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Ultra-Low to Emissionless Air Transport Design

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Introduction

After decades of studies and warnings, climate change is now very apparent and there are strident calls for across the board efforts to reduce the projected and dire nearer to midterm climate impacts [ref. 1]. These requisite efforts include CO_2 emission reductions, methane emission reductions, carbon sequestration, conservation, and adaptation. The prime CO_2 emission reduction approach is less expensive renewable energy – hydro, solar photovoltaic (PV), solar thermal, wind (on and offshore), geothermal, and biomass/biofuels [ref. 2]. Solar PV and wind are not self-storing; they require inexpensive storage, which is developing nicely, with costs dropping some 70% over the last three years [ref. 3]. An iron/air battery grid storage system is in development that proffers further cost reduction. Due to low cost, renewables are 90% of new generation [ref. 4] and produce a sizable percentage of electricity, with coal no longer competitive due to cost. The projections going forward are for renewables to be an ever-greater percentage of electrical generation. Their low and decreasing costs, along with their emissionless possibilities, are shifting transportation, manufacturing, and buildings toward electrification.

There are increasingly serious efforts to reduce air transportation contributions to CO_2 and other emissions. In the past, these efforts have mainly addressed aircraft efficiency and fuel burn. However, that approach usually applies to new airframes, which take too long to enter the fleet, and the amount of reduction worked in those programs was not large. The increasing scale of development of less expensive green renewable electrical energy and halopohytes for biofuels with huge capacity have massively changed the outlook for reducing aircraft emissions. What are now developing are technologies for CO_2 emissionless aircraft that are powered or fueled by green renewable energy [refs. 5,6]. The options for emissionless CO_2 flight vary and can include electrics using wholly emissionless batteries, drop in green fuels and electrics powered by green fuels and fuel cells which would emit water (green hydrogen) or water and NOx (green hydrocarbons (HCs) and biofuels). The technology levels of these emissionless approaches vary and they are all undergoing serious investment. For the long haul, the envisaged battery developments, in terms of energy density, require green fuels with propulsion, either via combustion or electrics.

Up until recently and with no realizable way forward, what was the dream of emissionless (with regard to CO_2) air transportation, is now a very definite reality with serious ongoing efforts by industry and worldwide. This report will address the possibilities to significantly improve aircraft performance and reduce aircraft and operating costs, along with reducing residual, non-CO_2 emissions, through simultaneous optimization of lift and drag (L/D), acoustics, weight, and configuration. These approaches, especially the L/D increases, could greatly improve the emissionless range of battery electrics for long haul across the speed range as well as when using green fuels. Also, for a given range would reduce size and costs much.

Going forward, aeronautical travel cost reductions will probably be required to compete with such as five senses virtual reality (VR), VR directly into the brain, and digital reality, providing an ever more serious tele-travel/immersive presence [ref. 7]. The COVID virtual travel experience indicates that for many purposes, virtual tele travel is acceptable, and in some respects better than physical travel. Teletravel now enables nonverbal/body language communications and superb educational experiences with benefits such as social distancing/working at home during pandemics, major cost reductions, and time savings, less time spent in airline security lines, less hassle, being almost anywhere at any time with the possibility of multiple contacts/places/meetings on a given day, lack of physical and health risks, no overcrowded sites/venues, greatly reduced emissions, and everyone can enjoy the thrill of travel.

Frontier Technologies & Approaches

The available and emerging technologies for long haul aircraft ideation, development, and optimization include the following:

- Printing manufacture, composites, up to 10X better materials
- Laminar flow control
- Favorable aero/propulsion/structural interactions/integrated designs
- Electric propulsion, super conduction, water cooling
- Advanced energetics - renewable energy, seawater-produced halophyte biofuels, advanced batteries, and fuel cells
- GTE [gas turbine engines] wave rotors, recuperators/regeneration, bypass
- Non-planar lift
- Flow control writ large, for ride quality, flutter, load alleviation, vortex control, laminar flow control, noise, high lift, “bird-like flight”/no “envelope,” weather, gusts, clear air turbulence, boundary layer inlets, flow separation control, thrust vectoring, etc.
- Morphing, multi-functional, “brilliant” materials
- Inflatable wing sections
- Autonomy, trusted autonomy including consideration of unknown unknowns
- Energy regeneration
- Exoscale class and beyond Computational Fluid Dynamics (CFD)/Mod-sim

The major overall civil long haul aircraft optimization approaches include combining aero functions with propulsion [ref. 8]. Militaries have long utilized this approach, resulting in major performance enhancements. The much-increased reliability of propulsion systems, and the major further leap in reliability associated with electric motors, strongly favors accruing the performance enhancements of such combinatorials. At the transport aircraft configuration level, given a commitment, not yet extant, to deviate from the 1950’s 707 configuration mantra, it is possible to ideate very synergistic advanced aircraft configurations via combining structure, propulsion, and aerodynamics. A third overall approach is to seriously target and reduce all drag sources. The fourth is the collection and energy conversion/application of up to 50% ofthe applied energy that is emitted as heat, or, in the case of cryogenic fuels, apply the low storage temperature to accrue further performance, especially via laminar flow control.

Emissionless Aircraft Approaches

As stated, CO_2 emissionless aviation is now rapidly developing due to the ever-increasing availability and lower costs of green renewable energy to charge batteries and produce green hydrogen and hydrocarbons. There is also a renaissance in air travel termed AAM [advanced air mobility] that is associated with increasingly autonomous small aircraft powered mainly by batteries [ref. 9]. This includes electric powered vertical takeoff and landing (eVTOL) operation capability. The extent of these efforts is extraordinary, with over 500 designs under development with a potential worldwide market (including personal air vehicles (PAV), on the order of $1T/year +, which would double the current civil aviation market. The current SOA [state of the art] battery is the 250 WH/kg lithium-ion, which, as an energy source, weighs more than an order of magnitude greater than HC fuel energy. Therefore, the range is limited, and even more so by the low L/D of these vehicles. Lithium sulfur, lithium-metal, solid state, and ultimately lithium air batteries are being worked, with potentials more than six times those of lithium ion. Given improved materials and L/D, the advanced batteries will eventually enable emissionless battery powered electric aircraft to subsume the near, and into the mid-range, transport markets. The current battery enabled range is approximately 400 miles. A factor of six better battery energy density would enable some 2400-mile range, and with greater L/D and lighter materials, far more than that going forward. That range subsumes well over half of air travel, and is wholly emissionless using battery electrics, no water nor NOx.

The long-range markets, “long haul” air transport, will require the energy density of green chemical fuels. There are three generic varieties of such fuels: biofuels, green hydrogen, and green hydrocarbons. The latter two are produced utilizing inexpensive green renewable energy to extract hydrogen from water for green hydrogen and utilizing atmospheric CO_2 to form hydrocarbons for green hydrocarbons. In two of these, biofuels and HCs, the CO_2 is “recycled,” simplistically no new net CO_2. However, when combusted in air in GTEs, these fuels produce water, NOx, and other chemicals which are greenhouse gases. So “emissionless aircraft” are only really such regarding CO_2 if combustion in air occurs. Fuel cells produce water and lower levels of NOx for green HCs and water for H_2. Improvements in aero performance and reductions in weight discussed herein would, along with reducing costs to offset the increased costs of green fuels, reduce these non-CO_2 emissions from combustion or fuel cells for long haul by reducing much the requisite fuel usage.

The essential decision for propelling (CO_2) emissionless long haul transports is whether to burn the green fuels in a GTE or load them into a fuel cell to produce electricity to power electric motors. Nominally, GTEs are some 40% efficient. Electric motors are up to 90% efficient , propellers some 90% efficient and fuel cells are on the order of 80% efficient, so electrics efficiency is 65% vs. 40% for GTES. However, fuel cells are not yet that light. A detailed analysis at the overall systems level indicates that electrics are better than GTEs, but by 8% or so, not by 25% [ref. 10]. Also, two of the green fuels, biofuels, and green HCs are drop-ins and can be utilized with modified existing equipment. Green hydrogen is relatively expensive currently and will burn in upgraded GTEs, but has many issues including cost, infrastructures, corrosion, cryogenic storage and storage volume on the vehicle, creating additional weight and drag. Boeing has chosen to go with burning biofuels, which is the near-term solution. Airbus is perusing hydrogen. The issue with biofuels is capacity. They are currently sourced from glycophytes which are freshwater plants. However, going forward biofuels can be sourced from the immense capacity and low cost of halophytes (salt plants), biomass grown on deserts and wastelands using saline aquifers and pumped seawater [ref 11]. Some 44% of the land is deserts and wastelands and 97% of the water is seawater, which contains about 80% of the nutrients to grow plants. Boeing is developing halophyte approaches to biofuel sourcing. Then there are biofuels from aquaculture such as cyanobacteria which produce more fuel per acre-year than land plants.

There are many benefits of electric propulsion as indicated below [ref. 9]. Their multiplicity and value should, going forward, result in green fuels being used in fuel cells vice sterling cycles which are less efficient, to power electric motor propulsion.

Advantages of Electric Propulsion:

- No motor gear boxes
- Regenerative energy recovery during descent and landing
- Electricity production heat losses could be utilized for cabin heating, deicing, or regeneration
- Higher altitude operation feasible
- Reduced cooling drag
- Quieter
- Reduced vibration
- Fewer inspections
- No engine flameouts or restarts
- Power train efficiency greater
- No power lapse with altitude at high temperatures
- Continuously variable transmission
- High reliability
- High efficiency over most of the power envelope
- Up to six times motor power to weight compared to combustion engines
- Reduced maintenance
- Far fewer parts
- Less expensive
- Higher torque
- Distributed, scalable propulsion

There are also major improvement approaches for GTEs including wave rotors and energy regeneration.

Advanced Aerodynamic Long Haul Aircraft Configurations [refs. 9, 12-14]

The prime design optimization issues for long haul airframe configurations are L/D, weight, and synergistic arrangement regarding aero, weight, and propulsion. Approaches to synergistic aero and propulsion interactions include the following [ref. 8]:

- Circulation control wings
- Flow separation control for shock-boundary layer interactions
- Thrust vectoring for control vice empennage
- Boundary layer inlet for increased propulsion efficiency
- Suction or wall cooling laminar flow control
- Goldschmied pump jet for static pressure thrust
- Wing tip engines for DDL reduction
- Blown flaps/augmenter wing

Synergistic Aero and structural interactions include:

- Strut/truss braced wings
- Span Loaders
- C Wings
- Box wing, ring wing
- Bi plane
- Double fuselage unswept mid-wing
- Yawed wing

The other major mix and match piece part for long haul configuration optimization is drag reduction across the board, viscous drag, drag due to lift, shock wave drag, roughness drag, etc.

The options to reduce DDL include:

- Increased wingspan
- Wing tip engines
- Wing grid
- Oscillatory span load [possibility]
- Tip region blowing
- Winglets
- Wing tip “windmills”
- Ring/box wings, biplane, distribute lift vertically
- Reduced weight

Viscous drag reduction approaches include:

- Laminar flow control, via pressure gradients, suction, cooling
- Reduced wetted area
- Riblets
- Plasma approaches

The above listings and more provide piece-parts that can be mixed and matched to create and ideate synergistic configurations with improved L/D and reduced weight. The 707 utilized swept wings to reduce high speed shock wave drag. The BWB [blended wing body] and span loaders put the lift where the weight is. A double fuselage/midwing configuration puts a fuselage at both ends of the midwing to reduce DDL [drag due to lift]. The following transonic configuration attempts to ruthlessly reduce drag to double or more L/D while at the same time reduce weight and improve propulsion efficiency.

First, double the wingspan to reduce DDL, some 40% of total drag, by some 75% and halve the chord. This reduces the Reynolds number by half and enables more area of natural/pressure gradient laminar flow. To support the wing, use an external truss to reduce the wing weight and allow the wing to be thinned down and almost unswept. This reduces shock drag, reduces wing cross flow, enabling natural laminar flow, low friction drag. The optimal design of the truss bracing elements requires research. Options include lift carrying, laminar flow, arching for strength, etc. This has not been thoroughly studied yet. For the SST [supersonic transport] case, the favored or best in class configuration with the greatest L/D is the Pfenninger strut braced extreme arrow. Using favorable shock interference via fuel containers on the wings and laminar flow control, the projected L/D is 16 vs. nine for conventional shapes [ref. 15].

Second, move the propulsion units to the back of the fuselage and vector their thrust for aircraft control. This obviates the empennage, the horizontal and vertical tails, their weight, and drag. The engines are incorporated into the base of the fuselage such that the fuselage boundary layer is captured by the inlet to increase propulsion efficiency. Also, this area is configured to attain what Fablio Goldschmied termed static pressure thrust. This provides a synergistic aero/propulsion interaction with the potential (from naval application pump jets) of additional thrust on the order of 20% of the fuselage skin friction. A grim wheel device might be considered to improve the incoming inlet flow.

Third, to reduce the fuselage skin friction drag, use riblets if left turbulent or design for fuselage laminar flow, which probably requires viewscreens instead of windows for the requisite smoothness. If cryo hydrogen fuel is employed, utilize cold temperatures to maintain laminar flow on the fuselage. Some boundary layer suction is also employed. Further DDL reduction is available from wing tip flow turned turbines, which produce additional electrical energy. The landing gear weight is typically on the order of half the fuselage weight. To reduce gear weight, use deployable chutes for refused takeoff instead of heavy brakes and automatic landings to reduce the human-produced occasional additional impulse loading due to hard landing. Minus the thrust vectoring for control and a laminar fuselage, per systems research at Virginia Polytechnic University (VPI) these approaches result in L/D values in the 40s to the 60s instead of the conventional 18 to 22. Pfenninger used a version of this technology with a laminar flow fuselage to attain an L/D of 100. Considered herein thus far in terms of drag reduction, for the usual drag breakdown of some 50% skin friction drag (half on fuselage and half on wings), 40% DDL and 10% roughness, pressure drag is 75% plus DDL reduction, 60% friction reduction on the wings, 10% (riblets) on the rest of the wing/fuselage, reduced wetted wing area due to reduced fuel weight, and obviation of the empennage drag contributions. The major remaining drag source, not mitigated except for riblets, is turbulent fuselage drag. There is a small transport aircraft under development which is successfully utilizing fuselage laminarization [refs. 16, 17]. The fundamental issues with fuselage laminarization include large Reynolds Numbers and a plethora of roughness, waviness, joint, and excrescence including radar domes, pitot tubes, windshields, windshield wipers, doors, windows, bug impacts/residual roughness, etc. Viewscreens could be utilized in lieu of windows. If the forward portion could not be seriously smoothed, then recourse could be made to relaminarize the fuselage boundary layer aft of the forward door. This could be done via suction of nearly twice the thickness of the turbulent boundary layer to remove the turbulent superlayer and injection of this ingested air as a wall wake into the turbulent wedge emanating from the fuselage/wing intersection region for sizable slot injection turbulent drag reduction. The rest of the fuselage could then be kept laminar via contouring for natural laminar flow pressure gradients and some boundary layer suction or wall cooling. Thinning the fuselage boundary layer by laminarization would reduce the momentum deficit entering the rear propulsion inlets, reducing their propulsion benefits. An alternative configuration approach for low drag, which also proffers low supersonic cruise, is the R.T. Jones yawed wing.

Additional potential design approaches to improve overall performance, reduce costs, increase range for a given fuel or battery weight include thin solar PV external films for additional electricity and regeneration of the waste propulsion heat from GTEs, fuel cells and electric motors, a potentially sizable amount of additional electricity. If hydrogen, which requires additional fuel storage volume, is used, the configuration can use this additional volume to help create the pressure distribution for greater natural laminar flow on the fuselage. To further reduce weight, employ printing manufacture that reduces the cost and weight of fasteners. Inflatable load carrying inner wings may be efficacious and there has been success in nano printing metals including high temperature metals and producing superb material microstructure which improves the material weight efficiency. Acoustics can be improved via injection of liquid water drops into the mixing regions to attrite the turbulent noise sources, which has minimal impact upon cruise weight as the water is utilized during takeoff.

Weight Reduction Approaches

The prospective weight saving approaches include: truss bracing the wings which saves 20% plus wing weight, inflatable inner wing sections, thrust vectoring for control, obviating the weight of the empennage, printing to obviate most fastener and strongback weight (and reduces costs via far less part count), frontier 5X materials (advanced composites and/or nano printed metals with superb microstructures), automatic landing gear/chutes for refused takeoff, electric motors vice GTEs, possibly structural batteries going forward, use of morphing components for high lift and shock wave drag reduction, and the reduced fuel weight from the improved aerodynamics. The weight increases are batteries, hydrogen storage tanks, and fuel cells, functions of which/what emission approach and technology level is used.

Energy Regeneration [ref. 18]

Energy Regeneration - All energetics systems have losses, the amplitude of which is a function of specific design details, with the losses usually occurring as heat. This heat is normally dissipated using radiators, heat exchangers, cooling towers, etc. In the design of many systems, there have been efforts to regenerate energy and reuse these losses, notably in auto braking, trains, wind turbines, elevators, buses, cranes, robotics, power plants, photo voltaics, fuel cells, etc. [ref. 19]. The components of an energy regeneration system include energy extraction, transmission, storage (depending upon the details of the reuse approach), conversion, control, and finally utilization. For “emissionless” class aircraft there are heat losses from GTEs, electric motors, batteries, and fuel cells which should be studied for energy regeneration potential.

Approaches to optimize regeneration include:

- High efficiency T-E
- High efficiency T-PV
- High efficiency Thermionics

For Storage:

- Frontier, eventually lithium-O2 batteries, up to 8X Li-ion
- Structural ultra-caps and heat batteries

What is apparently needed are systems studies of various combinations of regenerative system piece parts for one or several onboard, on body energetics sources/utilizations that might benefit from regeneration, be potentially downsized, with the metrics of overall cost, safety, reliability, size, and weight. This to determine the efficacy, benefits, and optimization of increased utilization of regeneration.

Acoustics

There are a sizable number of technical and system level approaches to reduce the acoustic levels of air vehicles, considereed as another "emission". These include:

- Electric motors, vice combustion devices, obviating exhaust, engine, transmission noise, a significant overall reduction
- Slow turning rotors, tip speed reduction
- Shifting radiated frequencies to above or below human hearing, perception
- “Cleaner” fluid flows, less and weaker vortex production, no flow separation, innately unsteady flows
- Utilization of aircraft portions and ground infrastructure as acoustic shields
- Identification and reduction of the strength of acoustic sources
- “Noise Perfume,” generation of acceptable to desirable covering noise
- Active noise cancellation
- Landing gear and flap flow cleanup
- Distributed propulsion, larger number of noise sources at different frequencies
- Injection of water droplets to reduce turbulence and associated noise source strength
- Flow turned “Grim Wheels” to make inlet and exhaust flows more uniform
- Drag and weight reductions to reduce requisite power, lift requirement

- Wall acoustic absorbers
- Altered duct acoustic modes
- Broad band, distributed vice sharp, narrow band noise generation
- Obviate as possible vortex breakdown
- Modulate blade rotation to mitigate blade/vortex interaction
- Vary blade spacing
- Active flaps and twist
- Tip treatments to reduce strength of tip vortex

Overall, at the system of systems, configuration, and operational design levels acoustic performance is of such import that it should be included as a prime critical design metric instead of a fix it later consideration. Electrics, distributed propulsion, active flow control, CFD, morphing smart active materials, and miniaturized sensors have created major opportunity spaces for acoustic level reduction(s).

Concluding Remarks

Climate change is increasingly serious and apparent, requiring immediate mitigation. The current major climate mitigation approach is lower cost green renewable electrical energy, which in turn enables electrification of other CO_2 sources such as manufacturing, buildings, and transportation, including aviation. Lower cost green electrical energy provides for aviation green battery charging (fully emissionless) and green fuels including H_2 (emits water, if combust emits NOx), HCs and biofuels (these emit water and NOx). There are currently major application opportunities associated with these wrt solutions to aircraft CO_2 obviation and reduced water and NOx climate impacts. If emit water can sense and fly around cirrus forming regions. If produce water in fuel cells can collect it, freeze it, and above the tropopause where water forms cirrus, eject it from the aircraft, utilizing ice particles heavy enough to drop below, but which will melt below 27K ft. altitude. If emitting NOx, can use either fuel cells (which emit less NOx) or advanced, lower temperature combustors. The batteries are currently too heavy for long ranges. However, several generations of batteries are in development which should soon enable ranges sufficient to power wholly emissionless flight for well over half or more of scheduled airline traffic. Such wholly emissionless ranges can be achieved earlier and more economically throughout via aircraft optimization for drag and weight, the technologies for which are discussed herein. For the other half of scheduled air traffic, the longer ranges, need the energy density of green fuels. There are currently cost and availability issues with green fuels, which will be mitigated going forward. Increasing aircraft efficiency regarding to drag and weight is one of those mitigation approaches and again, technologies and designs for such are discussed herein. The current aerodynamic efficiency metric, L/D, is on the order of 20. Serious design for low drag can increase that to as high as 100, so the reductio ad absurdum is some factor of four plus range increase for the same weight and cost of green fuel, with corresponding reductions in water and NOx, if emitted. Overall, the combination of ever lower cost green electricity and advanced-to-revolutionary aero related technologies can massively reduce aviation emissions.

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Approaches to greatly extend the range of wholly emissionless, battery powered aircraft for a given battery energy density and reduce fuel burn and NOx and water emissions for aircraft powered by green fuels. Approaches employ advanced aero configurations, reductions in skin friction and drag due to lift, and synergistic system level incorporation of structure, propulsion and aerodynamic design components. The aerodynamic approaches proferred along with the projected increases in battery energy density could enable wholly emissionless flight for surprisingly long ranges.

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