aero-online.org

April 2013

# AEROSPACE ENGINEERING™

## Eurocopter's $X^3$ Technology Demonstrator

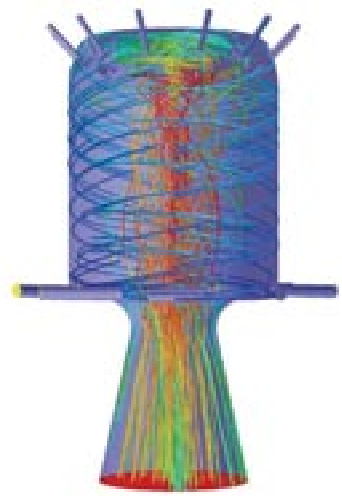
## UAVs Take on Fuel Cells

## Nanostructured Materials

SAE International®

## Top Articles of the Month

### Vortex rocket engine reaps the whirlwind



Orbital Technologies' vortex-cooled liquid engines inject liquid oxygen into the combustion chamber in such a way to generate a stable, tornado-like cyclonic flow that confines the combustion to the central region of the chamber, which protects the surfaces. Read more at ***www.sae.org/mags/aem/11560***.

### Tracking the health of aircraft electrical generators

Researchers have come up with basic modules of a proposed diagnostic and health-management system architecture based upon data-driven algorithms. Read more at ***www.sae.org/mags/aem/1166***2.

### Adoption of software-defined radio slower than anticipated

The proliferation of frequencies has driven a lot of interest in software defined radio (SDR), but the idea of using many programs on a single digital platform has not seen the success once envisioned. Read more at ***www.sae.org/mags/aem/11640***.

### For the "connected" airplane, young engineers have right mind-set

"I do a lot of recruiting. The kids I'm hiring now are phenomenal. They look at things differently. They're energetic and they're sharp," said John Craig, Chief Engineer of Network Systems for Boeing Commercial Airplanes. Read more at ***www.sae.org/mags/aem/1157***2.

### Advanced out-of-autoclave composites process accelerates curing, enhances adhesion of fasteners

A new IR-assisted advanced out-of-autoclave (OOA) process from Kubota Research Associates reportedly enhances adhesion properties and "significantly" accelerates the curing speed of thermoset resin systems for installing adhesive bonded fasteners onto composite fuselage and metal structures. Read more at ***www.sae.org/mags/aem/11522***.

## IVHM Focus of May Webcast

Ian Jennions

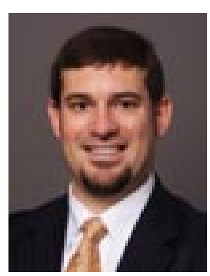
The new field of Integrated Vehicle Health Management (IVHM) aims to improve safety through the use of diagnostics and prognostics to fix faults before they are an issue, as well as improve availability of fleets through better maintenance scheduling.

Developed by plane manufacturers, IVHM expands the concept of selling a product and its spare parts to offering a full-service package, including the product and its maintenance, repair, and overhaul. This approach to commercializing high-value assets requires a thorough knowledge of how airline operators actually use these planes in the field. This is where IVHM technology comes into play.

Rhonda Walthall

Sensors are placed on the asset, and data is captured, transmitted, and analyzed to ascertain the plane's health. Depending on the diagnosis, decisions can be made for maintenance to be performed, with provision for personnel and spare parts, at a time when it's most convenient for the operator, reaping the benefit of early preventative action.

In a May 8 webcast, Taking Data to New Heights: How Airlines, Plane Manufacturers, and Suppliers Are Shaping the Future of Integrated Vehicle Health Management, IVHM will be explored from three different perspectives. The IVHM Centre, **Cranfield University**, will offer an academic view of the subject including educational offerings and research. **UTC Aerospace Systems** will provide a supplier's perspective of utilizing IVHM to improve field service and supply chain management for components of major aircraft systems. **Gulfstream** will discuss the subject of an airplane manufacturer that has IVHM-enabled its latest business jet, the G650. Webcast attendees will be invited to interact with the speakers during the program's live Q&A segment.

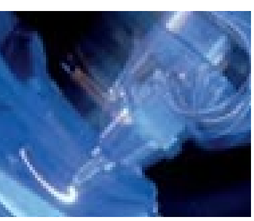


Robby O'Dell

The speakers will be Ian K. Jennions, Director, IVHM Centre, Manufacturing and Materials Department, Cranfield University; Rhonda Walthall, Prognostics and Health Monitoring Manager, UTC Aerospace Systems; and Robby O'Dell, Program Manager, G650 Technical Development, Gulfstream Aerospace Corp. To register for the IVHM webcast, please visit ***www.sae.org/webcasts***.

TRUMPF

# Accelerate your flight plan with lasers

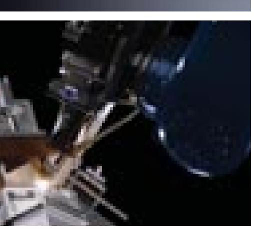


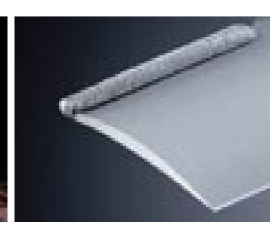
## TRUMPF Lasers

### Trusted quality for the aerospace industry

TRUMPF lasers and laser systems achieve consistent high quality results for countless applications in the aerospace industry. Applications include cladding of turbine blades and vanes, as well as well z-notches, seal seats and casings, welding of seat tracks and cabin and exhaust components, cutting of fuselage stringers and duct work, drilling of turbine blade vane cooling holes, and consistent quality marking of components for traceability. The broadest laser product portfolio in the industry combined with decades of experience makes TRUMPF the right choice for your laser needs.

www.us.trumpf.com



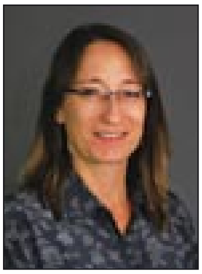


For more information scan the QR code with your smartphone.

**Free Info at http://info.hotims.com/45602-814**

# Editorial

## Under Fire for Progress



As a sign of Boeing's unwavering optimism toward its newest aircraft family, the 787 — the one that at press time had been grounded for nearly three months — The Wall Street Journal reported in early February that the company would "begin piecing together the next version [787-9] of its Dreamliner jet in the coming weeks, even without a fix for what has bedeviled the plane's electrical system or a timetable for resuming flights."

To those who have followed the travails of the 3.5-year delayed 787 program, hearing that production of the new 20-foot longer 787-9 would be commencing with body sections flown in from Japan being fitted to body sections flown in from Italy (the whole of which would then be flown to a Boeing facility in Washington and/or South Carolina to be fitted with other body parts, systems, and componentry made there or somewhere else), it was hard not to squirm in one's seat, like during a scary movie at which at times you feel compelled to yell at the cast to NOT go into the basement.

That said, one of the main reasons Boeing committed to marching on with production of the 787-9 was precisely to stay on course and avoid all the outsourcing and supplier missteps that derailed the 787 for so many years. As supply issues were seemingly fixed or successfully worked around, things began looking up for the 787, so to speak. At the time of the grounding, 50 were in fleet service and the company was ramping up to increase production of the 787 to 10 per month over the next couple years to try to keep up with orders.

Everything was fine, at least until January. For the movie buffs amongst us, it would seem that if Mike Nichols' 1967 movie "The Graduate" were re-made today, the advice whispered into recent-graduate Benjamin's ear would not be "plastics," it would be "batteries."

Or, at least some ground-breaking technological solution that does not involve anything related to the term "thermal runaway," whether it be, truthfully, at 40,000 feet or in your driveway. Seems that no good could really come of that, no matter your altitude.

In fact, that is a good segue into remembering that the aerospace industry is not the only industry to experience growing pains with batteries, which have been hailed as the next great technology breakthrough in terms of energy densities, durability, and an all-around greener world. It was only a little over a year ago that an uproar started about the Chevy Volt's batteries catching on fire, until the National Highway Traffic Safety Administration put that uproar out after a two- or three-month investigation by declaring that "NHTSA does not believe that Chevy Volts or other electric vehicles pose a greater risk of fire than gasoline-powered vehicles."

We don't know what we don't know about batteries, but we probably know more about batteries today than we knew about plastics in 1967.

That said, so far, reports have indicated that both 787 batteries in question were so badly damaged that engineers may never be able to exactly determine the cause of the fires. It is still to be determined if the DOT will settle on a solution to battery fires that focuses on containment (i.e., bigger, stronger, stainless steel boxes; ceramics barriers between cells; and a venting tube to expel fumes outside the aircraft should the need arise. Ideally, the latter solution would not occur while the aircraft is being refueled.) as opposed to addressing the cause.

Even if Boeing's most famous frenemy, Airbus, no longer has an interest in helping to solve the lithium-ion battery problems (it announced recently it has decided not to use that type of battery on its A350), there are plenty of others in the aerospace industry and beyond who are willing to put their heads together for any sort of lithium-ion solution that will ultimately fly.

***Jean L. Broge***
***Managing Editor***

# EXPANDING HORIZONS

## In the last fifty years, only one new transparent plastic has been approved by the FAA for aircraft windows. Ours.

At PPG, innovation for the aerospace industry goes beyond our advanced coatings and sealants that reduce weight for better fuel efficiency. We're launching a new transparent plastic for aircraft windows—the first to be approved by the FAA in 50 years. Lightweight, craze- and fire-resistant, OPTICOR advanced transparency material can be formed into complex shapes while maintaining optical clarity. Larger windows enhanced by our ALTEOS interactive window systems improve passenger comfort and view. AEROCRON electrocoat primer reduces component weight. And, our Customized Sealant Solutions simplify aircraft sealing while reducing process time, waste and weight. Visit **ppg.com** to learn how PPG innovation helps our aviation partners expand possibilities and exceed their performance goals.

**PPG Industries**
Bringing innovation to the surface.™

PAINTS - COATINGS - OPTICAL PRODUCTS - SILICAS - CHEMICALS - GLASS - FIBER GLASS

## NASA Langley Explores Nanomaterials for Next-Gen Structures

Steve Scotti, Chief Engineer for Structures and Materials at NASA's Langley Research Center, borrowed the Boeing mantra "atoms to airplanes" when explaining the wide range of capabilities his area possesses to a small group of media touring the Hampton, VA-based facilities.

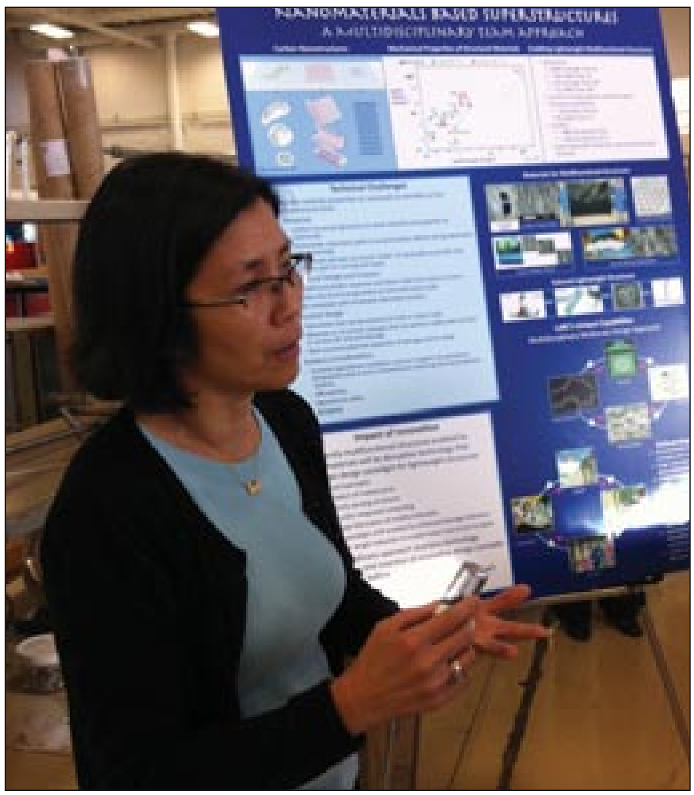
"We actually do that," he said. "We've got people looking at atoms in microscopes, and we can go up to the very large-scale structure, and all the things in between." Capabilities include durability and damage tolerance assessment, materials synthesis and processing, and computational materials design — and, of course, the necessary facilities to perform these diverse tasks. The nearly 800-acre NASA Langley campus includes 240 buildings and 71 labs. As Scotti noted, "A cook needs a kitchen."

One of those "cooks" is Mia Siochi, Senior Materials Scientist at Langley. And one of the main "ingredients" she and other researchers at Langley are examining, particularly in their efforts to reduce the weight of structural elements, is carbon nanotubes.

"For those of us who are working in this area, state-of-the-art is carbon-fiber composites," Siochi said. "So the question is, 'What is next-generation beyond that? And how much more weight can we save?'"

Carbon nanotubes' properties make them a promising candidate, according to Siochi. "What's novel about them is that because their diameter is so small and even though they're only a few microns, you have high aspect ratio, which allows you to carry a lot of weight. Also, the way it's bonded together is conducive for electro-conductivity."

Carbon nanotubes are 1,000 times stronger and about 50 times stiffer than aluminum. They are more than 10 times stronger and about five times stiffer than IM7 carbon fiber. Their current-carrying capacity exceeds copper, and thermal conductivity is about 20 times better than Al and nine times better than Cu. And, significant to Langley's goal of lighter weight, the nanotubes are almost half the density of Al and about 15% that of Cu.



Mia Siochi (pictured) and other researchers at NASA Langley are looking beyond the current state-of-the-art lightweight material — carbon-fiber composites — to promising nanostructured materials, namely carbon nanotube composites. (Photo by Ryan Gehm)

### Dispersion of Carbon Nanotubes for Structural Apps

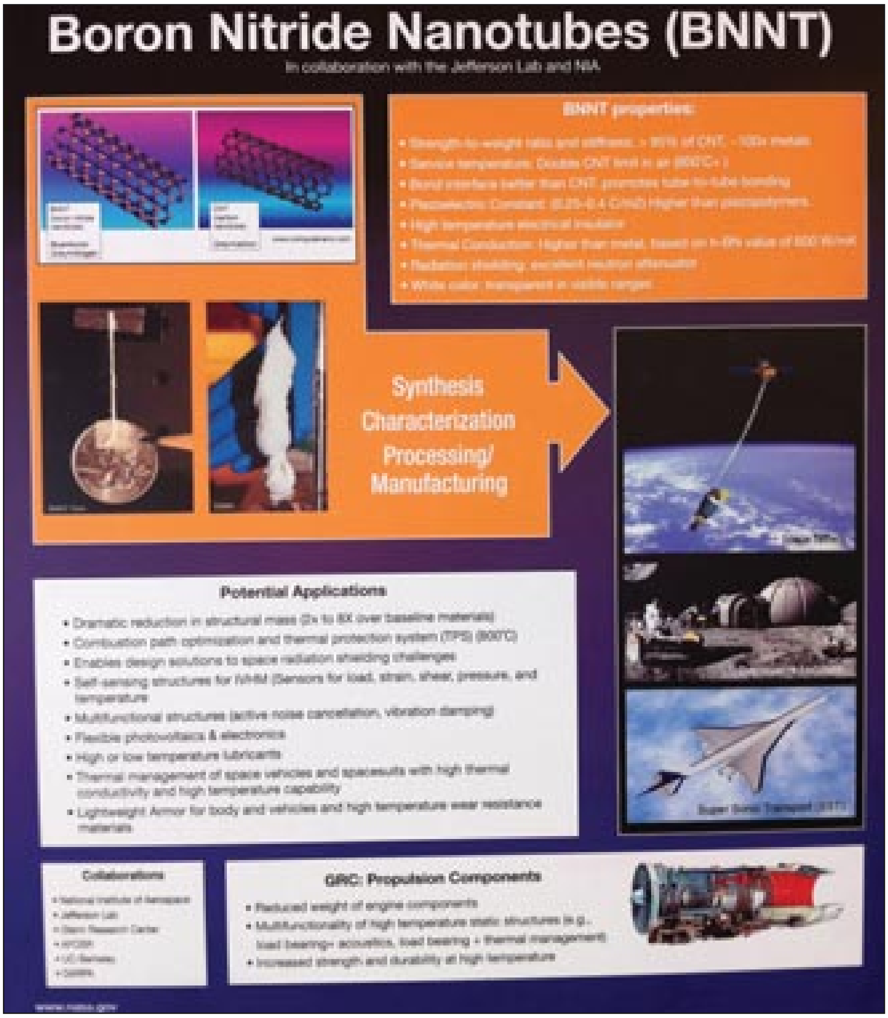
"The challenge, however, is that those properties are measured at the nanoscale," Siochi said. "When we started working with these materials back in around 2000, these cost about $500/gram. At that time, you were lucky to get some. So we were trying to understand how you take advantage of these properties in a structure."

The researchers first concentrated on how to disperse the "very little" bit of the material they had in a polymer matrix. They employed molecular modeling, synthesis, and characterization tools "that allow us to visualize what we make, so when we talk about dispersion, we can actually see it." That progress took about five to seven years, Siochi said.

"One of the big lessons learned is that if we are going to compete with [carbon-fiber] composites, doping a matrix with a small amount of this material is not going to get us there," she stressed.

Carbon nanotube-based composites have generated a lot of interest mainly related to conductivity because that's the "low-hanging fruit," Siochi said: a small amount of this material can greatly boost the electrical conductivity of a matrix. About two years ago, however, Langley researchers determined it was a good time to "redirect attention back to structural properties, which is probably the most challenging piece," said Siochi, because larger quantities of carbon nanotubes, from companies such as New Hampshire-based NanoComp Technologies, had become available.

"They're now available in the volumes that we can consider for making larger parts, so that is what we're focusing on right now. We are working to understand how we take a material like this, in sheets or yarns, and make it into structures," Siochi explained. "The problem is the focus has been [on electrical and thermal conductivity], and structural properties have been [largely] neglected. We're saying, get the structural [part of the equation], and the electrical and thermal will be a bonus because they already do it anyway."




Though less mature than carbon nanotubes, boron nitride nanotubes are also being pursued at NASA Langley because of their high strength and high thermal resistance properties. (NASA)

The researchers are exploring the use of conventional pre-pregging processes to determine how much of what they already know about carbon fiber composites can be translated to carbon nanotube composites for structures. "What is very different is surface area; it's got a very high surface area," said Siochi. "It's soaking up all that resin so you can get it to wet, but the adhesion is not there, so that interface is not optimal at this point."

## Collaborating to Compress Time to Market

Another focus of Langley researchers is to compress the development and insertion cycles of advanced technologies so they make it to market faster. As a point of reference, it has taken about 60 years from the discovery of carbon fibers to where carbon-fiber composites are now — comprising 50% by weight of the Boeing 787. Carbon nanotubes have been on the radar for about 20 years now, Siochi said.

The big question, however, is how to speed up the process. "The other experiment we're doing here is vertical integration — instead of taking a material and developing it in isolation, [then] passing it to the structures people and trying to convince them to use this for design, and then getting this inserted into industry, we actually are using a multi-disciplinary approach," Siochi explained. "On the team, we have people going from computational modeling, to synthesis, processing, characterization, structural design, structural analysis, systems analysis, and we're tied into manufacturers so that we can provide guidance on what can be tweaked to make materials to the necessary requirements.

"And we're also tied into industry, like Boeing and Lockheed, so we know where we can feed this to. The hope is that by having everybody on board from the very beginning, we compress that maturation in the insertion cycle and we can get these emerging technologies into structural elements much sooner than 60 years."

Siochi and other Langley researchers are confident that this collaborative parallel approach, rather than the traditional sequential approach, will be successful in cutting time out of the process. "Because when you do it [sequentially], you're always convincing the next level that this is worth looking at," she said.

These processes and development tools are also relevant for other nanostructured materials, such as boron nitride nanotubes, which Langley is also pursuing. "Besides carbon nanotubes, which are more mature, we also have the capability here to make boron nitride nanotubes," said Siochi. "This is experimental at this point, but the nice thing about boron nitride nanotubes is they have similar properties [as carbon nanotubes]; they're insulating instead of conducting, but they are also better at higher operating temperatures than carbon nanotubes" — 800 °C compared to 400 or 500 °C.

With carbon nanotubes as "a good working example," NASA Langley has the capability to start promoting "all sorts of nanostructured materials," said Rob Bryant, Advanced Materials and Processing Branch Head. "Some of them NASA might need, some of them NASA might not need, but we have the ability with the teaming efforts to transfer those into other industries," he said, calling out the automotive, medical, and tooling industries, among others.

*This article was written by Ryan Gehm, Associate Editor of Aerospace Engineering.*

# Hovering Aircraft Programs

***The AW609 tiltrotor and the X3 compound helicopter offer different technology solutions to the challenge of achieving higher speeds and higher-quality point-to-point air transport.***

by Richard Gardner, European Editor

The basic design parameters of tiltrotor aircraft and compound helicopters have been known since the 1950s, and many prototypes have been built over the years.

The tiltrotor design brings clear advantages in terms of providing optimum performance in all flying modes, with large propellers providing vertical lift for takeoff, landing, and hovering, and also high-speed cruise when swiveled into the horizontal position.

The compound helicopter, combining a large helicopter-style rotor for vertical flight with a small pair of wings and forward-driving propellers for cruise, is more of a compromise but involves a less radical mechanical solution than the tiltrotor.

At face value, the advantages of both types of aircraft are plain to see. They can carry passengers and loads from any open space, such as a city-center helipad or deck-equipped ship, and can then fly at high speed directly to the destination, which can be a similar site. Airports can be avoided completely if need be, or can offer a convenient interchange location for onward travel. The big gain is operating flexibility, with the convenience of a helicopter and the speed and reliability of a fixed-wing aircraft.

So why has it taken so long for this form of transport to arrive on the production line, rather than as a curiosity at an air show?

The answer is to be found alongside other aerospace developments that have enabled such designs to incorporate key weight-saving materials, high power-to-weight-ratio engines, digitized avionics systems, and advanced flight controls.

While the concept may not be new, delivering an attractive, production-standard product that offers significantly greater productivity, versatility, and profit potential is a new development that is now just around the corner, at least as far as the tiltrotor is concerned.

Boeing's V-22 Osprey multirole utility aircraft brought the tiltrotor concept forward for the first time into everyday use. The development, testing, evaluation, and introduction history of this machine was a painful and lengthy experience with many early accidents and incidents, but today the V-22 has matured to become a "must-have" tool in the inventory of the U.S. Marine Corps.

No longer regarded as an obscure design exercise, but a practical aerial transport vehicle with great prospects for further applications in both civil and military roles, the tiltrotor is now being readied for series commercial transport production in Europe in the form of the AgustaWestland AW609. This aircraft was originally a joint venture between Bell and Boeing before Italy's Agusta joined the project with Bell Helicopter

Textron, when the type became known as the BA609. In November 2011, the program became wholly AgustaWestland owned.

## Development Taking Off

AW's location at Cascina Costa, Italy, features a team of 250 representing engineering, flight-test support, prototype assembly, and program management. The facilities include a dedicated hangar, telemetry room, and a development simulator. There is also a special lab capable of testing the flight control system software and hardware.

The scale of the investment in the AW609 underlines the fact that this is not just another speculative high-tech concept project, but is a funded commercial aircraft program with a certification target set for 2016 and first deliveries due late that year.

Two development aircraft are flying, and the pace of systems integration and detailed design refinement is increasing. Aircraft No. 3 will join the flight test program this year, with another to follow in 2014.

The AW609 features a triple-redundant digital fly-by-wire control system, and BAE Systems is supplying an upgraded flight control computer. Pilot demands for this type of flying are high, and some of the potential operating sites, such as high-rise helipads or offshore oil and gas rig platforms, require high levels of concentration, with added risks from cross-winds, local air turbulence, and other site-related restrictions.

Fly-by-wire controls and advanced cockpit systems will give AW609 pilots a high level of situational awareness, and great efforts have gone toward developing a man-machine interface to create user friendly, responsive systems to deliver safe operations under a wide range of conditions.

Asked whether the aircraft would have conventional controls, as in a helicopter, or Airbus-style side-sticks, Richard Luck, AW609 Marketing Manager at Cascina Costa, explained to AE that in bringing the AW609 to market, the center stick, plus a collective control design, offered a familiar piloting layout that would allow an easy transition to tiltrotor flying.

AgustaWestland AW609 tiltrotor development aircraft is being prepared for full-scale production and delivery in 2016.

The Boeing V-22 Osprey is the first tiltrotor transport aircraft to enter production and is highly regarded in the U.S. Marine Corps. (Richard Gardner)

A head-on view of the AW609 with its engines tilted in the takeoff/landing mode.

The aircraft's control laws and flight control software would make the task of flying the aircraft straightforward, as flight-testing on the first two development aircraft has shown. In vertical flight mode for takeoff, the aircraft rises gently exactly as a helicopter would.


The AW609 with engines in the high-speed forward flight configuration.


AW609 development aircraft No. 2 on the flight line.


Eurocopter X3 development prototype showing wing tip-mounted propellers.

The engine pods gradually swivel as the transition begins at around 40 knot of forward speed, and then the fuselage remains horizontal as speed builds up. Top cruise speed offers a 30% advantage over today's civil helicopters, with a maximum of around 270 knot.

But the tiltrotor benefits don't stop there, as the AW609's pressurized fuselage enables it to fly above the weather, at 25,000 feet, offering the smooth transport experience that is standard today in turboprop commercial aircraft, but with the bonus of being able to land and take off almost anywhere. Another bonus over most conventional helicopters is that it will be certified to fly in icy conditions.

Transitioning back from cruise to landing is equally uneventful — the aircraft gradually reduces speed and within around 40 seconds, it performs just like a helicopter again, gently dropping to the touchdown point, with the pilot able to have visual references, as well as being able to use the advanced displays and controls.

Rockwell Collins is supplying the integrated avionics suite, based on its Pro-Line Fusion electronic display system, and the new version is due to be certified later this year. Featuring three 14" color display screens plus a pilot-operated cursor, the latest system is being developed for the production model 609 and will have interactive touchscreens integrated with a head-up display.

The pilot will be furnished with synthetic display images that can present terrain warning or virtual flight paths, with instant access via satellite navigation links to the weather situation and new flight information en route. The integrated cockpit environment will allow single-pilot operation under IFR conditions.

Two Pratt & Whitney Canada PT6C-67A turboprops will power the production AW609 and will introduce an upgraded performance beyond the existing PT6C-67 that currently powers the development aircraft. This engine is being optimized to deliver the appropriate high performance that can be exploited in a tiltrotor design, which must cover combined requirements for a helicopter and a fixed-wing aircraft. The new engine version is expected to receive certification by 2015.

## Faster and Further

So how is flying the AW609 going to change civil aviation? In this case, certification will involve meeting the official regulatory requirements for one aircraft that is both a helicopter and a fixed-wing transport.

Although digital technology has provided the new generation of helicopters with more data connectivity, safer systems monitoring, increased reliability, and lighter equipment, they still suffer from the mechanical and aerodynamic limitations of rotors that enable them to fly only slightly faster than earlier helicopters — and still have to avoid, rather than fly over, bad weather.

As speeds increase, the lift and drag limits imposed by the advancing and retreating rotor blades create more vibration and noise, which equates to less internal comfort and more external disruption. Tiltrotors now offer the opportunity to help create a breakthrough in performance, and in the civil market the AW609 is ahead of the competition. In fact, the nearest competition will come from slower compound helicopters (max speed around 230 knot) rather than another production tiltrotor product.

Once the AW609 is certified and enters everyday commercial service, there will be a new paradigm for would-be operators to study. Clearly, there will be an added capital cost involved because of the more complex technical specification, but the manufacturers are convinced that once through-life operating costs are considered, taking into consideration the far greater productivity that can be gained, the tiltrotor will emerge into the sunlight.

There is already a considerable level of civil and government interest in the AW609. "While we are presently concentrating on the engineering and support efforts and need to highlight the milestones in the development program, we are also identifying the business case for the aircraft in different sectors," said Luck.

In a light transport configuration, up to 10 passengers can be carried. In a VIP executive role, six could fly in a comfortably equipped cabin. For air medical transport, the cabin will accept two horizontal stretcher patients plus three or four medical attendants and accompanying passengers.

"The selling price will become clearer about two years before deliveries start — and that means around the end of 2014," said Luck. "The far greater productivity that will come with the increased speed capability and long range


Head-on view of Eurocopter X3 development compound helicopter.


Eurocopter CEO Lutz Bertling.

means that over the life of the aircraft, it will be able to generate very good profitability. We have around 65 commitments to date, and that is before potential operators are able to see production aircraft in service and what it can do."

## Compound Competition?

Compound, or hybrid, helicopters are making a comeback in the U.S., Russia, and Europe.

While Sikorsky has built a small, two-seat, high-speed technology demonstrator, the X-2, which has flown at 253 knot, it is not intended for production but as a test platform for the associated technologies and systems to be used in the design concept, which is built around coaxial contra-rotating main rotors and a rear-mounted pusher propeller.

There is no wing providing lift in forward flight. The company has taken the X-2 concept as the basis for an independent initiative, the S-97 Raider, aimed at offering a military OH-58D Kiowa replacement for the U.S. Army.

Russia is also developing two new high-speed helicopters. One, the Kamov KA-92, uses the coaxial rotors plus pusher propeller configuration and is in the Sikorsky S-92/Eurocopter Super Puma size category. The other, from Mil, is a smaller, simpler design.

However, the Eurocopter X3 compound demonstrator helicopter is flying, has undertaken a U.S. tour, and is likely, probably later this decade, to become the basis for a new production model, though no decisions have yet been made.

Although Eurocopter believes that the market is not yet ready for the launch of a production X3, the demonstrator is providing valuable feedback in terms of de-risking technologies and integrating systems.

Speaking to AE, Eurocopter President and CEO Lutz Bertling was guarded in his forecast concerning when the company might give a go-ahead for a production model or a derived design. However, he added that "in the tests we have performed over the last two years, the performance of the X3 has been better than predicted, and a production aircraft will be even higher."

He sees a big future for high-speed transport helicopters. "The case for this type of aircraft is all about increased productivity and through-life costs. It must be affordable, but the extra productivity will produce more revenue over the life of the aircraft," he said.

"The first step will be to agree with the certification authorities how to certify the (compound/hybrid) design as a helicopter, and then the other issue is how to get production development underway."

Advanced integrated avionics, increased pilot situational awareness through helmet-mounted displays, interactive controls, and highly automated fly-by-wire flight systems will make future designs safer and more capable.

Bertling stressed that these new technologies needed to be integrated, tested, and evaluated so that the right production products can come through as the market matures. "Now is a good time to invest in tomorrow's technologies," he said.

# PEFCs to Transform UAVs

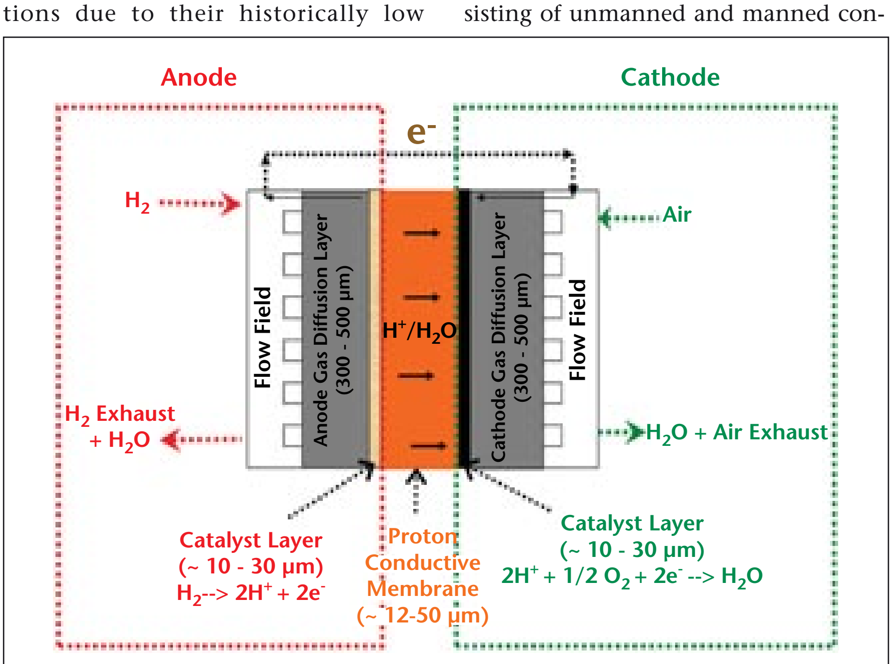
***Advancements in polymer electrolyte membrane fuel cells have resulted in longer-endurance missions for smaller UAVs, as well as an enabler for electric aircraft that require vertical takeoff and landing capability.***

UTC's PEFC-powered unmanned helicopter in flight.

A fuel cell is an electrochemical device that converts chemical energy directly into electricity and heat. The energy conversion process is much more efficient than a heat engine and produces little noise and no regulated emissions.

Although the first successful fuel cells predate modern heat engines, fuel cells have been limited in aviation applications due to their historically low power-to-weight and low power-to-volume ratios. Over the past 20 years, renewed interest in fuel cells for automotive and stationary applications has resulted in drastic increases in performance. As a result, fuel cells are viable solutions for increasing the endurance of electric aircraft.

Since the first fuel cell powered flight in 2003, multiple fuel cell aircraft consisting of unmanned and manned configurations have been developed. However, these aircraft have been limited to highly efficient fixed-wing aircraft, as power-to-weight limitations of fuel cell systems made them problematic for aircraft with vertical flight requirements.




A schematic of a cross-section of a polymer electrolyte membrane fuel cell (PEFC) with the electrochemical reactions. PEFCs are an attractive propulsion option for UAVs.

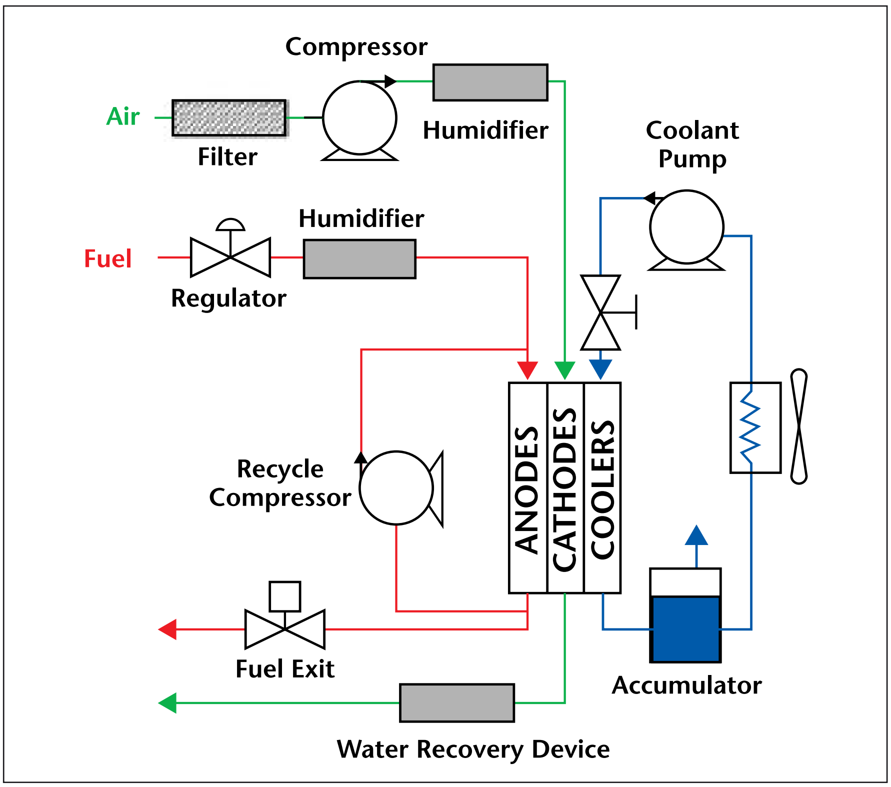
United Technologies Corp. (UTC) Research Center began developing a highly power-dense fuel cell system with the goal of enabling the first fuel cell powered rotorcraft. A polymer electrolyte membrane fuel cell (PEFC) was chosen that was based on UTC proprietary technology that had previously been employed in a stationary backup power device.

The system employed porous water-transport bipolar plates, which allowed for a simplified water-management design that reduced the weight of the system. The fuel cell system was used in a modified 1-kW class rotorcraft to make the first known successful vertical flight powered entirely by a fuel cell. The flight employed the use of compressed oxygen that increased power output of the fuel cell, but had limitations on endurance since only a fixed amount of oxygen could be stored within the weight constraints of the system.

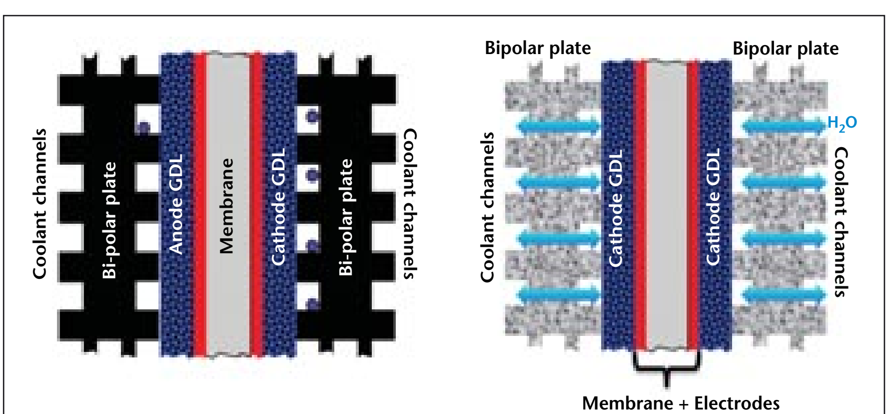
The next generation of the fuel cell system was optimized to operate using ambient air, which resulted in improved endurance and reduced overall volume of the system by eliminating the compressed oxygen tank. A rotorcraft flight of approximately 20 minutes was completed using this system.

UTC PEFC technology has direct application to small UAVs, which are very sensitive to power-to-weight of the propulsion system. Specifically, the PEFC can enable significant increases in endurance for small, fixed-wing UAVs that currently rely on battery energy storage. In addition, the increased power-to-weight enables a new class of vertical flight aircraft that can capitalize on the benefits of electric propulsion without being over-constrained by the energy limits imposed by batteries or ultracapacitors.

As a result, fuel cell vertical-flight aircraft can now be considered for Tier 1 UAV missions that are currently being performed by battery powered fixed-wing aircraft. This will enable new missions as fuel cell vertical-flight vehicles can achieve the same runway independence as current small UAVs without the limitations imposed by assisted launch and risks associated with net, hook, or deep stall landings.




Traditional PEFC system schematic showing numerous balance-of-plant components.




Schematic of the fuel cell components showing the contrast in water management between traditional (left) and UTC cell assembly.

## Fuel Cells 101

Fuel cells are related to batteries. Both convert chemical energy directly into electricity. The difference is that in a battery, the chemical energy has to be stored before it can be used. The fuel cell, on the other hand, is an energy conversion device that theoretically is capable of producing electrical energy for as long as the fuel and oxidant are supplied from an external source.

The fundamental mechanism of fuel cell operation consists of catalytic oxidation of hydrogen at an anode and reduction of oxygen at a cathode, which creates a potential difference between the two electrodes. By placing an insulating electrolyte between the electrodes, which allows the passage of charged ions, the chemical energy of the reaction is liberated as electricity, water, and waste heat.

This process is not subjected to the Carnot principle and its related limitations, which makes the fuel cell a highly efficient device. Fuel cells are mainly classified by the type of electrolyte used in the fuel cell, the catalysts used in the electrodes, and the process gas requirements.

A PEFC has a proton-conductive polymer as electrolyte that transports protons from anode to cathode to react with oxygen to produce water as a by-product. Due to its low temperature operation (65-85 °C), quick start-up times, high efficiency, and absence of moving parts, PEFC is an attractive propulsion device for UAVs, especially for unique missions that require low thermal signature, low noise level, and increased endurance relative to batteries.

To enable fuel cell stack operation and control, a balance-of-plant (BOP) containing additional systems is required. The BOP, which accounts for the majority of total fuel cell system weight and volume, includes fuel and air supply systems, a water-management system, and a thermal-management system. For power conditioning and control to meet the load demand, the fuel cell BOP also requires a power-management system.

## High-Power-Density Design

Water is critical to the performance and durability of a PEFC. The transport of protons through the polymer membrane depends on water as each proton (H+) migrates through the micropores of the membrane in the form of H3O+ dragging molecules of water from the anode to the cathode, a phenomenon known as electro-osmotic drag.

Inadequate membrane hydration can lead to cell performance loss due to high resistance to proton transport through the membrane. In addition, drying of the PEFC induces mechanical stress and chemical degradation of the membrane, which can result in performance failure.

Traditionally, the membrane is hydrated through humidified reactant gases. The saturation level of these gases as well as the operating conditions of a PEFC requires an intricate water-management system to maintain good and stable performance under steady-state as well as transient conditions. This requires maintaining a balance of all the forces that impact water transport in the cell (e.g., electro-osmotic drag, water production, and water vapor entering and exiting the fuel cell).

Insufficient water can lead to membrane dry-out and hence performance degradation. Too much water can block reactant flow fields, which can result in severe performance losses. In addition, the presence of excessive liquid water can restrict reactant gas transport to the electrodes and can result in severe performance losses.

Traditional PEM fuel cell systems often employ specific cell designs and operational methods that provide high reactant pressure drops in the cathode and anode with the need for accurate temperature and humidity control to help in alleviating excess water in the stack and reduce the impact of "flooding."

Such strategies generally render the fuel cell system more complex, more expensive, and less efficient. UTC's PEM

| UTC PEFC Technology | Traditional PEFC Tecnology |
|---|---|
| **Low-pressure operation**<br>• Improved efficiency<br>• Uses air blower<br>• Minimizes reactant leakage<br>• More reliable system | **High-pressure operation**<br>• High parasitic power loads<br>• Uses air compressor<br>• More sealing issues<br>• Less reliable system |
| **Internal humidification and water management**<br>• Simplified system<br>• Superior performance<br>• Low decay and improved lifetime | **No internal humidification or water management**<br>• Eternal humidifiers required<br>• Complex system<br>• Larger stacks and shoter lifetime |
| **Controlled start-up and shutdown proceedures**<br>• Minimizes performance losses<br>• No inert purge gases (e.g., $N_2$) required | **Inferior start-up and shutdown procedures**<br>• Accelerated stack performance<br>• Some use inert purge gases (e.g., $N_2$) |

Comparison of PEFC technologies.

stack technology effectively overcomes water-management issues in a simple and passive manner. Unlike solid bipolar plates used in traditional PEM fuel cells, UTC uses porous graphite bipolar plates filled with liquid water.

In the coolant side of the bipolar plate, liquid water is circulated at sub-ambient pressure to maintain a pressure differential between the reactant stream and the coolant stream. The water contained within the pores of the bipolar plates provides internal humidification to the fuel cell membrane when needed, and at the same time, the sub-ambient pressure maintained at the coolant side forces any residual liquid water away from the gas channels and into the coolant stream.

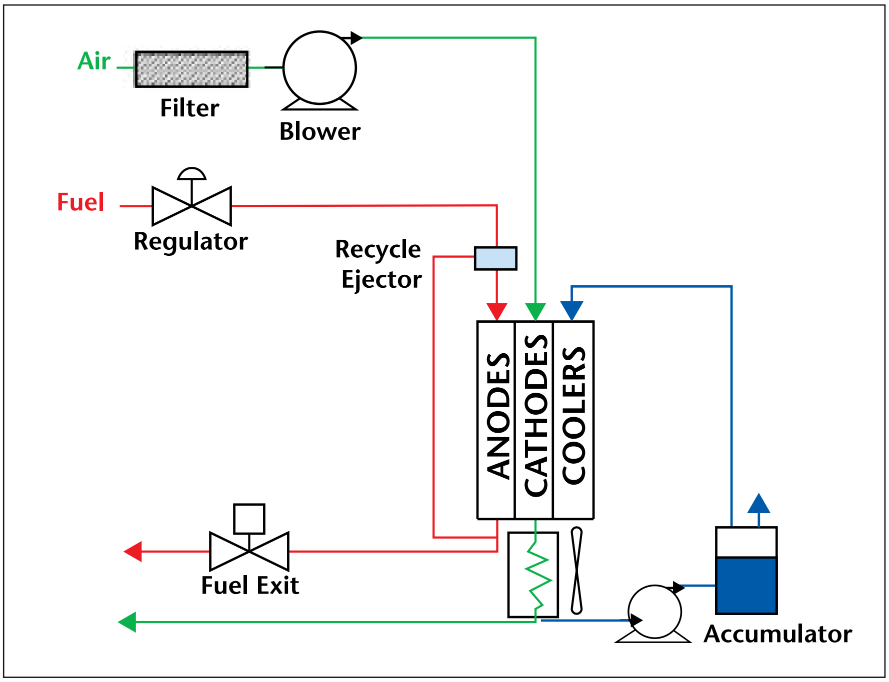
This pressure-differential force across the bipolar plate is effective in removing excess water and eliminates the need for complex water-removal methods such as high-pressure drop flow field designs and specific control strategies that enable high flow velocities and/or accurate control of temperature to promote water vapor removal.

Employing the porous bipolar plates allows the BOP to be significantly simplified. Rather than requiring all the components of a traditional PEFC system, the BOP required for a high-power, dense fuel cell system would require no external water-management devices (e.g., humidifiers) since the water is passively managed within the stack.

Additionally, the need for high fuel-flow rates to help remove water is eliminated by the passive water management. This enables the use of a blower instead of an air compressor, and enables the fuel-recycle system to be simplified by using the energy of the compressed hydrogen cylinders to drive a venturi ejector.

Another important differentiation is that the stack is cooled primarily by evaporation of water (i.e., latent heat), which reduces the amount of coolant flow by an order of magnitude relative to a system that relies primarily on sensible-heat removal.

An additional advantage is that high power can be achieved at near ambient inlet conditions, which helps simplify the BOP as well as the stack sealing requirements. Subsequently, each of the three sub-systems has fewer parts and the parts that do remain are smaller in size and less costly than those found in a traditional PEFC system. This inherently simple system requires less power



UTRC high power density system schematic. Note that there are no external water-management devices in this system.


The UTRC designed fuel cell stack with peak power of 1.75 kW. It operated at near ambient pressure and required no external humidification or cooling.

to run the BOP and is therefore more efficient.

In addition, the passive water management and simplified BOP enable the system to have improved reliability compared to traditional systems. UTC systems have also shown excellent performance and startup at ambient temperatures as well as start capability and proven durability in sub-freezing conditions.

As a result of the simplified BOP and cell power levels, fuel cell systems have been developed for UAVs that exceed 500 W/kg for the system including both the fuel cell and the BOP.

## PEFC Demonstration

To demonstrate a high-specific power PEFC, the development of a UAV-specific design was carried out by a team of researchers at UTRC. The result was a fuel cell with a stack specific power that exceeded 675 W/kg and an overall system specific power above 500 W/kg achieving the best-known specific power in its class.

Operation of the fuel cell stack was at near-ambient pressure and required no external humidification and cooling. The heat generated by the stack was removed by evaporation of liquid water contained within the stack, eliminating the need for a heat exchanger. This unique water-management system significantly reduced the overall fuel cell system size, weight, and complexity relative to traditional PEFC systems. During operation, the overall efficiency of the system exceeded 52%.

The fuel cell system was integrated into a modified electric rotorcraft in the 1-2 kW power class. The fuel cell was mounted in the center of the aircraft, and the blower protruded behind the stack. The high-pressure hydrogen tank was mounted in the nose of the aircraft. The brushless motor and its power electronics were located above the tank.

An off-the-shelf DOT-approved fuel tank rated to 4500 psi was used for the flight. The tank was connected to the fuel cell via pressure regulators and a remote controlled valve. Refilling of the tank could be done in less than a minute compared to the hour required for recharging lithium polymer batteries. The controls were provided with a 2.4-GHz radio control system, and the data needed to monitor the well being of the fuel cell was transmitted back on a 900-MHz link to a ground station.

The demonstration flight used a high-power-density PEFC stack. The remote controlled helicopter originally designed to run on batteries had a rotor diameter of 1.83 m and a GTOM of 10 kg. The duration of the PEFC-powered flight was approximately 20 minutes.

The endurance of the test flight was limited by the relative low hydrogen storage fraction of 0.023 for the off-the-shelf DOT tank. The PEFC system had excess power capability for this application, which could extend the endurance past 30 minutes by either adding a second DOT hydrogen tank or acquiring a larger custom-made lightweight tank.

Advanced batteries are capable of higher power-to-weight; therefore, for short endurances of only a few minutes, battery systems can be lighter and thus carry more payload.

However, battery systems are energy limited and only able to provide limited endurance, even with light payloads. For payloads less than 1.5 kg, the fuel cell powered rotorcraft can provide improved endurance over an advanced battery powered version of the same rotorcraft.

*This article is based on SAE technical paper 2012-01-2161 by Blake A. Moffitt and Rachid Zaffou, United Technologies Research Center.*