

Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport

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This review of aircraft electric propulsion architectures conveys that several aircraft system studies have indicated a potential benefit associated with using electrical systems to replace or augment the traditional fuel-based propulsion system. This exciting new approach for designing aircraft opens the door for new configurations. It is also important to convey that this field of study is in its infancy and much improvement is required across the breadth of supporting technologies if the promise of these aircraft concepts is to be realized.

I. Nomenclature

BLI	=	boundary layer ingestion
CFD	=	computational fluid dynamics
CO ₂	=	carbon dioxide
FPR	=	fan pressure ratio
g	=	gram
HP	=	horsepower
hr	=	hour
kg	=	kilogram
km	=	kilometer
kN	=	kilonewton
kW	=	kilowatt
lbm	=	pound mass
lb _f	=	pound force
m	=	meter
MW	=	megawatts
nm	=	nautical mile
NO _x	=	oxides of nitrogen
NRA	=	NASA Research Announcement
N3CC	=	an advanced conventional single-aisle aircraft concept
sec	=	seconds
N+3	=	aircraft three generations later than current state-of-the-art
N+4	=	aircraft four generations later than current state-of-the-art
STARC-ABL	=	Single aisle Turboelectric AiRCraft with Aft Boundary Layer ingestion
SUGAR	=	Subsonic Ultra Green Aircraft Research
TRL	=	technology readiness level
W	=	watt
WATE++	=	Weight Analysis of Turbine Engines

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II. Introduction

NASA challenged US industry and academia in the mid-2000's to identify technology paths for disruptive improvements in commercial aircraft fuel burn, emissions and noise. These studies, summarized in reference 1, outlined exciting and promising challenges in airframe design, propulsion design, and propulsion-airframe integration. These studies showed that substantial improvements in aircraft fuel burn, emission, and noise metrics would require significant changes and bold technical advancements. The use of electrical power distribution to augment propulsion was one proposed way to increase design freedom and to improve future aircraft. However, the identification of an efficient, viable aircraft with electrified propulsion is complex. The first challenge is the aircraft must obtain a system-level benefit from the modified propulsion system that outweighs the added complexity. The second challenge is that improvements must be realized in the electrical power conversion, distribution, and control components to reduce the weight of the electrical system without out compromising flight safety. The final challenge is the sheer breadth of concepts and technologies that are a radical departure from conventional aircrafts and podded, under-the-wing turbine engines. Aircraft concept studies require mature input assumptions for the electrical power system components and the electrical system research needs to be grounded with reasonable aircraft constraints. NASA's Advanced Air Transport Technology Project has approached the electrified aircraft propulsion challenge by concurrently exploring top-down aircraft concept definition and bottom-up electrical component technology research in order to identify one or more narrow-body (150-passenger class) aircraft concepts that would operate over typical commercial missions with reductions in both fuel burn and total energy consumption. These aircraft design concepts are reviewed and promising combinations of aircraft design concept and electrical propulsion technology are identified herein. It should be mentioned that many of the air-vehicle and propulsion-system integration options discussed here also could be achieved with mechanical solutions. Indeed, NASA is continuing its investment in advanced turbomachinery. Final aircraft design analysis will include a consideration of all competing propulsion options; for brevity only the electrified propulsion solutions are discussed here.

The aircraft concepts covered here will be organized by the manner in which the electrical powertrain is integrated into an aircraft. The aircraft powertrain classification shown in Fig. 1 defines one all-electric, three hybrid electric, and two turboelectric powertrains [2]. All-electric systems would use electro-chemical energy storage, typically batteries, for propulsive power. Hybrid electric powertrains can be implemented in several ways. In parallel hybrid architectures, a battery-powered motor and a fuel-powered turbine engine would both mount on the same propulsion fan shaft such that the fan could be driven by the two energy sources independently. In series hybrid architectures, some or all of the power in the gas turbine shaft would be converted to electric power and distributed to drive the motors and charge the batteries. Series/parallel partial hybrid systems would combine features of a pure series or pure parallel hybrid electric powertrain. Turboelectric aircraft would use on-board electric generation by the fuel-powered turbine for propulsive power. Commercial aircraft already generate both mechanical shaft power for propulsion and electrical power for non-propulsive loads. Each of these general powertrain classes can be applied in many different aircraft designs and some examples will be described here. Advanced propulsion design concepts are closely tied to technology maturation and therefore technology development assumptions must be explored in parallel. For example, the size of aircraft that can use an all-electric solution is closely coupled to battery technology advancement assumptions [3].

III. Hybrid Electric Aircraft Studies

The focus of early electrified propulsion research was fuel burn reduction, so augmenting jet fuel with batteries was a natural starting point. The Boeing-led Subsonic Ultra Green Aircraft Research (SUGAR) was a NASA sponsored study that performed a comprehensive battery-augmented, single aisle aircraft (SUGAR-VOLT) assessment [4]. The SUGAR-VOLT attempted to meet the aggressive goal of 60 percent reduction in fuel burn by combining a truss-braced wing and a hybrid-electric propulsion system. The truss-braced wing was responsible for significant aerodynamic and weight improvements with the parallel hybrid-electric propulsion system allowing battery energy to augment the engine thrust during cruise. Unfortunately, the SUGAR-VOLT implementation of a hybrid-electric propulsion system did not provide a reduction in overall aircraft energy usage, just on-wing fuel usage. This straight forward parallel hybrid powertrain implementation approach could make sense if terrestrial power generation were substantially cleaner and/or more economic than burning jet fuel in the air. For the foreseeable future, though, battery power energy densities and terrestrial charging do not provide a sufficient economic or environmental benefit to justify the SUGAR-VOLT implementation. However, this result does not provide information about other possible hybrid electric aircraft solutions. Two more research efforts were sponsored by NASA to further explore the hybrid electric

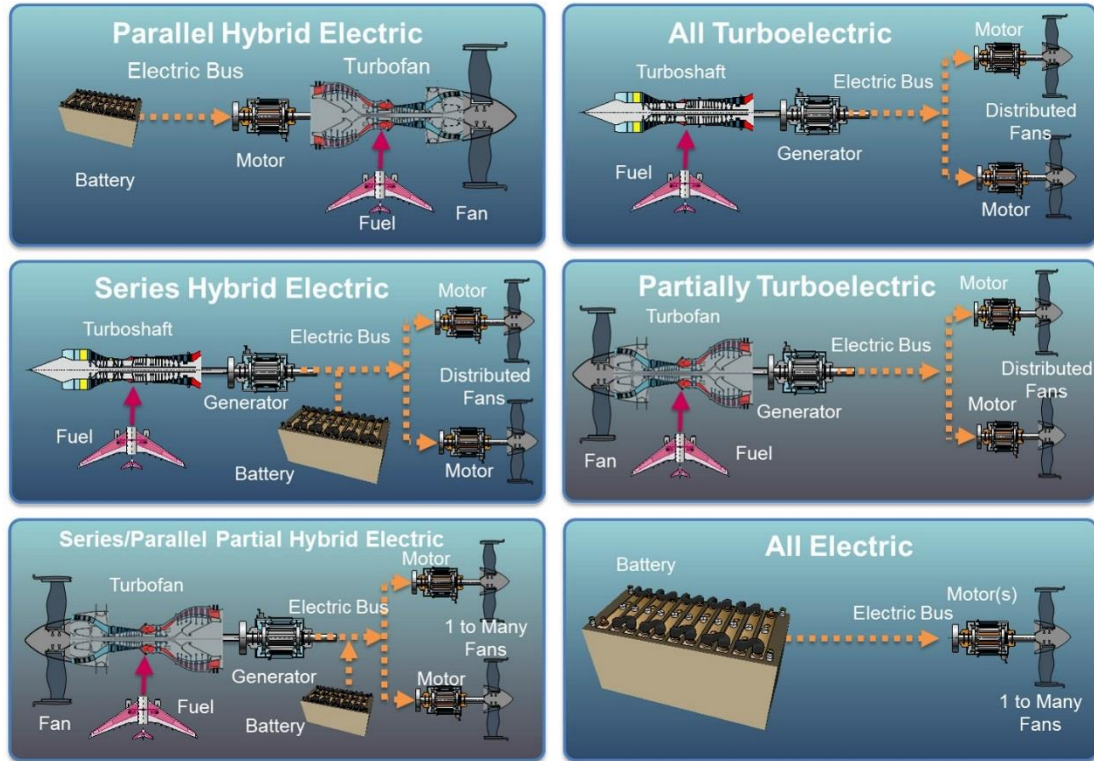


Fig. 1. Classification of electrical powertrains as applied to air vehicles.

trade space in the context of narrow-body aircraft. These efforts, competed under the NASA Research Announcement (NRA) system, were challenged to determine how overall energy efficiency of a commercial aircraft mission could be improved with a parallel hybrid approach. An entry into service date of 2035-2040 was assumed but fuel burn and energy benefits were calculated by comparing to an aircraft with comparable advanced technology improvement. Resizing of turbomachinery, best mission segments for battery augmentation, and concepts of operation were considered. The studies were required to design a vehicle that could meet a current design mission range of 6482 km (3500nm) but were also encourage to scrutinize the impact of hybrid powertrains on shorter missions of 1667 km (900 nm); these are the so-called economic missions that are the most common flight missions.

A. UTRC Hybrid Geared Turbopfan System

Under contract to NASA, United Technology Research Corporation has conceptualized a parallel hybrid version of their geared turbopfan engine. The parallel hybrid system utilizes a geared turbopfan providing 106.8 kN (24,000 lb_f) of thrust and 2.1 MW motor connected to the low spool tower shaft [5]. Keys to this design include an efficient bi-directional control of power between the low spool shaft and a motor/generator as well as an advanced fuel plus fan-flow thermal management. This arrangement allows the low spool to be powered by the low pressure turbine, or the motor, or any combination of the two. The electrical system would be used to provide boost power during takeoff and climb and this peak power shaving would result in a smaller core, which was expected to be 2.3% more efficient than a baseline geared turbopfan at cruise conditions. Mission analysis and sizing of the system were performed using the Boeing N+4 Refined SUGAR aircraft model as a baseline. This boost configuration required approximately 1300 kW-hr of energy storage. The electric powertrain and resulting vehicle efficiency were calculated based on a range of technology maturation assumptions. The ten-year horizon powertrain system was projected to provide a reduction in on-wing fuel usage and to break-even with respect to overall flight energy requirements for the 1667 km (900 nm) economic mission. Assumptions for 20-year improvements in system components, including battery system energy densities reaching 1000 kW-hr/kg, yielded concepts of operations with an overall energy improvement. These 20-year estimates resulted in a system benefit of 7 to 9 percent fuel burn reduction and a 3 to 5 percent energy reduction for the economic mission range of 1667 km (900 nm).

B. RRNA Variable Pitch Geared Turbofan System

Under contract to NASA, Rolls-Royce North America has been exploring a parallel hybrid concept that they call the Electrically Variable Engine. The optimization of the parallel hybrid electric propulsion trade space was performed at the subcomponent level, the aircraft level, and the fleet management level with the Electrically Variable Engine technology [6]. These studies are finding energy savings through concepts of operation and are exploring mission optimization using battery power to drive fans for taxiing, idle decent, and take-off power augmentation. One key operational aspect was to always utilize maximize take-off weight and optimize the balance between battery and fuel weight for the desired mission range. This allowed the more common short range missions to maximize the mission energy coming from the batteries. Motor sizes between 1MW and 2.6 MW were considered. The result was up to 28% reduction in fuel burn for a 900 nm mission, and up to a 10% total energy reduction for a 500 nm mission. Optimizing for minimum fuel usage predicts an 18% reduction in total fleet fuel usage. The analysis also explored optimization for minimum total mission energy (fuel energy + electrical energy), CO₂ production, or operational cost per flight. Notably, the system could not be optimized to minimize more than one objective at a time. For example a system optimized to minimize fuel burn consumed 1.5% more energy, cost 4.3% more, and emitted 7.2% more CO₂ than a system which was optimized to minimize each of the other objective functions separately.

IV. Turboelectric Aircraft Studies

The NASA N-3X concept vehicle is a classic “technology collector” design. Here, a broad collection of advanced technologies was considered together to explore a possible upper boundary in aircraft development. This vehicle was envisioned to be fully turboelectric, use a cryogenically-cooled superconducting powertrain, and employ a blended-wing body fuselage [7]. The concept analysis found significant fuel burn savings for an advanced aircraft compared to a 2005-baseline aircraft with nominally 20% of the improvements coming from the proposed turboelectric distribution. While these greatly advanced systems will continue to be the goal for future aircraft, electrified propulsion likely will be employed first in smaller aircraft and at lower power levels. A recent analysis considered a fully turboelectric powered aircraft for a conventional fuselage in the narrow-body aircraft class with state-of-the-art power components [8]. Not surprisingly, the aircraft did not close with net benefits and the size of the thermal management system was identified as one of the key technical challenges. Although a fully turboelectric powertrain offers the greatest configurational freedom, it may not be necessary to convert all of the turbine energy into electricity. A partially turboelectric powertrain, like a parallel hybrid powertrain, may allow some new propulsion-integration benefits with power systems in the one to two megawatt range rather than the 10 to 20 megawatt range.

A. Tailcone Thruster Partial Turboelectric Aircraft

NASA evaluated a tailcone thruster concept as one minimalist approach to partial turboelectric distribution. Version “A” of the Single aisle Turboelectric AiRCraft with Aft Boundary Layer ingestion (STARC-ABL) concept was published in 2016 [9]. This narrow-body, commercial transport concept with a turboelectric propulsion system architecture was developed assuming entry into service in 2035 and compared to a similar technology conventional configuration. The turboelectric architecture consisted of two underwing turbofans with generators extracting power from the fan shaft and sending it to a rear fuselage, axisymmetric, boundary layer ingesting fan. An exploration of the design space was performed to better understand how the turboelectric architecture changes the design space. System sensitivities were run to determine the sensitivity of thrust specific fuel consumption at top of climb and propulsion system weight to the motor power, fan pressure ratio, and electrical transmission efficiency of the aft, boundary-layer-ingesting fan. These results indicated that the turboelectric concept has an economic mission fuel burn reduction of 7% and a design mission fuel burn reduction of 12% compared to the conventional configuration. These encouraging results warranted further analysis and a summary of the Version “B” STARC-ABL concept is presented below.

Two single-aisle commercial transport concepts were refined assuming an entry into service in the 2035 timeframe. Both concepts, the advanced conventional configuration (N3CC) and the turboelectric concept (STARC-ABL), utilized technologies that were assumed to be at technology readiness level (TRL) 6 by the year 2025, mission profiles that use advanced air space management, and were similar in wing-body configuration. Key differences between the concepts were the turboelectric architecture, the rear fuselage BLI fan employed by the STARC-ABL concept, and the T-tail empennage resulting from the rear fuselage fan placement. Having the greatest commonality between the concepts was determined to be the best way to evaluate the impact of the turboelectric propulsion system architecture with a rear fuselage BLI fan. Both the N3CC and STARC-ABL configurations were updated since the publication of Ref. 9. The changes include increasing the design cruise speed to Mach 0.785, modifying the wing sweep angle, using the NASA Glenn N+3 geared turbofan model [10] with core limited to greater than 2.5 lbm/sec, adding propulsion system weight estimates calculated using the Weight Analysis of Turbine Engines (WATE++)

code, and decreasing the underwing engine fan pressure ratio to 1.3. Additionally, the mission constraints were modified to provide comparable performance to N3CC, the onboard voltage was increased to 1000 volts, and better weight estimates were included for the thermal management system. The N3CC turbofan was resized to exactly match the thrust required by the vehicle and to conform to the 2.5 lbm/sec limit on compressor exit correct flow rate. Another significant improvement entailed use of a coupled aero-propulsive analysis with powered CFD; previously only a simple superposition of a BLI ducted fan (propulsor) and a clean tailcone flowfield was employed. The coupled analysis included the interaction between the aircraft and the propulsor that are not captured when the propulsor is just dropped on top of a previously computed aircraft only flow field.

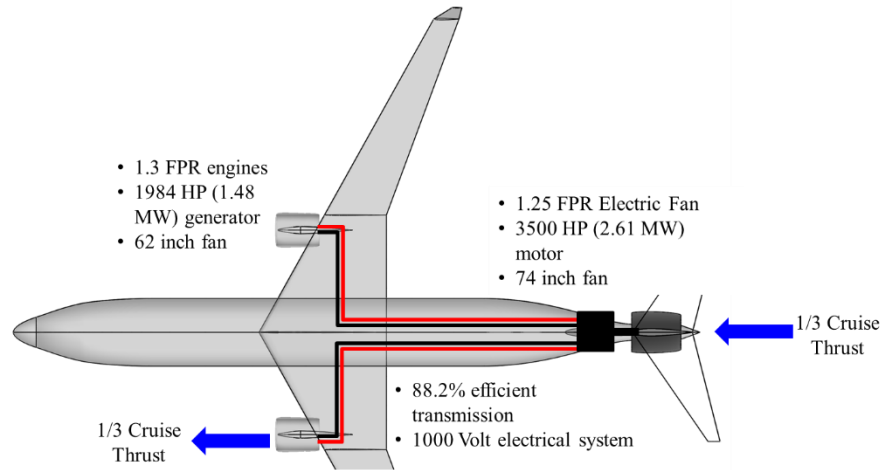


Fig. 2 Tailcone Thruster aircraft configuration with key propulsion and power system assumptions.

Many of the key powertrain and propulsion system assumptions remained the same and are shown in Fig 2. The electrical system modeling assumed 9.7% overall system losses. At a component level, the assumptions correspond to on-going technology development activities [11]. The specific power and efficiency of the motor and generator were assumed to be 13.2 W/g and 96 percent, respectively. The specific power and efficiency of the inverter and rectifier were assumed to be 19 W/g and 98 percent, respectively. The distribution cables were assumed to weigh 3.9 kg/m and be 99.6 percent efficient. The tailcone propulsor was assumed to have a fan pressure ratio of 1.25 and a maximum power of 2.61 MW that would throttle down along with the underwing engines.

Table 1 Aircraft system performance comparison.

		STARC-ABL Rev B2.0	N3CC Rev. B2.0	Delta
Wing Area (trap)	ft ²	1130	1120	1.4%
Span	ft	118	118	Fixed
Aspect Ratio	-	12.3	12.4	-1.4%
Sweep (LE)	deg	29	29	Fixed
Wing Loading	lb/ft ²	118.7	120.5	-1.5%
Empty Weight	lb	73890	73170	1.0%
Operating Empty Weight	lb	78510	77780	0.9%
Zero Fuel Weight	lb	109310	108580	0.7%
Takeoff Gross Weight	lb	134740	134880	-0.1%
Excess Specific Power	ft/min	480	440	10.4%
Time to Climb	min	26.4	21.7	21.7%
Thrust (Sea Level Static)	lb/eng	21410	21660	-1.1%
Altitude (Start of Cruise)	ft	37280	36400	2.4%
CL (Start of Cruise)	-	0.601	0.585	2.6%
Cruise Mach Number	-	0.785	0.785	Fixed
L/D (Start of Cruise)	-	21	20.7	1.6%
Takeoff Length	ft	8190	8190	0.0%
Landing Length	ft	6050	6120	-1.1%
Approach Velocity	knots	148	149	-0.7%
TSFC (Start of Cruise)	lb/hr/lb	0.468	0.480	-2.6%
Design Mission BF	lb	22550	23360	-3.4%
Economic Mission BF	lb	6240	6410	-2.7%

This new, higher fidelity assessment of the STARC-ABL concept still identifies a net fuel burn benefit and an overall energy savings compared to the N3CC aircraft with same level of assumed technical advancements. The resulting aircraft performance parameters are compared in Table 1. Although the empty weight is higher for the new aircraft configuration, the takeoff weight is slightly lower. In this design, the weight of the third propulsor is balanced by downsizing the fan and nacelles of the underwing engines. The projected fuel savings is 2.7 percent for a typical economic mission (1667 km or 900 nm) and 3.4 percent savings for the full design mission of 6482 km (3500 nm). Separate higher fidelity analysis showed that wing circulation has a significant impact on amount of ingested fuselage boundary layer and suggests placing the fan at the aft-most position. This placement sensitivity may be one factor that favors a motor-driven shaft rather than a direct turboshaft. The powertrain weight is also highly sensitive to cable weight and thus relatively high distribution voltages will be required.

Conversely, further improvements in the powertrain would provide additional energy saving; an additional fuel

savings of 4 percent is the upper boundary for no electrical transmission loss with everything else being equal. The comparison is likewise sensitive to the relative advancement of the advanced turbine engines. If turbomachinery improvements are greater than assumed, the advantage of tailcone thruster configuration would be reduced with everything else being equal.

V. Continuing Evolution of Aircraft Concepts

The previously discussed hybrid electric concept studies indicate that together mission, propulsion system, and energy storage optimization *can* improve the overall fuel burn or energy consumption. Similarly, the partial turboelectric aircraft analyses indicate that optimization of propulsion-airframe integration with energy distribution *can* improve vehicle energy consumption. However, these designs presume significant advancement beyond the state-of-the-art in the electrical powertrain components. Natural questions to ask are: 1) how realistic are these technology development assumptions, 2) when will these components and subsystems be available, and 3) how does the aerospace community focus their research efforts to reach these goals. As mentioned previously, and as described in Ref. 10, the technology assumption used in these recent studies for the electrical machines and power inverters are anchored by current technology development activities. Additionally, there is an ongoing investment in higher specific power and efficiencies for terrestrial power grid modernization and electrification of other vehicles. Table 2 illustrates the technology development needs that were identified by the system studies discussed in previous sections. Technologies that are foundational for multiple types of electrified aircraft, cells shaded green, are identified as high priority investments.

Table 2. Narrow-body electrified aircraft technology development needs for hybrid electric (yellow), turboelectric (blue), and technology common to both (green)

Energy Storage	Electrical Dist.	Turbine Integration	Aircraft Integration
Battery Energy Density	High Voltage Distribution	Fan Operability with different shaft control	Stowing fuel & batteries; swapping batteries
Battery System Cooling	Thermal Management of low quality heat	Small Core development and control	Aft propulsor design & integration
	Power/Fault Management	Mech. Integration	Integrated Controls
	Machine Efficiency & Power	Hi Power Extraction	

The studies described in section III explored parallel hybrid powertrains and how batteries could be used to make narrow-body, transport aircraft more fuel and energy efficient. Similarly section IV explored options for using turboelectric, particularly partially turboelectric, powertrains in narrow-body aircraft classes. Each of these designs give insight into the component and subsystem requirements for this new class of aircraft. The convergence of aircraft design solutions and technology improvements encouraged the next aircraft questions. In 2016, NASA solicited proposals for the conceptual design of an advanced, narrow-body-class, commercial transport aircraft that featured a significant amount of electrical propulsive power. The purpose of this study was to evaluate both technology and value proposition of vehicles with expected entry into service specified to be 2035 or earlier. The required payload was 154 passengers with a design mission of 6482 km (3,500 nm) and a design cruise speed of Mach 0.785. A frequent operation 1667 km (900 nm) economic mission was also identified. NASA required that the advanced electrified aircraft be capable of operating in the current infrastructure including Class C airport operations, that it should be designed to minimize mission energy use and life cycle carbon, and that it should show significant margins below the current stringencies for noise and NOx [12]. The infrastructure restriction was especially significant in this study because it disallowed recharging or swapping of batteries at the airport. The intent of this research program was to compare an advanced electrified aircraft to a conventional aircraft with the same technology level in order to determine what the benefits are and if they outweigh the weight, cost, and integration penalties associated with electrification. In addition, technology development approaches, safety issues, and certification challenges would be identified and

discussed. Finally, this research program would provide independent approaches to electrification of a commercial transport, which could be compared to the NASA STARC-ABL concept.

Two contracts were awarded under the NRA Single-Aisle Hybrid Gas-Electric Aircraft Concept topic in 2017. One of the contracts was awarded to Rolls-Royce North American Technologies (LibertyWorks) partnered with Empirical Systems Aerospace (ESAero). LibertyWorks and ESAero proposed a concept that features a wing-embedded distributed propulsion system that uses both mechanical and electrical power distribution for the propulsors. The concept configuration and wing-embedded propulsion system has some common features with the ESAero ECO-150 concept [13], which was used as a starting point. In addition to the wing-embedded propulsion system, the concept also features boundary layer ingesting (BLI) electrically driven propulsors on the aft fuselage. The series/parallel partial hybrid system uses a battery to provide boost power during takeoff and climb and to supplement thrust for operations under 3000 ft to reduce NOx emissions. This contract is currently scheduled to end in July 2018.

The second contract was awarded to Boeing, who had partnered with Rolls Royce LibertyWorks and the Georgia Institute of Technology. The Boeing team proposed a concept featuring a truss-braced wing and an electrically driven tailcone BLI propulsor. The Boeing concept's two turbofan engines employ motor/generators capable of accepting boost power from the battery, providing electrical power to the tailcone propulsor, or providing power to recharge the battery. The concept configuration has some outward similarities to the STARC-ABL configuration; however, the hybrid-electric architecture of the Boeing concept is significantly different from the turboelectric architecture of the NASA concept. This contract is currently scheduled to end in June 2018.

VI. Conclusions

As a technical community, we have spent the last 70 years perfecting the tube-and-wing aircraft and the podded turbine engine. Although there will continue to be improvements in each of these separately, enhanced propulsion and airframe integration is likely to be the cornerstone of future aircraft. Rapid improvements in power electronics will continue to increase the efficiency, specific power, and overall power of aircraft electrical systems. A spiral approach to advancing aeronautics-focused electrical technology in concert with electrically-focused aircraft design will continue to move the aeronautics community towards a powerful future.

VII. Acknowledgments

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