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SPECIAL TOPIC

ELECTRIC AIRCRAFT

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SPECIAL TOPIC

ELECTRIC AIRCRAFT

Electric cars have become commonplace, and the advances in batteries, motors and electronics already achieved by the automotive industry is beginning to impact aerospace. It is starting small, because today's batteries are poor reservoirs for energy compared with aviation fuel, but the trend is clear and accelerating.

Electric propulsion has reached the point where small, light, short-range aircraft are feasible for pilot training or recreation. The next step could be urban air taxis, two- or four-passenger aircraft that can make short hops over congested traffic within cities, circumventing the limitations of today's batteries by keeping the flights brief and recharging frequently.

But the question everyone in the aviation industry is asking is: when, if ever, will electric propulsion come to commercial air transport? Some believe it is on its way. Several startups are already developing small, short-haul regional airliners, promising dramatic operating-cost savings by switching from jet fuel to grid electricity and complex gas turbines to simple electric motors.

From Boeing-backed Zunum Aero's 12-passenger, 700-mile-range hybrid-electric aircraft, which it plans to deliver in 2022, to the hybrid-electric regional-aircraft demonstrator Airbus intends to fly in 2020 in a joint program with Rolls-Royce and Siemens, Aviation Week has covered the rapidly moving developments closely, in the stories presented here in this eBook.

Skeptics say electric propulsion will never make it to large commercial aircraft, but that is not stopping researchers within NASA, the engine manufacturers and elsewhere looking for ways to electrify tomorrow's airliners. Several concepts for hybrid turbine/electric narrowbody airliners that could enter service in the 2030s are being closely studied on both sides of the Atlantic.

In terms of early avenues to electrified aircraft, the most promising of these concepts integrate electric propulsors tightly with the airframe to improve aerodynamics and reduce drag. These designs promise to reduce fuel consumption and emissions beyond the future improvements that are expected to accrue from advances in turbine engine technology alone.

But many significant barriers to electrified aircraft lie ahead, not least the added weight of the energy generation, storage and distribution systems. The research now under way, and detailed in several recent Aviation Week stories presented here, is working to understand and overcome those challenges and unlock the potential of electric propulsion to usher in a new era of aviation.

Graham Warwick
Managing Editor, Technology
Aviation Week & Space Technology

Subscale Flights Show Potential Of DARPA VTOL X-Plane

Graham Warwick

Aurora Flight Sciences has shown through subscale tests that the unconventional configuration of its XV-24A LightningStrike can take off vertically, hover, transition to forward flight and back to a vertical landing. This has reduced some of the risks in the full-scale demonstrator planned to fly in late 2018 under DARPA's Vertical Takeoff and Landing (VTOL) X-Plane program.

The milestone was achieved using the same flight control system planned for the full-size XV-24A, which will use electric-powered ducted fans embedded in a tilting canard foreplane and main wing for vertical lift, forward thrust and flight control. The subscale demonstrator first flew in April 2016, shortly after Aurora won the $89.4 million cost-sharing contract to build and fly the high-speed LightningStrike.

An Unconventional Approach to High-Speed VTOL

- XV-24A LightningStrike has hybrid-electric distributed propulsion
- Electric-driven ducted fans are embedded in tilting tandem wings
- Subscale tests showed conversion between vertical and forward flight
- Reduced risk for full-scale vehicle planned to fly toward end of 2018

The major differences between the two vehicles are size and power. The 20%-scale demonstrator weighs 325 lb., including 120 lb. of batteries generating 110 kW of power. The XV-24A will weigh 12,000 lb. with a Rolls-Royce AE1107 turboshaft driving three generators producing a combined 3 megawatts of electrical power to drive 24 ducted fans—six embedded in the foreplane and 18 in the aft wing.

"By closely matching the configuration of the full-size aircraft and enabling conversion from hover to wingborne flight, we have done two things," says Ashish Bagai, DARPA program manager. "One is we have verified that the aerodynamic configuration is valid. The distribution of thrust between the canard and main wing and tilting of these surfaces enables conversion to wingborne flight without loss of altitude."

Transitions between vertical and forward flight showed the embedded propulsion "is effective in preventing wing stall during conversion flight and the aircraft is fully controllable throughout the conversion corridor," says Bagai. "All have been verified. And that's a big step because, although it is significantly smaller than the full-scale aircraft, this is not a toy. It is 325 lb., all-electric, equipped with embedded fans and it incorporates some novel approaches to building and testing subscale aircraft."

Aurora was awarded the contract for Phases 2 and 3 of the VTOL X-Plane in March 2016, and its LightningStrike was selected over designs from Boeing, Karem Aircraft and Sikorsky/Lockheed Martin. The program aims to demonstrate a vertical-takeoff-and-landing aircraft that can fly faster than 300 kt., achieve high hover and cruise efficiency and carry a useful load of at least 40% of the vehicle's gross weight.

The VTOL X-Plane competition was unusual in that, instead of specifying a mission, DARPA set out performance metrics designed to tackle the shortcomings of previous VTOL configurations. Helicopters can hover efficiently, but are limited in speed and cruise lift-to-drag ratio. High-speed VTOL aircraft such as the F-35 are fast, but inefficient at hovering, and their heavy propulsion systems consume useful load.

"The VTOL X-Plane program is a bit of an abstraction," says Bagai. "We had certain performance metrics in mind, while being careful to refrain from being specific about what types of missions we wanted to fly. This was deliberately an investigation into the art of the possible, the intent being that we did not want to converge on multiple aircraft with significant similarity, which is what we would have ended up with if we had set a mission-specific objective."

DARPA got its wish, four quite different configurations winning Phase 1 concept design awards. Boeing's Phantom Swift had two ducted rotors in the body and two tilting ducted fans on the wing tips. Karem proposed its variable-rpm Optimum Speed Tiltrotor. And Sikorsky participated with its tailsitting Rotor Blown Wing. But Aurora's design was the most unconventional: tandem tilting wings and a hybrid turbine-electric distributed propulsion system.

"The idea was not to pull a stunt, to go break the world speed record for a helicopter then go home and never touch it again. The focus was on what types of configuration and technology have evolved over the last several decades to enable future capabilities, whatever those may be," says Bagai. "This is not the only configuration that could have met those objectives, but what you are seeing here is the evolution of a new species in the taxonomy of vertical flight."

The subscale demonstrator has a single-channel version of the full-size XV-24A's flight control system.

DARPA

The LightningStrike poses many challenges, not least in flight control. Including variable pitch on the ducted fans, there are no fewer than 72 control effectors on the wing and canard. Each fan duct has upper and lower control surfaces, which Aurora calls elevons on the canard and ailerons on the wing. These surfaces vector thrust up or down relative to the wing, and also vary duct nozzle area to keep the fan operating at its optimum efficiency in both hover and cruise flight.

"We have used this subscale aircraft to fully develop the flight control system for the full-size XV-24A," says Bagai. The demonstrator is autonomous. Once the pilot commands launch, rotation of the wings to vertical, demanded power, climb rate, altitude hold and conversion from hover to wingborne flight are all performed by the model-based control system. "We went through a rigorous flight release, so we have also wire-brushed that process in preparation for the full-scale aircraft," he says.

A key objective with the subscale demonstrator was to prove the configuration has adequate control authority throughout the conversion corridor—the range of speeds and altitudes at which the aircraft can transition between vertical and horizontal flight. This was a shortcoming of several previous VTOL concepts. "Whether or not it was deliberate, we've done some pretty aggressive maneuvers with the small-scale aircraft," says Bagai.

"Winds aloft at 90-100 ft. turned out to be gusting significantly higher than at ground level, and we also flew the aircraft in a significant crosswind," he says. "You could see it crabbing down the runway, but that was intentional. It held its position well and responded well to gusts. That gives us confidence in the flight-control system maintaining the stability of the aircraft."

With subscale flights completed for now, attention has turned to another challenging aspect of the LightningStrike, the hybrid-electric propulsion system. This was chosen because battery power or mechanical drive of the ducted fans was not practical. "Battery technology right now will not permit all-electric for any meaningful endurance or range on a 12,000-lb. aircraft," he says.

"The only way to go to new configurations like this with distributed propulsion is to get rid of the overhead of mechanical transmissions," says Bagai. "It would not be possible to have such a large number of fans distributed through the wings if they were being driven mechanically." In the full-scale aircraft, AC power goes direct from the engine-driven generators to the ducted-fan motors, instead of being converted to DC for distribution then back to AC to drive the motors, with the losses that entails. AC coupling simplifies the power system, but it requires that the fan motors stay synchronized with the generator frequencies, which vary with turbine-engine speed.

The composite image shows the subscale aircraft taking off vertically, hovering and landing vertically.

In conventional electric propulsion, such as in a quadcopter drone, thrust for lift and flight control is controlled by varying motor speed. With AC coupling, that is not possible. "There is a price to be paid when we use power this way. With direct AC we lose our ability to use rpm as a control degree of freedom. So we go to variable pitch," says Bagai.

"Losing variable rpm means that we need to maintain synchronization of the fans to the generator frequency," he says. The 24 fans are divided into banks of eight, and synchronization must be maintained within each bank. "If we have a situation with one fan, we have to make sure the electromagnetic and aerodynamic damping from one fan to another does not result in a cascading effect where fans start dropping offline."

Testing of the full-scale power system has begun. The first 1-megawatt generator is going through acceptance tests at supplier Honeywell. The generator will be used in a "copper bird" test rig at Aurora. In this rig, the generator will be driven externally, and not by the AE1107 engine, and will power a smaller number of fans.

"We will be looking at synchronization of the fans and the ability of the generator to run continuously at the required power levels. And we will also be looking at power transmission, and the types of materials and wires we will be using," says Bagai. "It will be a first, highly representative look at a subset of the power generation and transmission and fan operation."

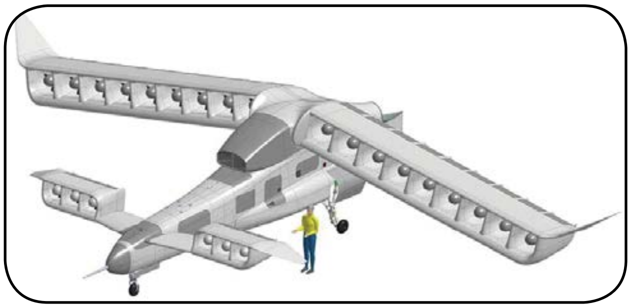
The next step will be the iron bird rig. This will have the actual engine, gearbox and generators powering a larger number of fans. "That will be the full system and will incorporate learning from the copper bird," he says. "That then leads to integration into the aircraft. We are trying hard to hold to our intent to fly toward the end of 2018. Some of that will be driven by any discoveries made in the copper and iron birds, if there is anything substantial."

Unusually for a DARPA program, there is no service partner on board to which to transition the concept after the demo is complete. "I don't believe that the aircraft itself is the transition opportunity. I think that the technology it demonstrates is viable for transition," says Bagai.

One technology is the flight control system. "We do not have a single aircraft today that has true configurability in its flight control system. You need an aircraft that can use multiple control surfaces to achieve the same desired effect," he says. "This aircraft would do that. We have so many control effectors. Every single fan could potentially be used as an independent control unit."

In addition to the variable-pitch fans, each duct has a variable-area diffuser to optimize its efficiency in hover and in forward flight. These flaps can also be deflected collectively or differentially for control in vertical and horizontal flight. "We have several different

Full-scale XV-24A LightningStrike VTOL X-plane is planned to fly in 2019.



control mechanisms: variable pitch, variable diffuser angle, variable or differential aileron or differential aerodynamic surface deflections to give the required forces for different flight modes," he says. "Now you can start developing control systems that lead to adaptive flight controls."

Power generation is another potential transition opportunity. "There are a lot of energy-hungry electric applications out there," says Bagai. Another is distributed ducted-fan propulsion. "Because of the distribution of the propulsion system, the ducted fans are effective in keeping the flow attached to the leading edge and the wing generating lift even at a very high angle of attack at low airspeed. That's an area of interest not only for the vertical lift community, but also for fixed-wing."

The AC-coupled power system has attracted interest from NASA, which is investigating a similar approach for large commercial aircraft under its high-voltage hybrid-electric propulsion program. "We were recently approached by folks at NASA who have a high level of interest in direct [AC] flight systems and who thought we are ahead of where they want to be. That gave us confidence in this approach."

Bagai acknowledges Aurora is pushing the envelope significantly with LightningStrike. "Just the configuration of this aircraft is challenging enough, but the power generation and distribution, the overactuated flight control system, the blending and reallocation of the controls between flight modes—are all orders of magnitude greater than what we have seen in the past," he says, adding "It's fair to say this program is turning out to be one that is not for the faint of heart."

Bagai's excitement, and relief, at the progress made so far is palpable. "I wouldn't say we are out of the woods, but we have a significant amount of increased confidence given the success of the subscale demonstrator flight-test program," he says. "I have seen the aircraft hold altitude and convert seamlessly from one flight mode to another with the wings tilted at 60 deg. in gusting conditions. By golly, I think it's a good one."

NASA Says Airframe Integration Key To Hybrid-Electric Regionals

Graham Warwick

With small, short-range battery-powered aircraft becoming a reality, attention is turning to larger sizes and whether electric propulsion could enable a resurgence of regional air transportation by reducing operating costs compared to today's jets and turboprops.

But it is hard to make a compelling case for all-electric or hybrid-electric regional aircraft without assuming significant advances in technology, because of the poor energy storage capacity of today's batteries in comparison to jet fuel and the inefficiencies in converting jet fuel to electricity.

Unlocking Synergistic Benefits of Electric Propulsion and Aerodynamics

- NASA started with the 48-passenger ATR 42-500 regional turboprop
- Initial study looked at four levels of electrification of the basic airframe
- Study showed huge improvements in energy storage are required
- Pegasus concept reduces energy cost and aircraft weight penalties

The key, engineers believe, lies in using electric propulsion synergistically to improve the aerodynamic performance of the aircraft, and so achieve an overall increase in efficiency that offsets the shortfalls in energy storage and conversion efficiency.

NASA designers have developed a concept for a 48-seat regional aircraft in which multiple electric and hybrid-electric propulsors are strategically located on the airframe to improve aerodynamics, and so reduce the total energy required and vehicle gross weight.

Presented at the American Institute of Aeronautics and Astronautics' Aviation 2017 conference in Denver in early June, the Pegasus (for Parallel Electric-Gas Architecture with Synergistic Utilization Scheme) concept is the result of a prior study that highlighted the challenges of developing a competitive regional airliner with electric propulsion.

The prior study led by Kevin Antcliff, an engineer with the Aeronautics Systems Analysis Branch at NASA Langley Research Center, analyzed an advanced regional aircraft that could enter service in 2030. Based on the ATR 42-500, the design was a 48-seater with a 600-nm concept range. The study analyzed the concept with four levels of parallel-hybrid electrification from 0-100%.

The study determined that battery energy density must be greater than 500 Wh/kg for the total energy consumption to be less than that for conventional turboprop propulsion. Today, the best battery energy density commercially available is about 250 Wh/kg. This compares with 12,000 Wh/kg for jet fuel.

Based on the ATR 42-500, Pegasus has five electric and hybrid-electric propulsors positioned to improve aerodynamic and propulsive efficiency.

NASA

But even at 500 Wh/kg, the economics would be less attractive than for the turboprop because of higher aircraft weight and energy costs, the study concluded. With 500 Wh/kg batteries, a 75%-electric aircraft would be 2.3 times heavier than a turboprop and energy costs 10% higher.

Weight and cost penalties decrease as energy density increases. At 1,000 Wh/kg, the aircraft would be 39% heavier than a turboprop, but energy costs would be 23% less. With that level of energy density barely on the horizon, the

study suggested optimizing the airframe around the propulsion system.

The result is Pegasus, an evolution of the parallel hybrid-electric version of the ATR 42-500 developed in the prior study. Also aimed at service entry in 2030, the concept has two hybrid electric propulsors at the wingtips, two electric propulsors under the inboard wing and another on the tail.

NASA

In the cruise, the all-electric inboard wing propellers would stop and fold away to reduce drag and save electrical energy.

The slipstream from each wingtip propeller attenuates the wing vortex and results in an estimated 18% increase in effective propulsive efficiency for these props, says Antcliff. This effect will be demonstrated in flight on NASA's X-57 Maxwell electric propulsion demonstrator, planned to begin flying early in 2018.

The inboard electric motors are powered for takeoff and climb, but shut down with the propellers folded in cruise. This eliminates windmill drag and the adverse impact of propeller swirl on spanwise lift distribution, providing a 10% reduction in induced drag. Folding props will be demonstrated on the X-57.

The tail-mounted propulsor is positioned to ingest the slowest-moving boundary layer air over the fuselage, reenergizing the flow to reduce the momentum deficit in the wake. Boundary layer ingestion (BLI) is expected to provide a 10% increase in effective propulsive efficiency for the tail prop, Antcliff says.

Electric-powered aircraft are extremely sensitive to design range because of the energy storage issue. The ATR 42-500's maximum range is 1,000 nm. For the previous hybrid-electric study this was reduced to 600 nm, but the analysis showed the aircraft was more competitive at 300 nm.

NASA's projections of 2030 transportation demand predict that 50% of regional trips will be 200 nm or less and 90% will be 400 nm or less. So Pegasus is designed to fly a 200-nm mission with all-electric propulsion, at 500 Wh/kg energy density, and a 400-nm mission with hybrid-electric propulsion.

For both missions, all five propulsors are used for takeoff and climb. The inboard propellers are powered off and folded for cruise, leaving the wingtip and BLI propulsors to provide efficient thrust. In the event of a propulsor failure in cruise, the inboard motors would be restarted.

NASA

Smaller turboprops mounted in the wingtip nacelles, along with batteries, drive the outboard props in a parallel hybrid architecture.

An issue with all energy-constrained electric aircraft is the reserves required by the FAA for instrument flight rules operations. The reserves assumed by ATR equate to an additional range requirement of about 300 nm—44% of the total energy onboard and a hefty penalty in an aircraft designed to fly 200-400 nm.

With current technology, only 80% of the energy in a battery can be used. If that limit is exceeded, the life of the battery is severely shortened. As a consequence, the Pegasus is designed to complete the full reserve mission solely on jet fuel. This results in the turbine engines being oversized.

Two methods were used to analyze Pegasus, both showing the design "has promising advantages over previous concepts . . . [with] a substantial decrease in electric energy and fuel consumption" compared with the previously studied 600-nm-range hybrid-electric configuration, Antcliff says.

Between the two methods, analyses showed a 27-39% decrease in energy usage over the advanced 2030 regional turboprop. At the same time, the increase in takeoff gross weight was halved, to 31% for Pegasus from

65% for a 60%-electrified hybrid-electric version of the baseline design.

"Comparing the aircraft weight and mission energy results between the Pegasus concept and the intermediate baseline hybrid-electric concept presents a strong case for electric and hybrid-electric vehicles that are designed for synergistic integration and operations," concludes Antcliff.

All-electric propulsor in the tail ingests fuselage boundary layer to reduce drag and also produces thrust throughout the flight.

NASA

As a next step, NASA plans to study whether a similar approach to synergistic propulsion-airframe integration will improve the operating economics of other sizes of electric and hybrid-electric aircraft, down to nine seats and up to 130 seats, he says.

Zunum's Software-Style Approach To Developing Electric Propulsion

Graham Warwick

Boosted by a research-and-development grant from Washington state, startup Zunum Aero is moving into construction of the prototype powertrain for its planned hybrid-electric small regional airliner. The $800,000 matching grant is the second-largest of five awarded by the state's Clean Energy Fund, its size proportionate to funding already raised from Boeing HorizonX and JetBlue Technology Ventures.

Describing the grant as "a significant amount, a significant endorsement and a significant investment at a national level in electric aviation," CEO Ashish Kumar says the money "supplements funds from out-of-state sources and will go toward prototype building."

Zunum, described by founder Matt Knapp as "mostly a propulsion company with some aircraft development on the side," plans to develop its hybrid-electric powertrain via a series of versions—more akin to software development than a traditional aircraft engine program. Updates to the drive-system hardware and control-system software will be released every six months or so as technology matures.

Natural laminar flow and ducted-fan propulsors will increase efficiency and reduce energy consumption.

ZUNUM AERO

This will continue into production and operation of the aircraft; Zunum is designing the propulsion architecture so that higher-performing batteries, electronics and motors can be plugged in over time. This way, the company intends to expand range from 700 nm in the early 2020s to 1,000 nm by 2030.

A large portion of the Washington-state funding will go toward hiring engineers. "We've been developing this for three years. . . [and] we've pushed the analysis as far as we can," says Kumar. "Now we are ramping up engineering and about to start building." By year-end the workforce is expected to grow to 20-25, from around 10.

In a coup for Zunum, Waleed Said, who led development of the power electronics and control systems for the more electric Boeing 787 and Lockheed Martin F-35 at UTC Aerospace Systems, has joined the startup as chief technology officer for power. His first task, says Kumar, is to conduct an analysis to challenge the assumptions Zunum has made in designing its propulsion architecture.

The goal is to have the copper bird running by year-end, Kumar says, referring to the full-scale ground-test rig for the hybrid-electric powertrain. "The next big milestone—within the next year—is to get the flying testbed in the air," he says. This is an existing twin-turboprop aircraft that will be modified in stages to demonstrate the hybrid-electric propulsion system.

Zunum's goal is to design a family of regional airliners that are optimized for shorter ranges than today's turbine-powered aircraft, and therefore suited to electric propulsion. The aircraft will have ducted-fan propulsors powered by battery packs, with a turbine range-extender to generate electricity in flight. But on shorter flights, or as battery technology improves, operators will be able to replace the range extender with a third battery pack and fly all-electric for lower costs and zero emissions.

Knapp says the company plans to work with an airframer on the aircraft while it focuses on being an electric powertrain producer. Because of the tight integration required between propulsion and airframe to make electric power work, he expects Zunum "to work more extensively with the airframer to optimize and integrate their airframe with our propulsion system."

Zunum has studied advanced propulsion-airframe architectures, including boundary-layer ingestion and wing-tip-mounted propulsors, to reduce drag, but they either introduced issues or did not provide a benefit at the small aircraft sizes being considered. Instead, the aim is to achieve extensive natural laminar flow to reduce drag and energy consumption.

The iterative development process will begin with the copper bird, which will be dimensionally correct but initially use off-the-shelf electric motors that are not flight weight. Zunum is designing custom flight-weight motors for the flying testbed. Initially, these will power propellers, with the ducted fans to be tested later on the copper bird and testbed.

Kumar says an extensive testing period will start by year-end. “We will give the engineers hardware to iterate on, so when we go for certification and production we will have aggressively matured the system.”

Initially, Zunum plans to use an off-the-shelf turbine as the range extender to give operators the option of fitting a used engine to reduce costs. But the company is working with engine manufacturers to identify opportunities for future improvements, such as quick-start capability to allow the range extender to be shut down in flight then restarted rapidly when needed.

Hybrid-electric propulsion provides flexibility in how power demands are met between batteries and generators. Initially, Zunum plans to meet the FAA’s requirement for reserves using the range extender, but replacing this with a third battery pack would provide a 45-min. reserve. “In the early 2020s a large part of battery capacity [will be] reserves, but that reduces by the late 2020s as batteries improve,” Kumar says.

Hybrid Electric Could Be Next Step Beyond Turbofans

Graham Warwick

At some point, the turbofan commercial aviation knows will no longer be able to provide the efficiency improvements the industry needs. No one knows when or what could replace the turbofan, but a gambler would be putting money on one solution—a turbine-electric hybrid enabling propulsion-airframe integration with an intimacy that promises benefits beyond anything the engine could do alone.

Interest in hybrid solutions is being driven by recognition that if turbofans advance as expected aircraft designs will have to change to accommodate ever-bigger fans. Airliners with wings that arch upward to make room for larger nacelles, or bigger engines mounted over the wing to avoid long landing gear, are on the drawing board. But these solutions have limits, and there are other possible approaches.

The Mathematics of Propulsion Electrification

- Jet fuel has higher energy density than batteries; electric motors are more efficient that turbines
- Hybrid turbine-electric propulsion combines the two, but adds weight and complexity
- Efficiency benefits from propulsion hybridization must significantly outweigh the penalties
- Net aircraft-level benefits require tight integration of propulsion and aerodynamics

One is to distribute propulsion across multiple fans that are integrated with the aircraft in ways that not only increase effective bypass ratio, and therefore propulsive efficiency, but also interact with airflow over the airframe in ways that improve aerodynamic efficiency. Powering those fans electrically rather than mechanically is potentially a simpler, more reliable solution.

Fully electric propulsion is not seen as viable for large commercial aircraft because of the massive difference in energy density between batteries and jet fuel. Batteries are now about 200 Wh/kg at the system level and could reach 500 Wh/kg by 2035 with new chemistries now in the laboratory. While 1,000 Wh/kg is a distant prospect, this compares with 12,000 Wh/kg for kerosene.

But even at 1,000 Wh/kg, an all-electric equivalent of the AirbusA320 or Boeing 737 would require 170 metric tons of batteries, says Safran's senior executive vice president and chief technology officer, Stephane Cueille. "You would have to build a much larger aircraft, as the A320 has an 80-ton maximum takeoff weight," he says. "Full electric is just not practical for larger, longer-range aircraft."

A hybrid system takes the energy density of kerosene and, using gas turbines for power generation, combines it with the high efficiency of electric motors. Energy can come from several sources, including jet fuel, batteries and fuel cells. "Now the design space opens wide, and the question becomes what is the configuration that gives benefits in terms of fuel burn," says Cueille. "Our estimate for larger short/medium-range aircraft is 3-12%, depending on the complexity of the configuration."

As turbofans get bigger, their installation on aircraft will become problematic.

ROLLS-ROYCE CONCEPT

But there are key challenges. One is weight. "By construction, this will be heavier due to the electrical system," he says. Others are complexity and reliability compared with conventional propulsion. "You still have the gas turbine and will have the additional electrical system," he notes. Those penalties can only be offset if the efficiency benefits

from propulsion-airframe integration are big enough.

"Integration is the key," says Alan Newby, director of Rolls-Royce's aerospace technology and future programs unit. "We have already learned we can improve the propulsion system by better structural and aerodynamic integration of the engine and nacelle," he says, suggesting the next steps in integration could be embedded and distributed propulsion.

At the American Institute of Aeronautics and Astronautics Propulsion & Energy Forum in Atlanta in July, NASA and three of the four major engine manufacturers showed similar concepts for an A320/737-size airliner with an additional fan embedded in the tail. This fan ingests the slow-moving boundary-layer airflow over the fuselage and reenergizes the wake, reducing momentum drag. This fan could be powered mechanically or electrically—"the basic fundamentals don't really care," says Newby.

In NASA's concept, called STARC-ABL (for Single-aisle Turboelectric Aircraft with Aft Boundary Layer propulsion), the aft fan is driven electrically by a 2.6-megawatt motor powered by generators driven by the two underwing turbofans. The drag reduction allows smaller turbine engines, and NASA studies show a 7-12% fuel-burn reduction compared with a conventional configuration.

Described as "lightly distributed," STARC-ABL is one concept being studied under a five-year technology challenge, launched in 2014, to identify a configuration that provides a net benefit from electrification only, before other technologies are factored in. "We think we have found at least one concept," says Amy Jankovsky, NASA's hybrid gas-electric subproject lead, adding: "STARC-ABL does meet the requirements."

ROLLS-ROYCE CONCEPT

An aft boundary-layer-ingesting fan reduces drag and allows for smaller turbofans.

Although GE, Rolls and Safran all showed similar configurations in Atlanta, not everyone is as convinced as NASA that boundary-layer ingestion (BLI) could provide a near-term route to hybrid-electric propulsion. "For BLI, there is more than one engineering solution. You can accomplish the same thing with mechanical, pneumatic, hydraulic or electrical drive," says Alan Epstein, vice president of technology and environment for Pratt & Whitney, adding he has not seen "any serious back-to-back comparison of these approaches for a particular aircraft configuration."

Depending on the mission, "double-digit improvements are certainly in the realm" for BLI, says Eric Ducharme, GE Aviation general manager for advanced technology. "To get it to work on a large transport, we are probably going to have to get to much higher voltages," he says. "There are challenges associated with that, with insulation performance at altitude, but the reduced weight of the cabling is compelling."

But a move away from current configurations, to NASA's STARC-ABL or other more unconventional designs, will be necessary to justify shifting to hybrid-electric propulsion. "It's no good simply taking today's aircraft and swapping a very efficient fan and gearbox for an electric motor, generator and some power electronics," says Newby. "It will just introduce additional weight and losses into the system."

Hybrid-electric propulsion will only gain traction in commercial aviation if the aircraft-level efficiency benefits are greater than the improvements provided separately by advances in engine and airframe technology. "The only reason this concept will work is if it allows you some freedom in the design of your airframe," says Newby. "Simple substitution is not the answer."

NASA Moves Electric-Propulsion Components Closer To Reality

Graham Warwick

Lightweight megawatt-scale drive systems are essential if electric propulsion is ever to succeed in commercial aircraft. Systems much more powerful than those in cars and far lighter than in ships are required.

NASA has launched research into electric motors and power converters at the megawatt level, as these could support the near- or medium-term development of partially turboelectric and hybrid-electric propulsion systems for aircraft up to single-aisle airliner size. Hardware is already being tested.

Electric drives comprise three main elements: power sources, distribution systems and loads that consume electrical power. NASA's focus is on electric machines that can be used as generators (sources) and motors (loads) and power electronics that convert AC to DC (rectifiers) and DC to AC (inverters). Some research is also underway into wiring systems to distribute high levels of electrical power.

NASA's Component-Technology Bets for Megawatt-Scale Electric Drives

- University of Illinois: permanent magnet motor and gallium nitride inverter
- Ohio State University: wet-coil ring induction motor
- NASA Glenn: self-cooled, superconducting wound-field synchronous motor
- General Electric: silicon carbide inverter
- Boeing: cryogenically cooled silicon inverter

Power, weight and efficiency are key goals as aircraft electric drives must be lightweight and highly efficient, to minimize the weight of the thermal management system required to handle the heat generated by electric machines and power electronics. At megawatt scale, electrical losses of only a few percent mean kilowatts of wasted energy must be removed.

NASA research agreements (NRA) have been awarded to the University of Illinois and Ohio State University to develop electric machines with a specific power goal of 13 kW/kg and an efficiency target of greater than 93%. NASA Glenn Research Center is developing a third machine with the goals of 16 kW/kg and greater than 98% efficiency. These power densities far exceed the 2020 target of 1.6 kW/kg set for vehicle electric motors by the U.S. Energy Department.

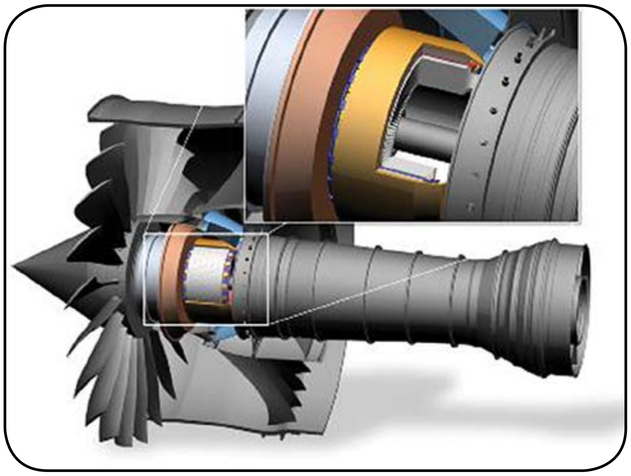
NASA has also awarded NRAs to General Electric and the University of Illinois to develop power converters with a specific power goal of 19 kW/kg and an efficiency target of 99%. A third NRA with Boeing is developing a cryogenic converter with the goals of 26 kW/kg and 99.3%. These power densities compare with the Energy Department's 2020 goal of 14.1 kW/kg for vehicle power electronics.

Concept with boundary-layer-ingesting electric fan in the tail is an option for a 2035-time frame partially turboelectric commercial aircraft.

NASA

The NRAs and internal efforts are pursuing different topologies for motors and inverters. While aviation has largely narrowed its propulsion focus onto gas turbines, and specifically high-bypass turbofans for commercial aircraft, there are many different ways of generating, distributing and consuming electricity.

Three different types of electric machine are being developed: permanent magnet, induction and wound field. Permanent magnet motors are used in electric vehicles and, as the name suggests, use permanent magnets rather than electromagnetic windings in the rotor. The University of Illinois is developing a 1-megawatt permanent magnet synchronous motor. This has an outside rotor with a carbon-fiber overwrap and permanent magnets that spins at 18,000 rpm.

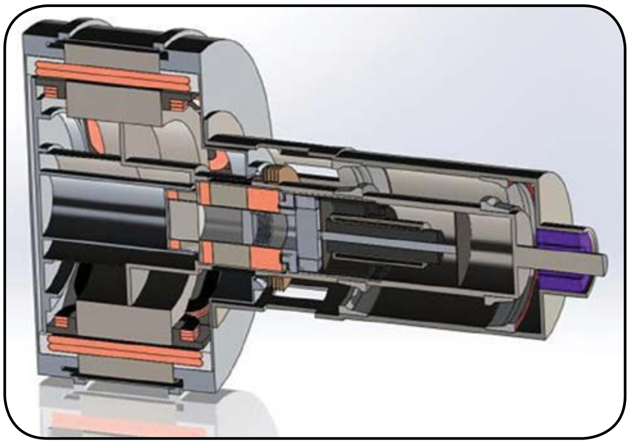


University of Illinois' 1-megawatt motor integrated into Rolls-Royce's Electrically Variable Engine parallel hybrid propulsion system concept.

NASA

The university has conducted full-speed rotor testing and design work on integrating the air-cooled motor into Rolls-Royce Liberty Works' Electrically Variable Engine. This is a parallel hybrid-electric propulsion system in which a battery-powered motor helps drive the turbofan for taxiing, takeoff and idle descent, reducing fuel consumption. Motor sizes of 1-2.6 megawatts have been studied.

When used as generators in turboelectric aircraft, permanent magnet machines pose a challenge—how to shut them down in an emergency. Induction and wound-field machines can be shut down by turning off the electromagnetic field, says Ralph Jansen, an engineer on the electrical aircraft propulsion team at NASA Glenn. Induction machines do not have the same power density as permanent magnet motors, he says, but require less power electronics.

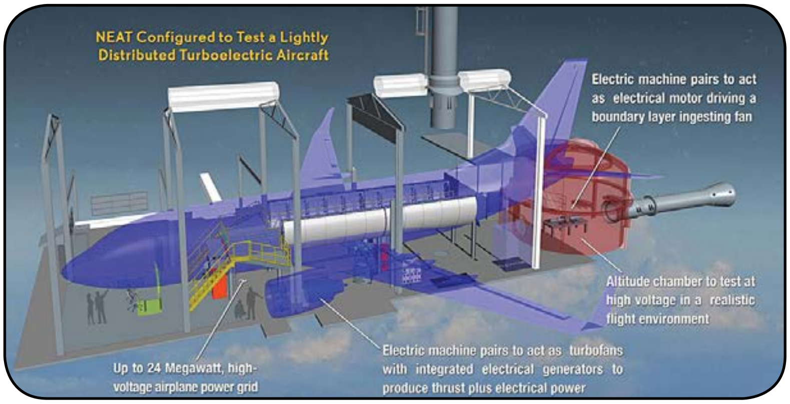


NASA Glenn Research Center's self-cooled, superconducting wound-field electric motor has the cryo-cooler integrated into the rotor.

NASA

Ohio State is developing a 2.7-megawatt ring induction motor. The motor is a 1-m (3.3-ft.)-dia. ring, rotating at 2,700 rpm, in which the outside rotor is driven by magnetic induction from the magnetic field produced by the stator winding. The motor uses a tape conductor that is wound round the stator. The portion of the conductor tape that is outside the active region has direct liquid cooling, allowing high current density in the stator and boosting specific power.

Ohio State is building 300-kW, 1- and 2.7-megawatt prototype motors to validate cooling, manufacturing and performance. The university has also designed a 10-megawatt ring motor integrated with a turbofan. Motor speed is raised to 5,000 rpm, which boosts specific



NASA

The NEAT facility is designed to enable end-to-end ground testing of flight-weight electric powertrains for Boeing 737-size aircraft.

power but complicates structural design and increases windage losses as speeds in the air gap between rotor and stator approach Mach 1. High motor speeds “make stress a key design driver,” says Jansen.

With higher specific power and efficiency targets, NASA Glenn’s 1.4-megawatt wound-field synchronous motor combines a self-cooled superconducting rotor with a slotless stator. This boosts power density and efficiency without incurring the weight penalty of external cryocooling. In generator mode, the wound-field machine can be shut down by deenergizing the field winding and without having to decouple the machine from its driveshaft.

High-temperature superconductors are used for the rotor winding, providing field strength above those possible with permanent magnets and conventional conductors. The cryocooler that cools the superconductors is integrated into the rotor. The 0.4-m-dia motor spins at 6,800 rpm, keeping rotor surface speeds relatively low compared to the other two machine types. This allows a direct-drive option in some aircraft configurations, says Jansen.

The jury is still out on whether power should be distributed as DC or AC. “We still need to compare them,” says Jansen. “If the source is a battery, then it is clear DC makes sense. If the source is a turbofan, it works with AC or DC. There is work to be done to figure out which is best...[and] it gets down to the types of machines used.”

Also to be determined is the voltage used for power distribution. Increasing voltage reduces current and allows smaller, lighter wires, but raises the risk of shorting. At high altitude and low pressure, arcing occurs at much lower voltages than at sea level. The highest voltage used in aircraft now is 540 (±270) volts, but distributing megawatt-scale power in a single-aisle aircraft will require higher voltage.

“Near-term we are looking at the 1,000-3,000-volt range,” says Jansen. While sufficient for a partially turboelectric or hybrid configuration, NASA is looking at the 5,000-10,000-volt range for its fully turboelectric N3-X large commercial aircraft concept. “That is comparable to ship power systems, but they operate at sea level,” he says. At 2,000 volts DC, cable weight to deliver 1 megawatt over 150 ft. would be reduced to 200 kg from 900 kg for a 540-volt system, NASA says.

The NRA work on power converters is focusing on DC-to-AC inverters and assuming input voltages of 1,000 and 2,400 volts DC. An inverter takes DC power from the distribution bus and converts it to controlled, variable-frequency AC that both drives the motor and regulates its speed and torque.

“There has been real progress in the converter arena with two new materials: silicon carbide [SiC] and gallium nitride [GaN],” says Jansen. “You can now buy commercial integrated power switches that you can build into converters that bring improvements in performance and reductions in weight.” SiC and GaN switches can operate at higher frequencies with lower losses, increasing efficiency.

GE is building a 1-megawatt inverter that uses SiC switch technology to convert a 2,400-volt DC input to three-phase AC output. The device uses GE’s 1.7-kW metal oxide semiconductor field-effect transistor power modules. The University of Illinois is building a 200-kW “flying capacitor” device that uses GaN-based field-effect transistor switches and is scalable to a 1-megawatt system. Bus voltage is 1,000 volts DC.

Both of these inverter types are liquid cooled. Boeing, meanwhile, is developing a cryogenically cooled 1-megawatt inverter aimed at meeting higher specific power and efficiency goals. This uses off-the-shelf silicon semiconductors. Phase 2 of the project is underway with fabrication of a liquid-nitrogen-cooled 200-kW inverter for risk reduction. Phase 3 will involve construction and test of a 1-megawatt inverter.

The NRAs will be completed in fiscal 2019 and the internal NASA work by 2020, says Jansen. The planned next step is to build the electric machines and power converters into a megawatt-scale drive system that can be tested in the NASA Electric Aircraft Testbed (NEAT) at Plum Brook Station in Ohio. NEAT is being developed to enable end-to-end testing of full-scale, flight-weight ambient and cryogenic electric powertrains for Boeing 737-size aircraft.

Boeing Details A Commuter X-plane Plan

Guy Norris

Having spent most of its first century building progressively larger and longer-range airliners, Boeing confirms a small experimental "X-plane" hybrid-electric demonstrator planned for the early 2020s could signal an unprecedented push into the commuter market.

The X-plane plan is being evaluated as part of the company's EcoDemonstrator technology testbed series and, if successful, could open the door to a new generation of small Boeing airliners seating 12-50+. The initiative, if sanctioned, may lead to a new product line from the mid-2020s, effectively taking the manufacturer full circle to its commercial transport roots—Boeing developed the 12-seat Model 80 trimotor, its first mainstream airliner, in 1928.

Although Boeing has previously studied entering the regional airliner field, most recently in the 2000s, the newest initiative is tied to a broader new strategic vision targeting expansion into largely untapped markets with low-operating-cost, fuel-efficient, advanced-technology commuter aircraft. The company first signaled its renewed interest in developing technology for this sector in April when Boeing emerged as an investor behind plans by Washington-state startup Zunum Aero to construct a prototype powertrain for a hybrid-electric small regional airliner (AW&ST April 17-30, p. 57).

New Directions

- Boeing studying potential commuter aircraft prototype for EcoDemonstrator
- Hybrid-electric propulsion in development by Zunum Aero
- Development targets 12-50-seat, short-range market
- Commuter concept supported by autonomous system ground and flight tests

Despite Boeing's disclosure of a possible all-new EcoDemonstrator at the Paris Air Show in June, it was widely assumed the research program would support hybrid propulsion developments for Zunum as well as future single- and twin-aisle Boeing airliners. However, the relationship has assumed far greater strategic significance following confirmation that Zunum is focused solely on the propulsion system and Boeing will be principally responsible for the airframe and systems integration.

Zunum is presently developing a ground-based "copper bird" test rig for its intended megawatt-class propulsion system, and plans to flight-test the technology on a modified twin-engine aircraft in 2018. However, the true test will come when the advanced propulsion and airframe features will be combined in the planned EcoDemonstrator.

"We may do a purpose-built demonstrator where we do a prototype of an airplane," says Mike Sinnett, vice president of Boeing Commercial Airplanes Product Development. "It could be that the EcoDemonstrator following 2019-20 is more of a prototype of a lightweight commuter. Boeing Commercial Airplanes has not really participated in that kind of thing before. It would be a sort of X-plane," he adds.

The initial aircraft is expected to have electric-driven, ducted-fan propulsors powered by battery packs, and a turbine range-extender to generate electricity in flight. However, the longer-term goal is for all-electric operation on shorter flights, or as battery technology improves.

Should tests prove the commercial viability of Zunum's high-power density battery-based hybrid system, then Boeing could use the technology as a springboard for the launch of the new commuter airliner family. While Boeing has offered few specifics about potential approaches to the market, Zunum has indicated the overarching goal is to design a family of regional airliners optimized for shorter ranges than today's turbine-powered aircraft. Zunum's initial target is 700 nm in the early 2020s, increasing to beyond 1,000 nm by 2030 as battery technology improves. The company's goal, and a fundamental driver behind Boeing's involvement, is achieve operating costs up to 80% lower than today's regional aircraft.

The new commuter product line "would be a logical outcome of hooking up with them," says Sinnett."It would be different for us. I'm not saying it is going to happen but that is why we are looking at that. I have talked about our aspirations as a company and wanting to grow, and some of that growth will come in areas where we are not currently playing."

JOE WALKER

Autonomous systems under test in a Boeing-owned Cessna Caravan could help the business case for potential parallel development of a new family of hybrid-electric-powered commuter aircraft.

Boeing was attracted to Zunum's expertise in power train and power conversion, explains Sinnett. "To that discussion we bring the capability of integrating the airplane—the airframe, avionics, certification, and the know-how of how to do that. To us it looked like a really neat way to bring together these capabilities and explore where that might go. The strengths were complementary.

"We have got to a point where technology, capabilities and requirements intersect and there is an opportunity for a new product and new ways to add value. It is very interesting to us. That does represent us really exploring, and it probably represents us being open to opportunities outside the typical mainstream business, and to thrive in the next century of flight," he adds.

The 20-50 seat commuter and utility market is currently made up of an aging fleet of turboprops, many of which are no longer being produced or were made by companies that no longer exist. A 2013 Embry-Riddle Aeronautical University survey estimated that 8,000 new aircraft in this size category will be needed by 2030 and that operators are "looking for performance and design characteristics that their aging fleets cannot provide."

Despite the trend toward "up-gauging" of regional turboprops, Sinnett says the potential could exist for new growth markets in the smaller capacity sectors. "The [Boeing] 777, 787 and [new midsize airplane] are all about point-to-point, but there is also door-to-door in there. What does that mean? How is the expectation of door-to-door capability going to change the technologies we go after and the things we bring to the market?" he ponders.

The timing of the potential commuter EcoDemonstrator in 2021 is designed to coincide with Zunum's test schedule and the completion of two major Boeing technology demonstration programs by 2020. The next EcoDemonstrator, a 777F leased from FedEx, will fly in 2018, followed in 2019-20 by a 787 testbed. Some of the work, particularly focused on the 787, will evaluate increased autonomy functions that Boeing sees as being critical to meeting what many predict will be a critical pilot shortage in the next decade.

"The bigger concern is the availability of pilots with an appropriate level of experience," says Sinnett. "I'm thinking 20 years down the line and, if we get smaller airplanes and if electric-hybrid propulsion makes 20-passenger [aircraft] substantially more cost-efficient than today, then the need for pilots will grow exponentially. The only way to stay out in front of that is to do this kind of work today," he adds.

Initial work to explore automation is underway at Boeing using a ground vehicle and the first of two recently acquired Cessna Caravans. "I firmly believe there are aspects of monitored autonomy that will be required for those smaller vehicles, like how a drone is operated today," says Sinnett. The ground vehicle is being used at Boeing's Moses Lake, Washington, site to test aspects of sensor fusion and data gathering. "There are a number of decisions the pilot has to make every day. We have chosen a subset of those, and are going to teach the machine how to make those decisions. We are not ready to talk about them yet, but we have selected them and are operating them in a simulator and gathering data," he says.

The system will be flown on the Caravan in 2018 in an advisory, rather than a closed-loop, capacity. Further tests of a more refined closed-loop autonomous system will follow on the 787 EcoDemonstrator.

Sinnett concludes, "At some point, we will engage the regulators to see if they want to partner with us in some of the experimentation and start thinking about what the framework might [be] for qualifying these things in an advisory or control capability. The industry is going to have figure this out regardless of what it is."

Rolls-Royce ‘Excited’ By Electric Regional Market

Guy Norris

Rolls-Royce has become the first of the Big Three large engine-makers to reveal active studies of electric propulsion systems for a potential new generation of low-cost small regional airliners that could be developed in the 2020s.

“We are starting to examine whether regional aviation is going to go through a major change as a result of this technology,” says Paul Stein, chief technology officer at Rolls-Royce. “If we can take off and land an aircraft on a very short runway with a very low noise profile, our belief is that this has a chance of starting to steal traffic away from rail because of the low cost per passenger-mile.”

Although General Electric, Pratt & Whitney and Rolls are all embarked principally on fundamental research into electric propulsion, until now most of this has been directed at larger hypothetical commercial applications. Revelations of Rolls’s interest in electric-powered regional transports follows Boeing’s disclosure earlier this year of plans to develop a small experimental “X-plane” hybrid-electric demonstrator in the early 2020s as a possible prelude to entering the commuter market (AW&ST Sept. 4-17, p. 25).

Traffic Stealer

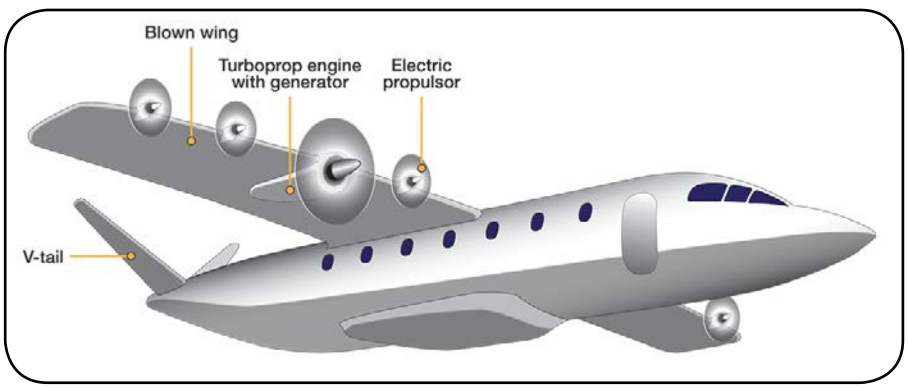
- Rolls-Royce study of hybrid electric regional aircraft indicates a market for 200-1,000-nm regionals
- Hybrid-electric propulsion work in UK includes Adour with embedded starter-generator
- U.S.-based Rolls’s electric propulsion work includes support of DARPA XV-24A demonstrator and Electrically Variable Engine

Speaking at the International Society for Air Breathing Engines 2017 conference here on Sept. 4, Stein added: “We have done some modeling of this—it’s not just an assertion, and it starts to make it look very attractive.”

The Rolls studies are anchored in the belief that lightweight, hybrid-electrically powered commuter aircraft could be operated at dramatically lower cost than similar-size pure jet or turboprop aircraft today.

Like Boeing, Rolls sees the potential for emerging markets in areas with large populations and, in most cases, lacking suitable infrastructure for short- to medium-length transport connections. “This includes countries with an undeveloped rail network such as, dare I say it, the U.S.,” says Stein. Other regions include South America, India, Indonesia and China. “All would benefit hugely from a fresh look at connectivity over 200-1,000 mi. [distances]. We are extremely excited by that,” he adds.

“Electrification is starting to impact more than aircraft systems, but also the propulsive force and the future of aviation,” says Stein. Springboarding from existence capability in its marine business, where it has developed electric and hybrid propulsion systems for submarines and ships, the engine-maker is on a “multipronged journey into aviation, and acquiring a lot of underpinning technology,” he explains.



ROLLS-ROYCE AND COLIN THROM/AW&ST

Rolls-Royce’s hybrid-electric regional concept includes wing-mounted propulsors driven by a generators mounted on twin turboprops.

In the UK, working under a Defense Ministry-funded program, Rolls is testing an "electrified" derivative of the Adour combat aircraft engine. The modified engine is fitted with an embedded starter-generator in place of a standard accessory gearbox, and connected to the high-pressure shaft. "It can directly extract power from the engine or put it in, which means new starting regimes for the engine," says Stein. "That testbed is running in Bristol, [England], and has been a resounding success. We have also moved across a lot of electrical engineers from the marine division to design the permanent magnet motoring drive system."

Rolls also recently worked with Airbus Group Innovations and Cambridge, Cranfield and Manchester universities in England on a series of electric propulsion-related studies. These include the Programmable Superconducting AC Machine demonstration and the Distributed Electrical Aerospace Propulsion study. This latter project focused on a 100-passenger, 2,000-nm-range, Mach 0.75-cruise concept aircraft with a superconducting propulsion system, called E-Thrust, in which a single embedded gas turbine generated electricity to drive six distributed fans.

In the U.S., Rolls's LibertyWorks is studying the Electrically Variable Engine (EVE), a parallel hybrid-electric propulsion system which could use battery power for taxiing, idle descent and to augment takeoff power. Initial studies of motors sized between 1-2.6 megawatts have shown up to a 28% reduction in fuel burn on flights of 900 nm. The University of Illinois also is working with Rolls on the project and has conducted full-speed rotor testing and design work on integrating an air-cooled, 1-megawatt permanent magnet synchronous motor into EVE.

"But we are hoping that the world's first series hybrid flying machine will be the Lightning Strike XV-24A," says Stein, referring to the DARPA-led experimental vertical takeoff and landing demonstrator, which is due to begin flight tests in 2018. Described by Stein as a "major step toward the electrification of flight," the 12,000-lb. Aurora Flight Sciences-built vehicle will be powered by a single Rolls AE1107C turbine and drive system connected to three Honeywell Aerospace-supplied 1-megawatt generators. These will provide electrical power to 24 ducted fans mounted in a tilting wing and canard.

Stein says Rolls "can start to see the use of a boundary layer ingestion (BLI) fan" for larger middle-of-the-market and widebody commercial aircraft. "That seems to be past a tipping point where that system is producing at least a 5%+ fuel-burn improvement in cruise, and it is just a matter of time until we will start to see these systems being introduced." Interest in BLI has grown with NASA's hybrid wingbody N3-X and Airbus E-Thrust future airliner designs, which ingest a large portion of the boundary layer.

However, more recent concepts such as NASA's STARC-ABL (single-aisle turboelectric aircraft with aft boundary layer) and Bauhaus Luftfahrt's propulsive fuselage design that ingest the boundary layer around the rear fuselage have attracted increased interest. "There are other benefits at aircraft level that we can't quite talk about yet, but it already buys itself on purely in terms of propulsive efficiency," says Stein.

"How fast will electrification move? Well at this stage we don't really know. All we do know is we are seeing a relentless step-by-step view that electrification will be a greater and greater part of our aviation world," he adds.

GE Set For Key Electric Propulsion Technology Test

Guy Norris

General Electric is preparing to run a lightweight megawatt-class power inverter, which is a key step toward development of a viable hybrid-electric aircraft propulsion system.

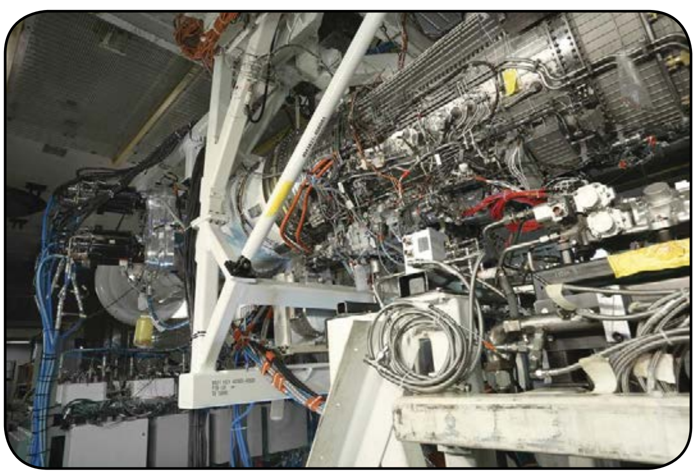
Tests of the liquid-cooled inverter, which will be conducted at GE's Global Research Center (GRC) in Niskayuna, New York, form the next phase of an accelerating company-wide drive to perfect technology for hybrid-electric, turboelectric and all-electric aircraft. In addition to inverters and other forms of distribution, research into advanced power generation, electric motors, energy storage, integration and propulsors is also covered.

The experimental GE inverter is made from a silicon carbide-based switch that can operate at higher frequencies with lower losses, increasing efficiency. The device is designed to convert a 2,400-volt DC input to three-phase AC output and uses GE's 1.7-kW metal oxide semiconductor field-effect transistor power modules. Developed under NASA and U.S. Energy Department-funded programs, the inverter is expected to "achieve industry best power conversion peak efficiency [a goal of 99%] and power density [a goal of 19 kW/kg] for the active components," says GE.

Switching Up

- GE advanced inverter could pave way for viable hybrid-electric aircraft propulsion
- Device designed to convert a 2,400-volt DC input to three-phase AC output
- Inverter uses GE's 1.7-kW metal oxide semiconductor field-effect transistor power modules
- Inverter tests are the latest phase of company-wide electric propulsion technology push

The GE device is one of three DC-to-AC inverter designs being developed and tested under NASA sponsorship; the others are being developed by the University of Illinois and Boeing. All are targeting higher bus voltages than current aviation power systems, which are restricted to a maximum of 540 volts DC (±270 volts). Higher voltages will enable the size and weight of the powertrain to be significantly reduced, making electric propulsion concepts viable. For example, by increasing the power system voltage to 2,000 volts to deliver a megawatt over 150 ft., the weight of the cable would be reduced to 440 lb. compared to 1,990 lb. to deliver the same power using a 540-volt system.



GE

Recent GE electric-propulsion-related research includes power offtake tests of an F110 in which 1 megawatt was generated, 250 kW from the high-pressure turbine and 750 kW from the engine's low-pressure turbine.

In collaboration with the GRC, GE Aviation has also developed and tested a 1-megawatt electric motor/generator. The high-power density device was tested at the company's $51 million Electrical Power Integrated System Center (EPISCenter) facility in Dayton, Ohio, followed by additional evaluation at the Peebles, Ohio, test site where it was used to drive an 11-ft.- dia. Dowty propeller. Opened in 2013, the EPISCenter is designed to test systems of 0.5-2.5 megawatts and can simultaneously support six twin-aisle size aircraft power labs. The U.S. test facility was developed two years after GE inaugurated the Electrical Power Integration Center, a 30,000-ft.2 facility located in Cheltenham, England, focused on power distribution and management.

GE is also revealing new details about a related parallel

research effort in which power extraction tests were conducted in late 2016 using a modified F110 combat engine. Unlike conventional power extraction systems that connected to the high-pressure (HP) turbine, the test engine demonstrated up to 1 megawatt in power offtake from both the low and high spool. GE says the effort, supported by the U.S. Air Force Research Laboratory and NASA, extracted 250 kW from the HP turbine and 750 kW from the engine's low-pressure turbine. "Equally important, this megawatt of electricity was extracted while the engine continued to generate conventional thrust and run at altitude conditions," GE notes.

The company's push into more advanced systems for electrical propulsion builds on a growing presence in the commercial and military electrical power sectors. In addition to supporting more than 10,000 power-generation units in current service on aircraft ranging from the Lockheed MartinC130J to the Northrop Grumman RQ-4, the company is completing development of the Electrical Load Management System (ELMS) as well as the backup generator and converter for the Boeing 777X. GE says the 777X power-generation system will generate twice that of the current 777, while the ELMS will control 30% more power in the same size envelope.

Boeing-Backed Zunum's First Aircraft To Be 12-seat Commuter

Graham Warwick

Startup Zunum Aero's first aircraft is to be a 12-passenger regional airliner with hybrid-electric propulsion. With venture-capital backing from Boeing and JetBlue Airways and support from Washington state, the early-stage company is aiming to certify and deliver the aircraft in 2022.

Headquartered in Kirkland, Washington, Zunum emerged from stealth mode in April with the stated goal of rebuilding the atrophied U.S. regional air transport market with a family of commuter or commercial aircraft somewhere between 10 and 50 seats that have electric propulsion for low operating costs.

Inside Zunum's First Hybrid-Electric Regional Aircraft

- 12-seat economy or nine-seat business/economy configuration
- 700+ mi. range, 340-mph speed on current battery technology
- Targeting operating costs of 8 cents per seat mile, $250 per hour
- Similar size to the PC-12, but 3-5 times lower operating costs

"We have been fairly cagey on what our first product might be. Now we are saying the first aircraft we are bringing to market is going to be a regional-size, up to 12-passenger commuter type," says Matt Knapp, Zunum Aero chief technology officer and co-founder. "You can configure it with six seats for business class, but we see the primary application as being a nine-seat business/economy or 12-seat all-economy commuter aircraft, serving regional markets on point-to-point and hub feeder routes."

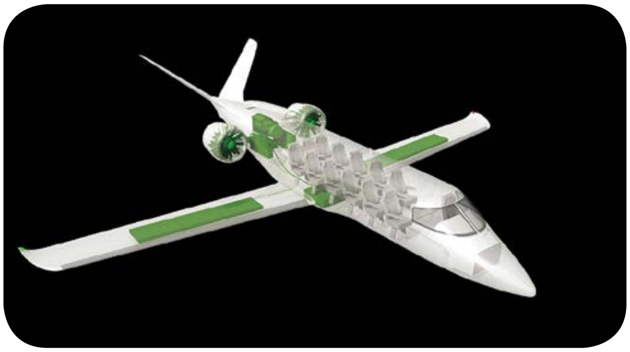
The aircraft has a maximum takeoff weight under 12,500 lb., enabling certification using industry-developed standards under the FAA's revamped Part 23 regulations. Maximum range is more than 700 mi. and cruise speed 340 mph. The aircraft has a 1-megawatt-class series hybrid-electric propulsion system with a 500-kW-class turbogenerator burning jet fuel, charging batteries and driving dual ducted fans. "It is roughly the size of a [Pilatus] PC-12, maybe a bit bigger with the ducted fans," says Knapp.

Zunum is targeting an operating cost—including fuel, electricity and batteries—of 8 cents per seat mile, or $250 per hour. "That is an unbeatable number," he says. "You cannot operate a [Boeing 737] for that if you are flying 300-500 mi. It would compare closely with the [Bombardier] Q400 if you are operating at 300-400-mi. range, and it would be 3-5 times cheaper than running similar-size aircraft, be it a PC-12 or a [Beechcraft] King Air."

Zunum is aiming for 2022 certification and delivery of its initial 12-passenger hybrid-electric commuter aircraft.

ZUNUM AERO

That reduced operating cost comes from the lower price of grid electricity versus jet fuel and the higher efficiency of electric drivetrains versus gas turbines. Batteries account for less than 20% of the aircraft's maximum takeoff weight, but their energy density is low compared with jet fuel, so the turbogenerator acts as a range extender. Only 800 lb. of fuel is carried, compared with more than 2,700 lb. in a PC-12. Zunum plans to replace the range extender with batteries as technology improves.



ZUNUM AERO

Swappable batteries are integrated into the wings, while the turbogenerator sits between the ducted-fan propulsors.

Zunum believes dramatically lower operating costs can revitalize a regional air transport system that has contracted as aircraft have increased in size.

"Back in 1980, there were close to 300 small carriers in this country, and they were operating things like the Beech 1900. They averaged about 20 seats and about 150-mi. stage lengths. For those of us that travel, that is almost unheard of now," Knapp says. "There are now well less than 300, and they are averaging 60 seats and 450-mi. stage lengths. They are not called regionals anymore."

These airlines now fly large turboprops and regional jets. "They basically left the regional market, because now they are filling that many seats," he says. "They are using the major airports. They need the longer runways." The regional market has been left without an economically viable aircraft to serve it, Zunum argues.

"What we have seen is the door-to-door times are worse than they were 50 years ago, and we have left communities without any access to air service," he says. "A lot of secondary cities have seen their air service decline as the airlines have pulled out of hubs or combined their hubs."

One solution could be high-speed rail, but "that is just a concentrated mode [of transportation]," Knapp argues. "It serves two highly dense hubs and does not really work for regional." Road travel is the other alternative, "but there is a physical speed limit, so that really leaves air," he says. "Air is a fantastic mode for regional. It is highly distributed. The infrastructure is in place. You just need an economically viable way to serve this market, which is what we are proposing with our hybrid-electric regional aircraft."

Zunum believes it can bring mainline-type economics to routes shorter than 700 mi. by the early 2020s. "As batteries improve, our speed gets faster, range gets longer and our costs come down," says Knapp. Hybrid-electric, ducted-fan propulsion will also significantly reduce emissions and noise.

"Noise is a major consideration," he says. "If you were to start flying a lot of King Airs or Q400s in and out of local airports, people are going to complain. The very recognizable and not typically welcome drone of the turboprop is one of the primary reasons why we are looking at ducted fans to bring that noise down, so we can serve community and regional airports without impact."

Zunum's 2022 Aircraft by the Numbers

Weights (lb.)

Max. takeoff	<12,500
Max. payload	2,470
Standard fuel	800
Battery weight	<20% of MTOW

Performance

Max. cruise speed	340 mph
Max. range	>700 mi.
Max. altitude	25,000 ft.
Takeoff distance	2,200 ft.
Landing distance	2,500 ft.
Time to 25,000 ft.	18 min.
Stall speed	73 kt.
Max. power	1-megawatt class
Emissions	<0.3 lb. CO_2/ASM
Sideline noise	65 EPNdB

Source: Zunum Aero

Performance goals for the initial aircraft are based on the energy densities being achieved with lithium-ion batteries now coming out of Tesla's "Gigafactory," Knapp says. "That is something that we could fly on right now, though we might increase the electric generation a bit or decrease the range a bit to match them. But batteries have been improving at a pretty reliable rate, so we are prepared to fly with batteries that will be available in the next year or two."

The series hybrid power-train architecture is agnostic to battery technology, he says. The batteries are housed in modules, which are installed in the wing and can be switched out as technology improves. The aircraft could even be

ZUNUM AERO

The 2022 aircraft is similar in size to a Pilatus PC-12, but Zunum is aiming for 3-5 times lower operating cost.

rewired at a C check to operate at a higher voltage, Knapp suggests .

"We are picking the correct architecture for what is available today, for what we need to certify and sell, but leaving our options open," he says. "Really the only decisions are that it is going to seat this many people and fly this fast, which dictate the aerodynamics. Beyond that, it is a modular system, and we are not locking ourselves into any one aspect of it."

Zunum's intent is to allow the operator to recharge the batteries or swap them between flights for a faster turnaround. "That is a great design challenge," says Knapp. "That is part of our technology that we are not releasing details on at the moment."

The company has decided to develop its own motor, but has a request for information out to manufacturers for the turbogenerator. "We have invited them to bid on both the turboshaft as a piece or the generator as a piece or, preferably for us, on combining them," he says.

Zunum is working toward a preliminary design review in 2018 and a critical design review in 2019. "For us, the big milestones are setting a high-power 'copper bird' ground-test facility for the power train by the end of the year," says Knapp. "Following that will be a flying testbed, which is a converted airframe with an electric power train in it." Flight tests are planned for 2019.

Zunum's plans include developing a larger and longer-range 50-seat hybrid-electric regional airliner.

ZUNUM AERO

The company has "strong confidence" in its low operating-cost projections based on the savings achieved from using hybrid-electric propulsion in other modes of transportation such as buses. "Some of those don't carry across, such as regenerative braking, but there are substantial reductions in operating costs and substantial increases in operating efficiency, especially at regional range," he says. "The low operating costs of the motors are not a big unknown."

Knapp has described Zunum as primarily a propulsion company, and it is hoping to work with an established airframer to produce the aircraft. "We are looking for potential partners to do the airframe," he says, but will not be drawn out on the extent of Boeing's involvement. The "plan of record" remains to build up a team able to do the "full-stack" development of a complete aircraft, Knapp says, adding: "But we are actively looking for potential partners in the detailed design and build of the aircraft."

Startup Ampaire Takes Retrofit Path To All-Electric Regional

Graham Warwick

Startup Ampaire is taking a "very pragmatic approach" to developing an electric-powered regional aircraft, says CEO Kevin Noertker, who co-founded the Los Angeles-based company in March 2016. The company promotes a sleek, ultraefficient concept called the Tailwind, but its first electric aircraft will be much more modest and practical.

"Just as Tesla started with the Roadster, based on the Lotus Elise, the first step for Ampaire is to do a retrofit into an already-certified aircraft and obtain supplemental type certification [STC] for the electric drivetrain," he says. Performance will be limited, but will improve as technology advances.

Ampaire is focusing on power train development and plans to fly an experimental testbed—a modified six-seat, 5,000-lb. aircraft—next year, to reduce risk. The company is aiming to certify its first product by the end of 2020, Noertker says—a nine-seat passenger and cargo aircraft based on a "common turboprop."

The company was founded by Noertker, who previously worked in Northrop Grumman's advanced technology group, with Chief Technology Officer Cory Combs and Chief Financial Officer Ryan Bilton. The eight-strong team includes airframe, power train and certification engineers from SpaceX, Virgin Orbit and electric car startup Faraday Future.

Ampaire is operating within the Los Angeles Cleantech Incubator and is a portfolio company of Starburst Accelerator, which is focused on providing aerospace startups with access to seed funding and venture capital.

Ampaire's longer-term Tailwind all-electric airliner concept emphasizes aerodynamic efficiency to minimize energy consumption, with a clean high-aspect-ratio wing and boundary-layer-ingesting ducted propulsor to reduce drag.

AMPAIRE

The company joins startups Zunum Aero and Wright Electric in pursuing the vision of electric airliners. Backed by Boeing and JetBlue Airways, Zunum is aiming to certify a 12-passenger hybrid-electric regional aircraft in 2022. Wright is working with EasyJet to define a 120-seat, all-electric ,short-haul airliner for entry into service within a decade.

But Ampaire's approach is to rely on existing technology. Noertker says available electric motors with power densities greater than 5 kW/kg are sufficient. There are battery manufacturers claiming energy densities of more than 400 Wh/kg at the cell level, but the 350 Wh/kg available today is viable, he says.

Battery energy density limits the initial aircraft to a range of 100 nm, plus reserves. "Our approach is rooted in feedback from potential future customers," says Bilton, adding that Ampaire has letters of interest for "over 120 aircraft" from seven airlines now flying routes under 100 nm with turboprops or piston twins optimized for longer ranges.

"That range will cover the essential flights that are the pain point for our customers," says Bilton. The aircraft's marketing promise is operating-cost savings of up to 25% over existing aircraft, based on the relative prices of grid electricity and aviation fuel and the greater reliability and lower maintenance costs of electric drives.

While the original engine and fuel system will be removed, the need to keep maximum takeoff and landing weights the same as the certified aircraft limits the weight of batteries that can be installed. "In certain cases, customers can remove passengers and add batteries for more range," says Noertker.

Electric propulsion will also eliminate inflight "tailpipe" emissions and combustion engine noise. Initially, Ampaire plans to match the power train to the existing propeller rpm, "but we have future opportunities to more drastically modify the propeller design for slower rpm to decrease noise," he says.

Although it is not revealing which aircraft it plans to modify, Noertker says Ampaire already has two aircraft in-house for ground testing, one for use as an iron-bird test rig and one for taxi testing. After the next, Series A, round of fundraising, the company plans to buy a flyable airframe for flight testing.

Flight hardware for the experimental testbed is also in-house, and the company is looking at a number of suppliers of components for the production aircraft. Ampaire plans to hold the STC but has talked with other companies that perform STC modifications about establishing a global installation network.

Ampaire won the Airbus-sponsored aerospace prize at the Hello Tomorrow 2017 Global Startup Challenge in Paris in October. The 2016 winner was German electric vertical-takeoff-and-landing aircraft developer Lilium, which went on to raise $90 million in Series B funding to develop its Lilium Jet.

"We are not as capital-hungry," says Noertker. "We don't need $100 million."

Editor's note: This article was updated to clarify that Ampaire has letters of interest from seven airlines.

Airbus E-Fan X To Pave Way For Electric Regional Aircraft

Graham Warwick

The potential for regional aircraft with lower operating costs, emissions and noise that can bring air transport closer to customers is the driving vision behind Airbus' plan to fly a hybrid-electric propulsion demonstrator in 2020.

The European manufacturer has partnered with Rolls-Royce and Siemens to fly the E-Fan X, a BAe 146 regional airliner modified to flight-test a 2-megawatt, serial-hybrid propulsion system—eight times more powerful than the highest-power electric aircraft now flying.

The E-Fan X could pave the way for a 50-100-seat hybrid-electric regional aircraft to enter service by 2030-35, says Mark Cousin, Airbus head of flight demonstrators. But the manufacturer's ambitions go further. Work is already underway with Siemens to develop a 10-20-megawatt superconducting power train. "Our real aim is a next-generation single-aisle with 20-40 megawatts," he says.

Inside Airbus' hybrid-electric X-plane

- Rolls-Royce AE2100 turbine drives integrated 2.5-megawatt generator
- Airbus-developed battery provides 2 megawatts of power
- 3,000-volt DC power distribution reduces wiring size and weight
- Siemens 2-megawatt motor drives AE3007 fan in modified nacelle

Revitalizing regional air transport is the vision already articulated by U.S. startups Zunum Aero and Ampaire, which are developing small electric and hybrid-electric commuter aircraft that promise significant cost savings over short routes.

Airbus and its partners believe electric propulsion could allow regional aircraft to compete with rail transport. Cousin says several airlines have already expressed interest in the technology, particularly if the future cost of electricity becomes cheaper as new forms of generation emerge.

"Quieter aircraft using shorter runways than today's regional turboprops and jets would allow us to move air transport closer to communities and connect city pairs more efficiently so we can start stealing traffic from rail," says Paul Stein, Rolls-Royce chief technology officer. "This is particularly true in emerging economies."

The BAe 146 has been chosen for the E-Fan X because it has four engines, and its ALF502 turbofans are the right size for one of them to be replaced by a 2-megawatt electric-driven fan. Based on initial testing, Cousin says, a second engine could be replaced.

The three companies are self-funding the project but asking the UK government for financial support because of the "alignment of the partners," says Cousin. "We have provisionally selected the 146 as the platform, and the intent is for most of the work to be done in the UK. We have the option to do it on an Airbus platform if it does not work out," he says.

Siemens will supply the electric motor and its power electronics; Rolls-Royce will contribute the gas turbine, integrated electrical generator and its power electronics; and Airbus will provide the power distribution, battery and control systems and be the overall integrator.

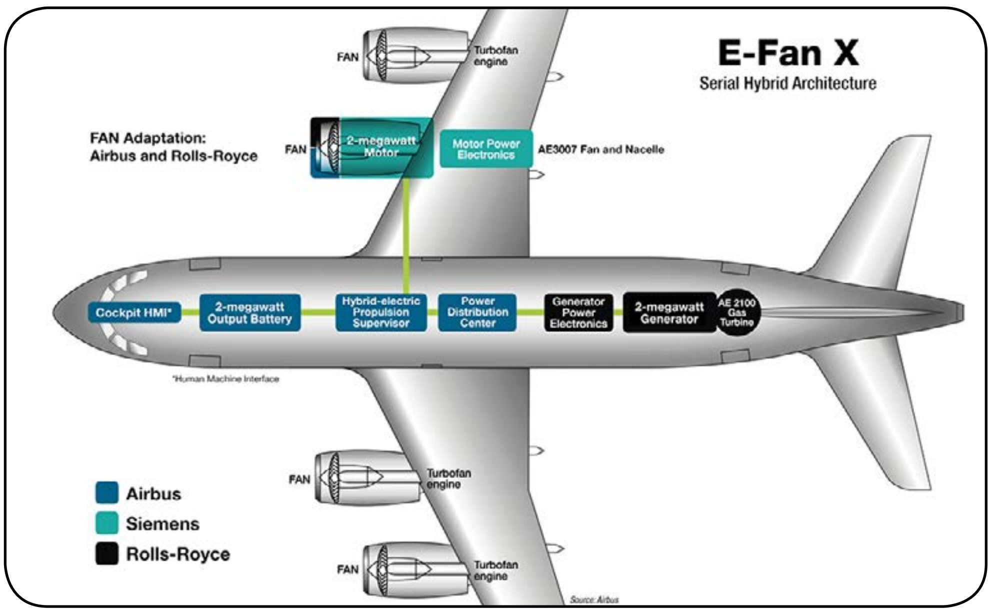
The electrically driven Siemens fan will be fitted into the starboard inner engine nacelle, painted green in this concept.

AIRBUS CONCEPT

The Rolls AE2100 turboprop powering the C-130J airlifter is mounted in the rear cabin of the 146, its inlet installed behind the wing. The propeller gearbox is removed and the engine's power turbine instead drives a 2.5-megawatt generator. In a later version, the generator will be driven directly by the engine shaft, producing a fully integrated turbo-generator, says Stein.

Designed by Rolls itself, the generator is oil-cooled using supercritical carbon dioxide as the intermediary exchange fluid. This builds on Rolls-Royce Liberty Works' power system for Aurora Flight Sciences' XV-24A LightningStrike. Scheduled to fly in 2018, this is a high-speed vertical-takeoff-and-landing aircraft with distributed electric propulsion, Rolls' AE1107 turboshaft driving three 1-megawatt Honeywell generators via an accessory gearbox. The AE1107 uses the same core as the AE2100.

The E-Fan X's serial-hybrid architecture allows the turbo-generator to operate continuously at its most efficient speed, supplying 3,000 volts of DC power to the motor and battery. Weighing about 2,000 kg (4,400 lb.), the battery is housed in the forward and aft lower cargo hold and is sized to produce 2 megawatts of power for takeoff and cruise, says Airbus. No energy-density figure is given, but the plan is to use available technology, not advanced batteries.



AIRBUS

"We are not betting on batteries, we are betting on hybrid-electric," says Cousin. "The generator produces power for the cruise and the battery adds power for takeoff and climb. We can do something with today's battery technology and not have to wait for experimental battery technology."

In addition to using batteries to boost power on takeoff, pure electric propulsion during descent would reduce noise as well as fuel burn and local emissions. "The objective is to reduce the overall environmental impact. We are aiming for a significant reduction in fuel burn per sector, in the double digits," he says.

To reduce the electric current and minimize the size and weight of wiring, electronics and machines, the power-distribution voltage is far higher than the ±270 volts DC used in the latest aircraft. Voltages as high as 3000 volts are already used for electric propulsion in ships and vehicles and will be essential for future 10-megawatt-plus power systems, but in aircraft such high voltage introduces the risk of electric arcing at high altitude, known as the corona effect. The solution is expected to involve a mix of pressurization, insulation and separation.

Electric power will be supplied to the starboard inboard nacelle where Siemens' power electronics will convert DC back to AC to power the 2-megawatt SP2000 liquid-cooled motor. This will drive the fan, taken from the Rolls AE3007 turbofan, which is part of the same family as the AE2100. The nacelle outer mold line will not be changed, to help with airworthiness approval of the modified 146.

The main challenges of the E-Fan X program, says Cousin, include building electric machines with a 10-times-higher power-to-weight ratio. The most powerful motor now flying is Siemens' SP260D in the Extra 330E aerobatic aircraft. This produces 260 kW and weighs 50 kg (110 lb.) but is eight times smaller than the E-Fan X mo-

tor, says Frank Anton, head of Siemens eAircraft. “We believe we can get there,” says Cousin.

Related technical challenges to be overcome include the electromagnetic interference generated by a 2-megawatt electrical system, thermal management of the motor, power electronics and turbo-generator, and partial discharge and radiation effects.

Another major challenge highlighted by Cousins is certification. “We are getting great support from [the European Aviation Safety Agency], which really understands that we want to set up the right certification system for hybrid-electric propulsion, one that will be meaningful for the next 5-10 decades.”

A third major challenge “is getting a program kicked off with an OEM that says ‘yes, I want to do a hybrid-electric aircraft,’” says Cousin. “We need a demonstrator to address all those challenges,” he says, acknowledging that the goal of flying the E-Fan X in 2020 is aggressive.

“It is important to fly; you can only learn with a flying demonstrator,” says Anton.

DARPA, NASA, Airbus Among Those Developing Electric-powered Aircraft

Graham Warwick

From X-plane demonstrators to prototypes, a wide range of electric-powered aircraft are set to fly in the next few years as industry seeks to establish whether the technology is ready to enter mainstream aviation.

Leading The Charge

Electric-powered aircraft are nearing the test phase, using various configurations

Technology readiness remains an issue

Entry into national airspace timing is uncertain, depending on obstacles encountered

Airbus E-Fan X

Serial hybrid propulsion

Rolls-Royce AE2100 turbine with 2.5-megawatt integrated generator

Siemens 2-megawatt motor driving AE3007 fan

3,000-volt DC power distribution

2-megawatt-output battery (Airbus)


AIRBUS CONCEPT

Airbus CityAirbus

Electric VTOL

Eight 100-kW direct-drive motors

140 kWh of energy in four 140-kW batteries

Eight ducted, fixed-pitch propellers in coaxial pairs


AIRBUS CONCEPT

NASA X-57 Maxwell

Distributed electric propulsion

460-volt DC power distribution

Dual-redundant, 16-module battery pack

60-kW wingtip cruise motors

12 leading-edge high-lift motors with folding props


AIRBUS CONCEPT

DARPA/Aurora XV-24A LightningStrike

VTOL distributed electric propulsion

18 variable-pitch ducted fans

Six variable-pitch ducted fans

Tilting foreplane and wing

AC-coupled power distribution

Three 1-megawatt Honeywell generators

Rolls-Royce AE1107 turboshaft


AIRBUS CONCEPT

Batteries Ready To Power Electric Regional Aircraft, Says Eviation

Graham Warwick

Is battery technology ready to power a small regional aircraft? Israeli startup Eviation Aircraft believes it is, and it has selected South Korea's Kokam to supply lithium polymer batteries to power a full-scale prototype of its Alice nine-passenger, all-electric regional aircraft by early 2019.

Kokam supplied the batteries for the Solar Impulse 2, which flew around the world on solar power in 2015-16. Eviation CEO Omer Bar-Yohay says Kokam supplies a "stable, safe, high-energy-density" cell in a pouch form factor that allows the company to pack a large battery into the Alice. "We are building a big battery so as not to overstress it," he says.

Using the Kokam cells, which have an energy density of 260 Wh/kg, Eviation will build up a battery system with a capacity of 900 kWh. This will give the Alice a range of up to 650 nm at a cruise speed of 240 kt. and altitude of 10,000 ft., says Bar-Yohay.

"We are claiming 1,000-km range [540-nm] so as not to overpromise, and the Alice will have that range from the get-go," he says. Range is expected to increase over time with improvements in battery technology, but "the first few aircraft will use Kokam batteries," he says.

To achieve that range, the battery will be tightly integrated into the structure and will make up about half the aircraft's maximum takeoff weight. "[The pouch format] allows us to fit the dimensions of the cell to what we need to better optimize capacity," says Bar-Yohay. While not load-bearing, "the battery has a structural function, so shape matters a lot," he notes.

The unpressurized aircraft's cross section, with a flat lower fuselage, serves both aerodynamic and structural functions, providing more space under the floor for batteries. The cabin will also be wider than in competing aircraft. "The flying experience has to change," he says, adding, "We have worked with one of the biggest design companies on the cabin."

Full-scale prototype of the nine-passenger Eviation Alice is expected to fly by early 2019.

EVIATION AIRCRAFT

Eviation is aiming Alice at existing operators flying piston- and turboprop-powered aircraft such as the Cessna 402, Beechcraft King Air and Pilatus PC-12 on regional services under 500 nm. "We expect the direct operating cost to be very low," says Bar-Yohay. The company is aiming for $200 per hour or less, based on U.S. industrial electricity prices. This compares with $600-1,000 per hour for existing aircraft, he says. "And the buying price will not be dramatically different to a similar-size aircraft," he adds.

Alice will be recharged between flights, and Eviation is testing both 300-kW and 400-kW chargers. "Our goal is to recharge 1 hr. in the air with 0.5 hr. on the ground," says Bar-Yohay. Fast charging can reduce battery life, "but it is a very big battery, so [it] will not take a beating." The electric drivetrain will work at a higher voltage than the electrical systems in current aircraft, he says.

The Kokam cells have been tested to more than 1,000 cycles, he says, and Eviation is assuming the battery in Alice will be replaced after 1,000 cycles, equivalent to 3,000 hr. of flying. Replacement cost will be around $250,000, or about half of the direct operating cost, and "not dramatically different to overhauling a piston engine," he says.

The startup has flown a 650-lb. unmanned, subscale aircraft to validate the aerodynamics and flight control of the Alice, which has three 260-kW motors driving propellers on the wingtips and tail. The wing-mounted propellers operate in the tip vortices to improve efficiency. The company plans to certify Alice to the FAA's revamped Part 23 regulations.

Alice has three 260-kW electric motors powering wing- and tail-mounted pusher propellers.

EVIATION AIRCRAFT

Eviation is now building the prototype, called "Alice for TC" (type certification), says Bar-Yohay, and risk-sharing partners are on board for the composite structures, fly-by-wire computers, flight-control logic and flight deck. "They have all worked on something like this before," he adds. Landing gear is supplied by Italy's Magnaghi Aeronautica, which produces the gear for the similarly sized Piaggio P.180 Avanti.

Eviation is being funded by private investors up through first flight of the prototype, after which Bar-Yohay says the company plans a public offering to raise the financing for certification and production. "We are building the full-scale aircraft as fast as we can," he says. "We expect to test the drivetrain by the end of the summer and the integrated system—batteries, motors and controllers with the fly-by-wire flight controls—within 2018. Flight test will be in late in 2018 or early 2019."