific energy battery you can buy off the shelf today at 710 Wh/kg (0.432 hp-hr/lbm) power[6]. Arguably lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$) is the second highest specific energy battery. Other SOTA battery chemistries are shown for comparison. For the trade study the author anticipates steady near term battery improvements matching the unique needs of the endo/exoatmospheric aircraft concept, being labeled "improved" in the status block. Specific energy of the "improved" battery is identical to as current SOTA, but discharge time and cycle life are greatly improved and brought in line with the needs of the endo/exoatmosphere commercial vehicle concept. It is important to note multiple technical groups are claiming Li/$SOCl_2$ chemistries will reach unprecedented specific energy densities of 2,600 Wh/kg[7] in the near future, a 3.7-fold improvement over SOTA which some scientists believe is both the theoretical and practical limit of Li/$SOCl_2$ battery chemistry. Battery specific energy values shown in Table 2 assume voltage cutoff, average cycle degradation, and depth of charge losses are already included in the stated performance numbers, which are dependent on how individual battery manufactures state their performance.

One approach to avoiding aircraft dispatch delay while waiting for arriving aircraft batteries to be charged, is for airports to recycle and recharge a stocked inventory of batteries on site. Such that arriving aircraft with near discharged batteries quickly change them out to fully charged replacements ideally before all of the passengers have deplaned. If realized, a battery powered commercial aircraft charging from non-polluting renewable energy sources become a true “zero carbon footprint” air transportation system, releasing zero CO_2, NOx, and other green house gases into the atmosphere.

Fuel cells offer potentially superior specific power over batteries. Although an oxygen/hydrogen fueled system has the greatest potential, LOX/CH_4 along with LOX/room temperature/pressure storable hydrocarbon systems are also in the trade space. A current challenge with fuel cells is their relatively lower hardware specific power that may be overcome in the future.

Battery Type	Status	Specific Energy Wh/kg (hp-hr/lbm)	Time to Full Discharge (hr)	Battery Cycle Life (no. of cycles)	Comments
$LiCoO_2$	SOTA	200 (0.122)	1	500-1,000	Well characterized
$LiNiMnCoO_2$	SOTA	220 (0.124)	1-2	1,000-2,000	Well characterized. Long cycle life
$LiNiCoAlO_2$	SOTA	300 (0.183)	1	500	Good discharge time, fair cycle life
	Improved	300 (0.183)	1	1,500+	Near term improvement of SOTA required
Li/$SOCl_2$ Family	SOTA	710 (0.432)	Long	Low	High energy, unacceptable discharge & cycle
	Improved	710 (0.432)	1	1,500+	Near term SOTA improvement required
	Future	2,600 (1.581)	Unknown	Unknown	Industry est. No discharge or cycle life data

Table 2 ***Electro-chemical Battery SOTA and Near Term Anticipated Improved Performance Estimates***

Power Source to Drive NMP Thruster	Operating Flight Environment	Typical Performance	Modified off the Shelf (MOTS) Applicability	Comments
Turboshaft Engine	Endoatmosphere (air breathing)	0.5 lbm fuel/hp-hr	High	SOTA. Easily adapted to mechanical shaft or electric generator driven NMP
Oxidizer/Fuel Combustion Chamber Driving Gas Turbine	Endo/ Exoatmosphere	>10 lbm propellant/ hp-hr	Low – Requires new rocket engine combustion chamber Low - Adapt gas turbine stage	Uses rocket engine combustion chamber in off stoichiometric mixture to feed warm gas to turboshaft like efficient multi-stage inter turbine burner (ITB) gas turbine. SFC still too high. Not practical
Electro-chemical Storage Battery	Endo/ Exoatmosphere	0.432 hp-hr/lbm of battery	Low – Requires custom chemistry, greatly improved discharge rate, and cycle life	Improved Li/$SOCl_2$ battery chemistry used as baseline battery in trade study. Uses SOTA specific energy but requires near term improvement of full discharge time and life cycles. See Table 2 for detailed comparison
Fuel Cell	Endo/ Exoatmosphere	Potential advances over battery	Med-Low – Scaling and weight Issues	LOX/H_2 and LOX/CH_4 versions show high power potential usually greater than batteries, but has SOTA challenging fuel cell mass

Table 3 ***Four Categories Identified as Power Sources for NMP Thrusters***

C. Flight Scenario Trade Space and Downselect

An operational flight scenario trade space is shown in Table 4. Different flight scenarios (e.g., does the aircraft take-off horizontally or vertically) for all flight regimes are evaluated, as well as other factors including for example, if the aircraft is compatible with other commercial aircraft, and able to use the same air traffic and landing patterns as conventional aircraft. Other important subjective attributes including passenger comfort are included. Adding up all possible combinations there are 6,912 starting possible flight scenarios identified for a commercial aircraft with disruptive propulsion.

Downselecting to a manageable number of flight scenarios, each element in Table 4 is assessed a number between one and five. Number one is the best rating possible while five is a non-starter rating meaning an unacceptable operational flight scenario. The non-starter five rated flight scenario elements are identified in a side trade as follows: (a) Climb-Ballistic like Trajectory to Space/Reentry, (b) Cruise at Altitude-Ballistic Trajectory, (c) Compatibility with Other Aircraft-Incompatible, (d) Passenger Comfort-Significant Discomfort, and (e) Passenger Comfort-Severe Discomfort. It is concluded that ballistic like space launch profiles are unacceptable in terms of passenger comfort from both high g-force ascent/reentry and perhaps more importantly the apogee-like zero g-force consideration (people throwing up). It is furthermore subjectively determined this new aircraft will have to be compatible or at least pseudo compatible with current commercial aircraft, sharing landing patterns, airport infrastructure, etc. By eliminating these five elements, the total number of possible operational flight scenario outcomes drops to 1,296. Still too high to develop a trend or identify the final downselect candidate.

Take-off	Climb	Cruise at Altitude		Descent	Land	Compatibility with Other Aircraft	Passenger Comfort
		Method of Lift	Flight Regime				
Horizontal	Conventional Airfoil Lift	Aerodynamic	Endo	Aerodynamic	Horizontal	Compatible	No Discomfort
Vertical	Vertical Thrust	Vertical Thrusting	Exo	Aeroheat Reentry	Vertical	Incompatible	Little or No Discomfort
	Airfoil Lift + Vertical Thrust	Orbital		Powered Vertical	Horizontal or Vertical	Pseudo Compatible	Significant Discomfort
	Ballistic like Trajectory to Space/Reentry	Ballistic Trajectory					Severe Discomfort

Table 4 ***6,912 Possible Flight Scenario Outcomes Identified for Commercial Aircraft with Disruptive Propulsion***

The next downselect side trade study focuses on aircraft cruise and descent phase, centering on aerostructure aeroheating effects from flying through the atmosphere at hypersonic speeds. This study excludes the challenge of hypersonic flight in overcoming high drag, less mature air breathing engines etc., and other challenges. Hypersonic speed is defined as speeds of Mach 5 or above for local conditions. Many decades of technical data exist on the subject of thermal protection systems (TPS) in the form of theoretical analysis, cost, maintenance, as well as important empirical flight data. The short answer appears to be atmospheric supersonic flight to about Mach 2.0 is practical with modern materials. But achieving and sustaining Mach numbers well above this into the hypersonic flight regime and beyond for a commercial aircraft sized vehicle may not be practical with today's materials or even near term emerging materials.

Table 5 lists broad classes of TPS materials and their summary approximate collective attributes. The first three materials listed are a sort of who's who of past accomplishments in practical supersonic and hypersonic flight. The third material class represents modern carbon fiber composites held together with high temperature resins like bismaleimide (BMI) as used on the F-35 fighter aircraft, capable of about Mach 2. Silicon Carbides as well as other families of carbides including HfC, ZrC, TaC, etc., are thermo-mechanically well characterized, generally produced in production scale quantities, have reasonable specific densities, and possess relatively high service temperatures. Unfortunately, carbides come with high costs due in part to their long required processing times.

Reinforced Carbon Carbon (RCC) materials demonstrate excellent hypersonic flight application (including RCC infiltrated with other carbides), being found on the Space Shuttle nose cap, leading edges, etc., all of which experience full stagnation temperature during reentry. RCC however is not immune to high temperature sublimation, erosion, oxidation, atomic oxygen etc., losing only a small but significant surface mass during every flight. RCC materials are relatively very expensive and time consuming to produce, taking sometimes months to process by a method called chemical vapor deposition/chemical vapor infiltration (CVD/CVI), where molecules are put down literally one layer at a time. For relatively cooler surfaces on the Space Shuttle a novel and very successful thick tile composed of 10% silica fiber and 90% air was used with a service temperature of about 2,300°F. Requiring over 20,000 tiles and extensive rework after every flight, this TPS approach for relatively cooler non stagnation temperature surfaces does not seem practical for our application. There are significant advances over Space Shuttle tiles in the form of light weight thermal blankets, light weight ceramic and refractory foams, etc., yet they may have inherent large weight penalties or large scale producibilty challenges.

There is considerable active research in high temperature ceramic matrix composite (CMC), metal matrix composite (MMC); and many hybrids and variations therein. Many marry high strength fiber backbones to compatible high temperature matrices and top with oxidation resistant coatings. Although some high temperature composites approach or achieve some hypersonic environments, scale up, price affordability, ability to survive 35,000+ thermal cycles, lack of demonstration in a very large scale part, and overall lower near term technology readiness level (TRL) may forestall the use of this promising technology.

Another major TPS class is active cooling usually in the form of transpiration cooling, film cooling or some variation thereof. In one example, exposed surface structure contains thousands of tiny holes leading from the surface inside to outside, through which an endothermic like fluid is pumped through, actively cooling the structure as it leaves the control volume. Studies as well as empirical testing underscore its effectiveness to control surface structure temperature, yet the challenge of carrying significant liquid cooling mass potentially undermines its overall benefit.

Weighing all attributes found in Table 5 for all categories the question "Acceptable for >Mach 5 Aircraft Structure?" is asked in the last column. The response is that none of the nine TPS or structural material classes listed is acceptable for a large endo/exoatmosphere flying commercial aircraft.

TPS or Structural Material Class	Example Aircraft Application	Approx. Maximum Mach No.	Acquisition Price	TRL Maturity	Maintenance of Very Large Structure	Long Term Hypersonic Flight (>35,000 Cycles)	Acceptable for > Mach 5 Aircraft Structure?
Aluminum	Concorde	2.0	Excellent	9	Excellent	No	No. Melts
Titanium	SR71	3.4	Poor	9	Excellent	No	No. Price
Inconel	X-15	6.7	Poor	9	Excellent	Unknown	No. Unacceptably High Density
Carbon Fiber/BMI	F-35	2.2	Very Good	9	Very Good	No	No. Melts
Carbide Family	Research	Reentry	Poor	Varies	Varies	No	No. Price, Large Structure Complexity
RCC	Space Shuttle	Reentry	Very Poor	9	Poor	No	No. Price, Erosion
Si Tile	Space Shuttle	Reentry	Very Poor	9	Poor	No	No. Price, Fragility
CMC and MMC	Research	Reentry	Very Poor	Varies	Poor	No	No. Price, Large Structure Complexity
Active cooling	Research	Reentry	Very Poor	Varies	Poor	Yes	No. Price, Minor Flaw Criticality, Large Fluid Mass

Table 5 ***No TPS Materials Identified Capable of Both Hypersonic Flight Temperatures and Repeated >35,000 Flight Cycles***

If we go back to Table 4 and eliminate the Cruise at Altitude-Regime-Endo option, basically saying we cannot fly hypersonically in the endoatmosphere, our number of possible trade combinations drops in half to 648. Although still a large number our trade space is shrinking still further in a cascading like manner. Since we are ascending to the vacuum of space the Take-off-horizontal option can be traded out over the more advantageous Take-off-Vertical option. This helps trade away the Climb-Conventional Airfoil Lift and Climb-Airfoil Lift + Vertical Thrust over the preferred Climb-Vertical Thrust. And still further this trades out the Cruise at Altitude-Method of Lift-Aerodynamic, and Cruise at Altitude-Method of Lift-Orbital, primarily because you cannot reasonably fly through the atmosphere at sustained hypersonic speeds, achieve and then reverse minimum orbital velocity of about 25,600 ft/sec at any kind of a workable fuel fraction. Based on flight mechanics it takes significantly less power to perform a Descent-Powered Vertical as opposed to a Descent-Aerodynamic due in part to aeroheating issues and poor lift at very high altitudes. This is also true for the Descent-Aeroheat Reentry approach based on the need of carrying significant TPS mass fraction, offsetting its advantages. For the landing mode an endo/exoatmosphere commercial aircraft operating to and from conventional airports with other aircraft, needs to both vertically takeoff and land, as well as fly in conventional landing patterns. This trades out both singular Land-Horizontal and singular Land-Vertical trade options. Again, in a cascading manner of previous trades this allows you to drop out Compatibility with Other Aircraft-Incompatible and Compatibility with Other Aircraft-Pseudo Compatible options. The overall result is a single downselection for each of the eight categories shown as shaded boxes in Table 4.

D. Conceptual Endo/Exoatmosphere Operating Commercial Aircraft

A simple calculus piece-wise trajectory analysis coupled to a rough order magnitude (ROM) commercial aircraft concept is used to perform trajectory analysis. From the trade study outcome the vehicle performs the following flight trajectory: (1) vertically ascends from the departing airport to a minimum vacuum of space of at least 62 miles (328,100 ft), referred to as the 100 km Karman line to avoid drag and aeroheat, (2) accelerates forward while maintaining altitude with vertical thrusting, (3) coasts while maintaining altitude with vertical thrusting to make range, (4) reverses thrust to decelerate with vertical thrusting to maintain altitude, and (5) performs a vertical powered descent, or alternatively enters a conventional landing pattern to its arrival airport thousands of miles away.

The conceptual vehicle shown in Figure 1 is technically described in Table 6. It is based largely on the Boeing 737 MAX 9 (hereafter referred to as MAX 9) in terms overall 180 passenger count capacity and a similar maximum take-off weight target. Adjustments to this template include shrinking vehicle overall length by using a wide body oval fuselage cross-section, and adding additional battery mass above the original MAX 9's maximum fuel weight. Wing area of the canard-like four airfoil layout is less than one third the area of the MAX 9, requiring unprecedented wing loading and higher loiter speeds for level flight. For low speed flight, aerodynamic lift is augmented with vertical thrusting.

The NMP output thrust to weight ratio and output thrust efficiency shown in Table 7 is used for parametric studies only and is not directly tied to any technically defensible demonstrated data. The 4.32 lbf/lbm-hr thrust performance estimate is calculated as follows:

4.3 lbf (thrust)-hr/lbm (battery mass) = 0.432 hp-hr/lbm (battery mass) x 10 lbf (thrust)/hp

The 0.432 hp-hr/lbm (battery mass) value comes from Table 2 while the 10 lbf (thrust)/hp is a performance metric assuming NMP has similar propulsive efficiency of momentum propulsion counterparts. In this case the 10 lbf (thrust)/hp value represents the approximate thrust efficiency of a hovering helicopter out of ground effect, where one horsepower of engine output provides about 10 lbf of lift, the parametric trade number for this exercise.

Figure 1 illustrates SOTA thrust efficiency for NMP (<< 1.0 lbm thrust/hp) plus its potential future range, and then benchmarks it against SOTA momentum propulsion (MP). This quantitative check indicates the 10 lbf (thrust)/hp efficiency used in this parametric study at least falls within a reasonable demonstrated MP efficiency range.

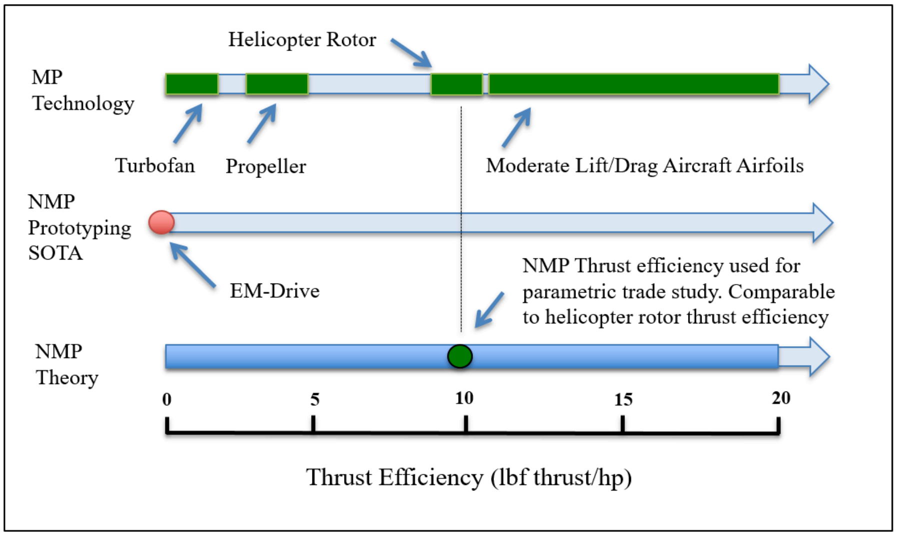
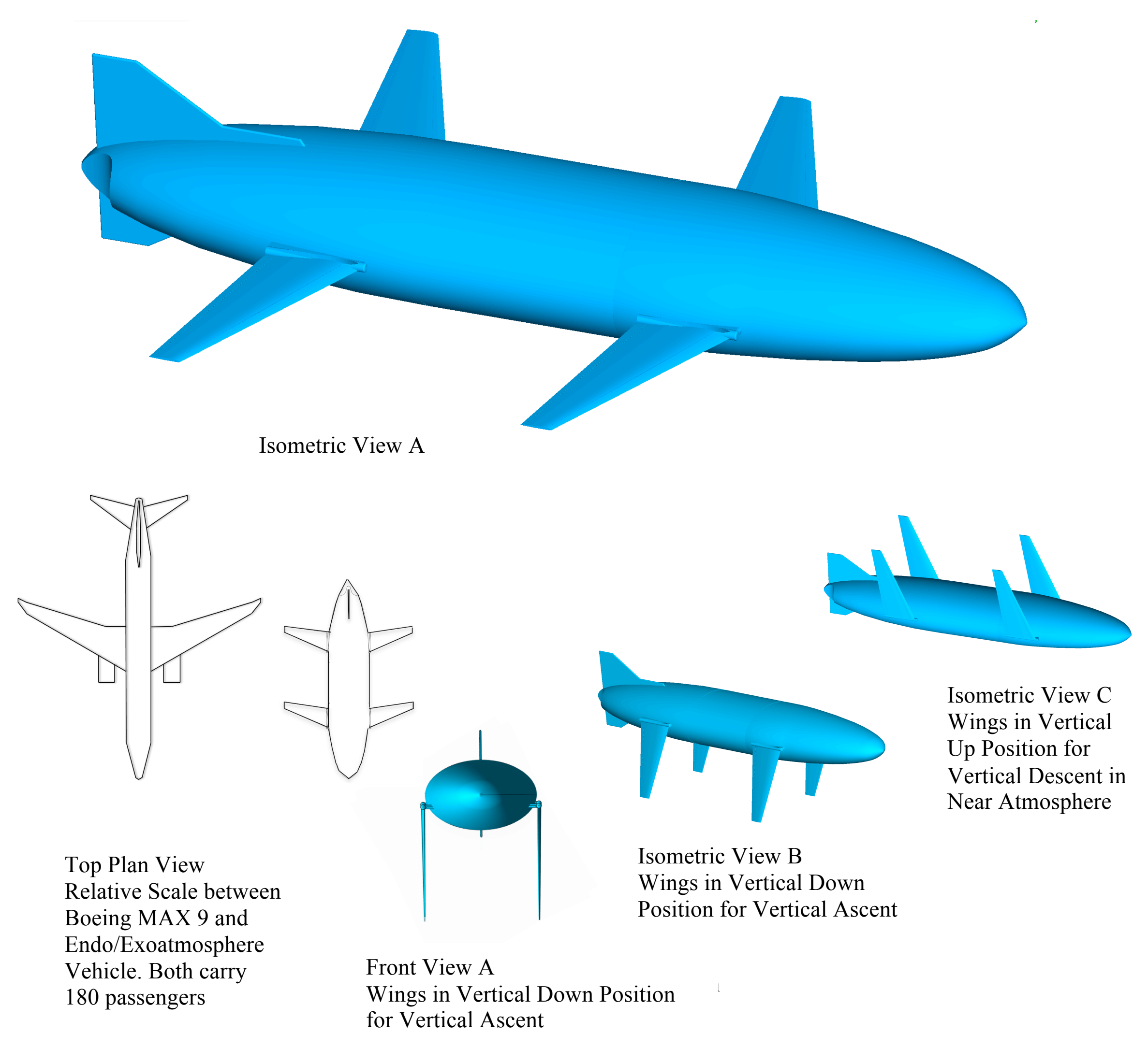


Figure 1 ***NMP Theory Benchmarked Against Actual MP Thrust Efficiency***

Figure 2 illustrates the overall conceptual Endo/Exoatmosphere operating commercial aircraft. The design is preliminary and should be treated only as a low fidelity concept pathfinder. Isometric View A illustrates overall vehicle layout, exhibiting an oval fuselage with four attached airfoils in an equal wing area canard-like layout. This unconventional wing layout is very similar to the successfully flight proven early unmanned aerial vehicle (UAV) called Outrider UAV. Since the vehicle spends the majority of flight in thin atmosphere or the vacuum of space, there is notably less emphasis on aerodynamic efficiency. Front View A illustrates the oval fuselage cross-section, sized to the Frigate EcoJet commercial aircraft concept[8], complementary to NASA's fuselage cross-section configuration studies. This oval configuration accommodates 10 across passenger seating, significantly reducing fuselage length over a conventional Boeing 737 or Airbus A320 aircraft round cross section fuselage with only six across passenger seating.

Isometric View A illustrates wings in the horizontal level position, for the case when flying with other conventional aircraft in a descent, approach or holding pattern. Total wing area is less than a third of MAX 9's, requiring the vehicle to fly faster in certain aerodynamic flight modes, offset only moderately by oval fuselage lifting forces when in a positive angle of attack. Vertical thrust augmentation is utilized for slower speed flight. The vehicle has non-momentum propulsion (NMP) vertical thrusters in a tight array located on the fuselage belly center of gravity point, as well as a small number of horizontal NMP thrusters located at the aft end of the fuselage. The aft end thrusters are potentially combined cycle, running on either electrical storage battery power or using a conventional air breathing turboshaft engine to drive the NMP.

The Top Plan View shows an approximate size comparison between a MAX 9 aircraft and the concept vehicle for overall scale comparison. By truncating the Frigate EcoJet fuselage straight length, passenger capacity becomes 180 persons, equal to MAX 9's dual class layout.



Isometric View A

Top Plan View
Relative Scale between
Boeing MAX 9 and
Endo/Exoatmosphere
Vehicle. Both carry
180 passengers

Front View A
Wings in Vertical Down Position
for Vertical Ascent

Isometric View B
Wings in Vertical Down
Position for Vertical Ascent

Isometric View C
Wings in Vertical
Up Position for
Vertical Descent in
Near Atmosphere

Figure 2 ***Endo/Exoatmosphere 180 Passenger Commercial Aircraft Views***

Front View A shows all four wings folded vertically down for the vertical assent flight mode. Prior to takeoff the wings are horizontally level or vertically up. Just after liftoff wings are repositioned to the vertical down position. This minimizes aerodynamic drag during vertical ascent and adds aerodynamic stability by placing the center of pressure behind the center of mass. This is further illustrated in Isometric View B.

Isometric View C illustrates wings in a vertical up position when executing a vertical powered descent reentry. This adds aerodynamic stability the same way Scaled Composites' SpaceShipOne uses an aerodynamic "feathering" device by placing the center of pressure vertically above the center of mass.

E. Vehicle Flight Mechanics and Performance – The Art of the Possible

Figure 3 illustrates a representative flight profile for the endo/exoatmosphere concept aircraft traveling between two commercial airports separated by great distances, while Table 6 tabulates estimated performance data. An overall description is as follows:

(A) Departure Airport Vertical Take-off - Aircraft located at the departing airport loads passengers and taxies a short distance from the passenger gate to a small concrete take-off/landing pad having sufficient offset distance between active adjacent conventional runways. Alternatively, but not preferred the aircraft mixes with conventional aircraft, using conventional runways.

(B) Vertical Ascent - During vertical take-off the wings are repositioned to the vertical down position while the aircraft maintains a level attitude (zero pitch and zero roll) for passenger comfort. There is significant aerodynamic drag early on in the vertical ascent from a combination of dense air and a relatively large plan view area of the fuselage, coupled to a relatively large drag coefficient for the flat-on major axis oval geometry. This is deemed acceptable for maintaining passenger comfort based on the trade's "no passenger discomfort" downselect. As the aircraft ascends vertically it quickly reaches terminal vertical velocity in the lower atmosphere due to high aerodynamic drag on the fuselage but then builds up speed as the air density drops with altitude. Above about 50,000 ft aerodynamic drag is only about 15% of sea level drag, allowing the vehicle to accelerate and build up vertical velocity. Above about 125,000 ft the vehicle starts to approach but not exceed the local atmospheric speed of sound. Flying below the local speed of sound is accomplished by reducing vertical thrust, preventing shock waves from forming and then reaching the ground. At very high altitudes supersonic speeds may be permissible if the shock wave is too weak to be perceptible by a ground observer. It is important to note relatively minor aeroheating occurs, being acceptably mitigated by low air temperatures, and higher service temperature composite structures used in the manufacture of the aircraft (e.g., carbon fiber/BMI resin used on the Mach 2.2 supersonic F-35 aircraft).

(C) Transition to Altitude - Vehicle passes through remaining upper atmosphere while vertical thrusting is reduced to nearly zero allowing gravity to bleed off vertical velocity. The idea is to just reach minimum acceptable vacuum of space altitude with zero vertical velocity. During this transition aft fuselage mounted horizontal thrusters begin to work for the first time, producing thrust and adding horizontal velocity.

(D) Horizontal Acceleration - As the vehicle crosses maximum altitude above 328,100 ft (62 mi), it pitches down at a moderate minus 5 to 7°, splitting vertical thrust into both vertical and horizontal thrust components. This pitching angle is similar to regular commercial aircraft flight modes. Vertical thrust magnitude maintains altitude while horizontal thrust accelerates the vehicle forward. The aft end horizontal thrusters may also be used to accelerate the vehicle until required horizontal velocity is achieved. As horizontal velocity increases, orbital like centripetal acceleration moderately reduces vertical thruster requirements.

(E) Coast – Using vertical thrusting to offset gravity, the vehicle coasts along in the absence of atmospheric drag to make range. Consideration for avoiding potential hypersonic aeroheating flow of the sensible atmosphere although very thin, extending just below and above the official space altitude is required. A 12,500 ft/sec cruise speed combined with lower gravity at altitude moderately offsets gravity, requiring less vertical thrusting during this phase.

(F) Horizontal Deceleration – Repeat flight phase (D) in reverse. Retaining some minor forward velocity at the end of the deceleration phase will reduce delta velocity requirements. However, this velocity component will be added to the vertical descent phase resultant velocity. In one scenario the vehicle stops directly over the arrival airport, some 62+ miles above and executes a vertical descent.

(G) Vertical Powered Descent – Repeat phase (B) in a reverse like order. Throughout the vertical powered descent, vertical thrusters are maintaining a minimum level thrust, providing passengers the feel of a normal like reduced g-force gravity. Vehicle descent rate is adjusted when reaching the higher density air mass so that aerodynamic drag does not cause significant g-forces on the passengers.

(H) Alternate Conventional Landing – If the vehicle cannot execute the preferred direct vertical descent and vertical landing at the arrival airport, it may enter a conventional aircraft landing pattern.

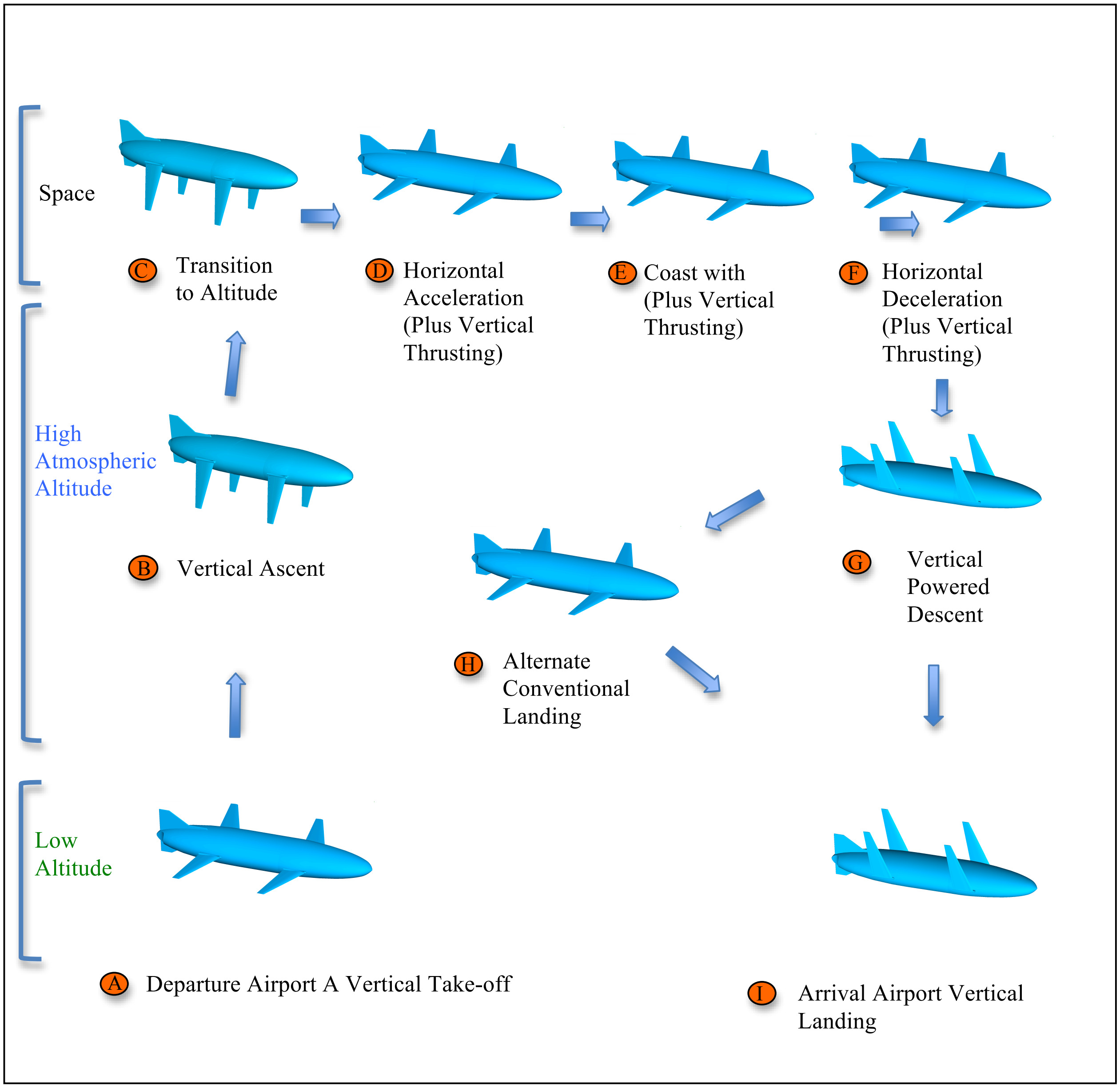


Figure 3 ***Endo/Exoatmosphere Flight Mechanics of Concept Commercial Aircraft***

(I) Arrival Airport Vertical Landing – Upon completing the vertical powered descent the vehicle vertically lands at one of the destination airport's small takeoff/landing pads. Vertical landing can potentially avoid all conventional aircraft takeoff and landing stack ups and delays.

Table 7 illustrates a 5,000 mi commercial aircraft trip length, representing a typical Salt Lake City to Paris international flight, while the 12,500 mile trip length shown equals about half the circumference of the earth. Hence the moniker, "fly anywhere in the world in about two hours." Although there are not many such ultra-long city pairs, at least not today. Required battery capacity to perform each flight with minimum reserves is calculated by adding all the flight phase's average thrust x phase time together as found in Table 6. Numbers to be treated as estimates only.

F. Results and Conclusions

Starting with 6,912 possible flight scenario outcomes for a hypothetical commercial aircraft with disruptive propulsion, and then downselecting to a single concept, all the while inventing the vehicle along the way, was both challenging and fun. The end result is both a technical narrative on what disruptive propulsion can do if realized, as well as the creation of a novel commercial aircraft concept with disruptive potential all its own. This paper in exploring the art of the possible, enlightens a path for future commercial aircraft to “fly anywhere in the world in about two hours.”

Fig. 3 Label	Flight Phase	Vehicle Velocity (ft/sec)		Phase Flight Time for Given Range (minutes)	
		Vertical	Horizontal	5,000 mi	12,500 mi
A	Airport Vertical Take-off	0	0	5.0	5.0
B	Vertical Ascent	0→1,000	0	8.7	8.7
C	Transition	1,000→0	0→273	0.5	0.5
D	Horizontal Acceleration	0	273→12,500	12.7	12.7
E	Coast	0	12,500	22.3	75.1
F	Horizontal Deceleration	0	12,500→0	12.9	12.9
G	Vertical Descent	0→1,000→0	0	8.7	8.7
I	Airport Vertical Landing	0	0	5.0	5.0
Total Flight Time =				1.3 hrs	2.1 hrs

Table 6 ***Endo/Exoatmosphere Commercial Aircraft Flight Trajectory***

Vehicle Parameter	Value or Description	Concept Description
Length Overall	96.8 ft	About 30% shorter than a Boeing 737 MAX 9 which is 138.5 ft long
Width	62.4 ft	Wings in horizontal position. Used for aerodynamic lift
	25.0 ft	Wings folded to vertical position. Used for vertical flight stability
Fuselage Diameter	20.5 width x 13.0 ft height elliptical cross-section	Sized to Frigate EcoJet commercial aircraft concept. Elliptical diameter fuselage with 10 across seating and shortened cylinder length
No. of Passengers	180	All coach seating. 10 across
Primary Structure	Carbon/BMI composite	Boeing 787/Airbus A350 like composite construction using higher service temperature commercial BMI resins
Max zero fuel wt.	156,500 lbm	Uses MAX 9 baseline. Estimate only for parametric study
Battery Mass (estimate only)	62,000 lbm (5,000 mi trip) 105,000 lbm (12,500 mi trip)	Battery replaces MAX 9’s original fuel mass plus additional mass. Maximum takeoff weight grows 8% and 30% respectively for two trip lengths over original MAX 9 weight limit. Min. battery power reserve
Max Take-off Weight	209,826 – 252,826 lbm (MAX 9 is 194,700 lbm)	Max take-off weight listed for different trip lengths. MAX 9’s max fuel weight is 46,874 lbm. Assume MAX 9 can fly full fuel, full passengers
Thrust-to-Weight Ratio	1.5 maximum for both trip lengths	Acceptable human factors related to g-forces for flight have not been determined and may reduce maximum allowable thrust to weight ratio
NMP Output Thrust Efficiency	4.32 lbf-hr/lbm battery	Parametric study uses value as potential NMP thruster performance. Not based on actual test data

Table 7 ***Conceptual Endo/Exoatmosphere Commercial Aircraft Flight Characteristics***

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