

Flying farther on less

Escalating jet fuel prices are bringing fresh interest in NASA-led research into technologies that promise to reduce the amount of fuel needed to fly an airliner from gate to gate. Whether conservation comes through increasing jet engine efficiency, minimizing drag on the aircraft, or using lighter materials for the airframe, NASA's aeronautical innovators are considering many options.

Their goal is to develop technology that would enable airplanes to burn only half as much fuel by 2020 and at least 70% less by 2025, compared to one of today's most fuel-efficient aircraft, a Boeing 777 with GE 90 engines. Such significant fuel savings are one of three ambitious goals of NASA's green aviation technology research.



by Jim Banke
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*Researchers are testing a wind tunnel model with specially designed wings in NASA Langley's National Transonic Facility. They are trying to see if they can test for natural laminar flow on an airliner wing at flight conditions in a wind tunnel.
Credit: NASA/Sean Smith.*

The others are to minimize harmful emissions and attenuate noise. NASA expects to see simultaneous improvements in airplanes entering service in 2025 or later.

Realizing these outcomes is challenging, because they are not necessarily complementary. For example, fuel saving technologies should have a direct positive effect on emissions, because the less fuel an airplane burns, the less carbon dioxide, sulfur, and soot it releases. But one means of increasing energy efficiency—burning fuel at hotter temperatures in the engine—actually produces higher concentrations of nitrogen oxides, which degrade local air quality.

NASA is working to understand the physics behind these trades so it can develop methods for increasing fuel efficiency and decreasing emissions simultaneously, which would reduce carbon and emissions footprints and improve local air quality. While the environmental benefits remain a driver, the economic benefits of burning less fuel become more important with each increase in the price of petroleum.

“Fuel is a big part of the cost for an airline, and the price is not something they have much control over,” says NASA Langley’s Rich Wahls, project scientist for the agency’s Subsonic Fixed Wing Project.

There are concerns that prices will return to record levels not seen since 2008. According to the DOT’s Bureau of Transportation Statistics, in March of this year (the latest available data), jet fuel averaged \$2.79 per gallon, \$0.55 more than the annual average of \$2.24 in 2010. At that rate, commercial carriers spent \$38.8 billion on the 17.2 billion gallons of fuel they burned last year. The highest price on record was \$3.83 per gallon in July 2008.

Although there are practices that save fuel now, the technical innovations that NASA and its partners are studying promise the greatest increases in fuel efficiency during the next few decades.

The power and the glory

Engine designers can approach the problem of reducing fuel consumption by improving either propulsive efficiency or thermal efficiency. Propulsive efficiency usually

is enhanced by slowing the speed and increasing the mass of air moving through the engine. Thermal efficiency, how the energy in the fuel is converted into power, usually is enhanced by increasing the pressure of air entering the combustor, running the combustor at a hotter temperature, or using less air to cool the turbine.

The bypass ratio—the proportional relationship between the amounts of air moving either past the engine core or into it—is the key to improving propulsive efficiency. In a modern jet, a fan housed inside a nacelle draws air into the engine. Some air flows into the engine core and gets compressed, mixed with fuel, and burned. The resulting hot gas, which passes over turbines that provide mechanical energy to spin the fan blades and generate electricity for the plane, is then expelled out of the back of the engine. The higher the bypass ratio, the greater the amount of air that

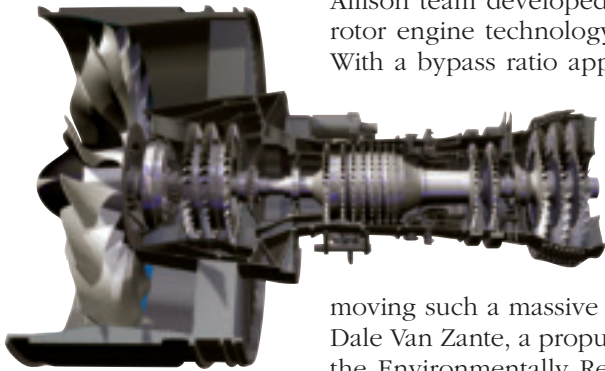
After more than a century of flight, it might seem that advances in aerodynamics have reached their practical limits. But researchers at NASA believe ambitious goals in areas such as reducing fuel consumption may still be achieved in tandem with limiting noise and pollution effects. From exotic new materials to greener manufacturing methods, intensified efforts are leading NASA into some futuristic technologies.

moves past the engine core, and the slower the speed of the exhaust. This all means, in theory, that less fuel is being consumed, because making a lot of air move slowly takes less work than making a smaller amount of air move fast.

Ideally, a jet engine with an open rotor, characterized by fan blades so big that a nacelle becomes impractical, offers the greatest improvements in propulsion efficiency. But the associated noise and structural issues have made open rotors impractical.

The open rotor concept is problematic for three reasons. First, because the giant blades are not shielded inside a nacelle,

This cut-away view shows the Pratt & Whitney PW1000G PurePower engine. Image credit: Pratt & Whitney.



they are very noisy and would disturb people both inside the aircraft and on the ground. Also, the large open rotor systems envisioned, with blade lengths approaching 14 ft, will not fit any existing aircraft; a new vehicle must be designed to accommodate them. Finally, because of their propeller-like appearance, open rotors have been slow to gain the flying public's acceptance.

General Electric and a Pratt & Whitney/Allison team developed and studied open rotor engine technology in the late 1980s. With a bypass ratio approaching 30, open rotors proved that they could beat the fuel burn efficiency of other engines 'hands down,' because the blades were moving such a massive amount of air, says Dale Van Zante, a propulsion engineer with the Environmentally Responsible Aviation (ERA) Project at NASA Glenn. Recently, NASA and GE revived the investigation of open rotors with the aim of improving their practicality.

For researchers seeking to improve thermal efficiency, all the action is in the jet engine's core. NASA is working separately with GE and P&W on ideas that address the thermal efficiency of engines already in use or envisioned for the future.

With GE, NASA is attempting to dramatically increase the pressure of air that passes through an engine compressor, but without adding too many rows of compressor blades. More blades mean a longer and thus larger engine, and can induce unwanted vibrations. The work is under way at the High Speed Multi-stage Compressor Facility at Glenn.

"The challenge we face with this idea is that the flow characteristics of the air moving through the core become difficult to manage at this higher aerodynamic loading. You have transonic flow with shock waves, and there is a tendency for the flow to separate from the compressor blades, which

can result in loss of aerodynamic efficiency and potential compressor stall," says Jim Heidmann, chief of the Turbomachinery and Heat Transfer Branch at Glenn.

The potential short-term solution is the use of better 3D design tools; the long-term solution is using flow control in the compressor using suction and directed air to help keep the air moving through the engine as it is designed to do, Heidmann says.

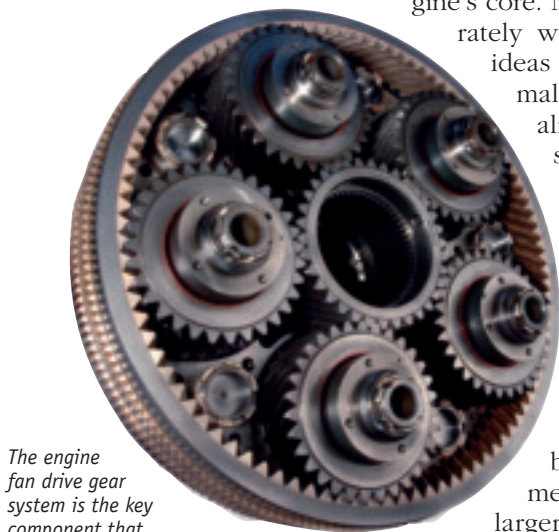
One concept that addresses both propulsive and thermal efficiency is the geared turbofan, which NASA has teamed with Pratt & Whitney to investigate. In most turbofan engines a shaft connects the fan directly to the low-pressure turbine, which is part of the core engine. The fan turns at the same speed as the turbine. Slowing the fan speed, which has noise and propulsive efficiency benefits, requires an increase in the size of the turbine, because the turbine is most efficient at higher speeds. In the geared turbofan, a gearbox connects the fan to the turbine. The gearbox enables the turbine in the core engine to run efficiently at high speed while the fan runs efficiently and quietly at low speed.

This change in configuration enables an increase in fan diameter without increasing core engine size, so the bypass ratio increases. The higher bypass number allows for improvements in propulsion efficiency. At the same time, changes in design within the core allow it to burn the fuel at higher pressures and temperatures, improving the thermal efficiency. These characteristics and their contribution to improving overall fuel burn efficiency, along with the noise benefit offered by slower fan speeds and nacelle, are what excite researchers about the technology.

"This is a revolutionary technology," says Chris Hughes, manager of the ultra-high bypass engine technology research at Glenn for ERA. "The question is, how far can we push the technology and grow it to fit an entire range of aircraft?"

Although the geared turbofan provides slightly less overall propulsion efficiency than an open rotor, it is much quieter. The thermal efficiency challenge in the core engine of an open rotor system is similar, if not identical, to that of a ducted propulsion system with a nacelle, so the developments in core engine technology benefit both ducted and open systems.

Another way to improve fuel efficiency is to



The engine fan drive gear system is the key component that makes it possible for the P&W geared turbofan engine to work and thus to increase the engine's fuel efficiency. Image credit: Pratt & Whitney.



A NASA experiment will be flown on this jet to test improving laminar flow over an aircraft wing. The marked area on the left wing shows the area where an experimental glove will be located. Image credit: NASA/Tony Landis.

reduce drag. The less drag, the less thrust engines must generate to maintain the aircraft at a given speed and altitude, so the less fuel they burn. The two major sources of drag confronting aircraft designers are skin friction—how smoothly air passes over the vehicle surface—and induced drag caused by the finite wingspan. NASA is focused on finding practical solutions to reduce skin friction drag. One approach is to control turbulent air near the surface of the aircraft; another is to reduce the size of aircraft surfaces.

No matter how aerodynamically smooth the surface of an aircraft is, after only a couple of flights the wing leading edge and cockpit windshield will be spattered with insects and debris that can trigger turbulent flow and increase drag. NASA researchers are working to quantify what they call the ‘knock-down’ factor—just how detrimental the insect accumulation can be to laminar flow in an operational environment.

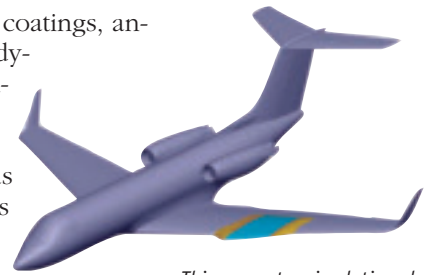
“One of our goals is to find a way to treat the leading-edge surface with a coating, or some kind of surface modification that is self-cleaning, so that dirt doesn’t accumulate very fast on it, insects also don’t accumulate very fast, or the insect residue is reduced,” says Langley’s Tony Washburn, chief technologist for ERA.

Washburn says researchers have tried several commercially available products and have formulated new compounds with the desired nonstick properties.

System studies typically show that a 6-10% reduction in overall aircraft drag is possible with laminar flow technology, depending on the configuration and mission profile. The coatings work is intended to improve the odds for maintaining a high rate of return from laminar flow in an operational environment.

While one group looks at coatings, another is looking at what aerodynamic enhancements are possible when roughness is applied judiciously to a wing. NASA, with contractor Texas A&M University, plans a series of test flights in late 2012 or early 2013 with a Gulfstream III business jet. A portion of one aircraft wing will be fitted with a glove—a test article designed to demonstrate a relatively new idea for enabling laminar flow on commercial airliners.

The leading edge of the glove is covered with microscopic bumps known as discrete roughness elements, which are 6-12 μm in height (about the thickness of plastic wrap) and spaced about 4 mm apart. Flight tests will determine whether such roughness elements can maintain laminar flow over a 6-ft section of wing. It seems counterintuitive, but without discretely spaced roughness elements, air flowing over a swept wing tends to develop small vortices that grow in intensity until the air-flow over the wing is fully turbulent. This



This computer simulation shows what the wing glove looks like and how it will be placed on the testbed aircraft. Image credit: NASA/Ethan Baumann.

increases drag and reduces fuel efficiency. Vortices created by the roughness prevent the naturally occurring vortices from growing and destroying the laminar flow, thus reducing skin friction.

Wind tunnel tests have shown this approach to laminar flow works at laboratory conditions. The question is whether it works in the thinner boundary layers experienced in flight.

Another means of minimizing drag may be to make airplanes with smaller vertical tails. NASA and Boeing are pooling resources to investigate active flow control, which is a way to shrink the tails and still maintain control of the airplane during critical flight phases such as takeoff.

Designers think pulsing air along the rudder hinge line is one way to give the airplane full control over its yaw, even with an engine out and the tail smaller. The concept involves a series of small jets placed along the rudder hinge line. The jets would make the air better follow the contour of the rudder, causing the rudder to generate more force than it otherwise could. This allows for a smaller tail, with less surface area to create drag when the airplane is cruising. Recent wind tunnel tests indicate that it is possible to achieve a 40% improvement in the force created by the rudder.

The heavier an aircraft is, the more fuel it will need to get off the ground and stay aloft. One key to fuel efficiency is new materials that are as strong as anything used today but can do the same structural job with much less mass.

Electron beam free form fabrication, EBF³, technology uses an electron beam, a computer, a moving base inside a vacuum chamber, and wire to create structures one layer at a time. Having progressed for several years, the technology is becoming available commercially, but its applications in aviation and in space are still being researched.

“You start with a CAD model of the part you want to build, you push a button, and out comes the part,” explains Karen Taminger at

Langley, the EBF³ technology lead in the Fundamental Aeronautics Program.

Normally an aircraft builder might start with a 6,000-lb block of titanium and machine it down to a 300-lb part, using many gallons of cutting fluid in the process and leaving 5,700 lb of material to recycle. “With EBF³ you can build up the same part using only 350 lb of titanium and machine away just 50 lb to get the part into its final configuration,” says Taminger. “Because the part is built up layer by layer,” she adds, “you also have flexibility in engineering the materials and shapes of the stiffeners to tailor the resulting structure, resulting in something that cannot be built with conventional manufacturing practices.”

The weight savings comes through the freedom the EBF³ process allows: to use less material while manufacturing parts that are more structurally efficient, meaning they weigh less and still meet or exceed the necessary strength and safety requirements.

Another weight-savings possibility is nanotubes, in theory 100 times stronger than steel. “These tubes are not just strong, they also are highly conductive,” says Mia Siochi, a research scientist with NASA’s Subsonic Fixed Wing and ERA projects. Could they be the next generation of aircraft structural composites?

“The promise of having it multiple times stronger than carbon fiber is not yet realized, [but] we’re working on that,” says Siochi. She adds that researchers are starting small, through nanoscale modeling of materials and research into the manufacturing of nanotubes, and are trying to make increasingly larger structures. It could take another 15-20 years for the technology to be ready for use on commercial airliners, either as large structures such as wings, or even as wiring for power within an airliner.

Another candidate technology for building large, lightweight structures for future aircraft is pultruded rod stitched efficient unitized structure, or PRSEUS. Layers of carbon-fiber composite materials are stitched together with a special thread to give the layers structural integrity. Once the stitching is done, the carbon fiber is infused with epoxy resin under vacuum pressure to pull the resin through, and then placed into an oven to bake.

Unlike using traditional composite fabrication techniques, making PRSEUS does not require the high pressure of an autoclave, so the material costs less to process. The stitching arrests damage and keeps a

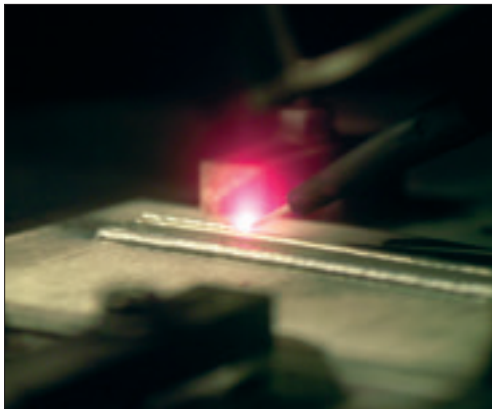
The electron beam free form fabrication process was used to make this sample titanium part. NASA innovators are working on scaling up the process to build larger components. Image credit: NASA.



small puncture or crack from growing out of control. The key is that with stitching, one can achieve the fail-safe design load limits of metals, but with lighter weight. Carbon-epoxy systems are about half as dense as aluminum, so the resulting structure weighs less.

“We’re trying to develop technology to make aircraft lighter, and we’re doing that by looking at new ways to put together composite structures where they are lighter than metals and get rid of all those fasteners, all those rivets,” says Langley’s Dawn Jegley, PRSEUS lead for ERA.

Overcoming the many technical challenges of reducing the aviation industry’s thirst for fuel while also meeting air traffic growth expected during the next few decades will keep NASA and its research partners busy for the foreseeable future. What is clear is that there is no single solution to the problem; boosting fuel efficiency will require a host of innovative ideas and in-depth efforts on multiple fronts.



An electron beam free form fabrication is shown at work laying down a metal part one layer at a time. The EBF³ process allows for more intricate components to be manufactured using smaller amounts of raw materials than conventional methods use. Image credit: NASA.

Editor’s note: *This is the third of four features describing the challenges associated with trying to invent a truly ‘green’ airplane. The first feature (March 2011) covered research into reducing nuisance noise around airports. The second (May 2011) concerned efforts in lowering aircraft emissions and improving air quality. The final feature will examine the nation’s air traffic management system to find means to handle aircraft in a more environmentally responsible manner. ♣*

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