

Military aviation

The combination of alternative fuels, even more efficient engines, and airframe changes both minor and dramatic should result in greater fuel efficiency, a plus for both the military and the world it is sworn to protect.

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A KC-135R refuels an F-22 with a new synthetic fuel. The test was done as part of the secretary of the Air Force's initiative to certify the entire fleet on synthetic fuel, an effort to lessen dependence on foreign oil. (Photo by Master Sgt. Rick Sforza.)

goes green

In May 2008, the USAF flew its 1 millionth sortie since September 11, 2001, just one of approximately 300 military flights per day in Iraq, Afghanistan, and the surrounding areas. With so many flights, it is no surprise that the Air Force consumes more than 2.5 billion gallons of fuel each year. In 2008, that translated directly into expenditures of nearly \$7 billion, slightly more than half the total fuel bill of the entire U.S. government.

To put that into perspective, \$7 billion represents about half of Canada's entire military expenditure; it is roughly three times what the USAF spent internally on science and technology work in the Air Force Research Laboratory (AFRL); and it is equivalent to the flyaway cost of 51 new F-22 fighters. And every unexpected increase in the cost of a barrel of oil can translate directly into significant unplanned fuel costs; a \$10/barrel rise in oil prices means a \$700 million cost increase over the entire Air Force fleet.

The direct cost of fuel is not the only issue; there is tremendous extra cost involved in delivering that fuel to the warfighter. It has been calculated that the average cost of fuel delivered to a convoy is \$13/gal. Put that fuel in a tanker and pump it into a fighter in flight, and the so-called "fully burdened" cost skyrockets to an average of over \$40/gal (some estimates place it as high as \$200/gal, depending on the mission). As a result, increased aviation fuel efficiency has become an S&T priority for the military.

Aviation fuel consumption is not just an economic concern—there are significant environmental costs. Aircraft release about 600 million tons of CO₂ each year, but those gases

have a greater impact than other sources of combustion byproducts. Because aircraft deliver greenhouse gases directly into the atmosphere where they do the most harm, emissions such as carbon dioxide and nitrous oxide compounds may have a relatively greater environmental impact than those from ground-based fossil fuels.

Thus, even though aviation accounts for just 8% of the total use of refined oil, and only 3% of greenhouse gas emissions, the overall climate effect from aviation greenhouse gases is about 13% of the total from fossil fuels. The race is on to burn less fuel, or to use fuels that have a smaller environmental impact.

ENGINEERING TO CONSUME LESS

In 2004, the Air Force Scientific Advisory Board, a group of about 50 scientists and engineers who advise the secretary of the Air Force and the chief of staff, initiated a six-month study on increasing fuel efficiency for military aviation. That analysis divided potential technology solutions into four categories: fuels, engines, airframes, and behavior.

Alternate fuels with higher energy content than conventional hydrocarbons translate directly into less fuel consumption. Such fuels might include everything from hydrogen (clean burning but hard to handle) to various synthetic propellants produced from coal, natural gas, or biomass. Synthetics have the additional advantage of reducing dependence on foreign sources. It remains to be seen whether these fuels can be produced with processes that, as a whole, do less environmental damage than their fossil-derived counterparts.

Improvements in propulsion systems—engines that can consume less fuel for a given



On December 17, a C-17 Globemaster III flew over New York City after completing the first transcontinental flight on synthetic fuel.

range—involve everything from making existing engines more energy efficient through servicing and cleaning to entirely new systems that maximize overall cycle efficiency.

The development of new aerodynamic configurations and aircraft structures that can improve overall performance also offers great promise. Lighter weight structures and higher lift shapes could yield dramatic increases in range for a given amount of fuel or reduce fuel requirements for a given range.

Of course, the fourth option for using less fuel is, fly less. This can include expanded use of simulation for training, or eliminating some manned aircraft missions in favor of smaller, more efficient UAVs. Migrating training from flight to simulator is happening across the board in the DOD and has already taken hold in the civil sector. Modifying pilot behavior, including paying closer attention to steps that can reduce fuel consumption, may also help.

BREWING NEW FUEL

The broad interest in alternative aviation fuels was expressed in a letter from representatives of the U.S. aviation industry, including the Air Transport Association, the Aerospace Industries Association, and synthetic fuel organizations, to the Obama administration. Writing in January 2009, they called for “an entirely new fuel dynamic,” and promised the new president that aviation will be an “enthusiastic purchaser of environmentally friendly alternative fuels when they become available.”

These groups have been involved with the FAA to form the Commercial Aviation Alternative Fuels Initiative, which seeks to enhance energy security and environmental sustainability for aviation through alternative fuels.

Not all alternate fuels are environmentally friendly, and even the friendly fuels may not work well with existing aircraft. It is hard to

beat existing jet fuels, not only for cost but also for both energy content and handling characteristics. Burning 1 kg of jet fuel releases over 40 million joules, enough energy to power 185 standard light bulbs for an hour. That is about 90 times more energy per kilogram than the best available batteries. And a jet fuel such as JP-8 remains a liquid down to -47 C and has relatively high density, so it can be stored in a relatively compact volume.

In contrast, a fuel like hydrogen can be very environmentally friendly—its combustion product is water (though commercial hydrogen is itself mostly derived from fossil fuels), and it has three times the energy per kilogram of jet fuel. But it must be stored as a cold liquid, at temperatures below -253 C, and it leaks out of tanks very easily. Hydrogen’s density is also less than one tenth that of jet fuel, so a hydrogen-powered aircraft would require large fuel tanks, and thus a large structure. In addition, some atmospheric scientists point out that water vapor is the most effective greenhouse gas, so releasing seemingly harmless water exhaust at airliner altitudes could have noticeable climate impact.

The first alternate fuels to be adopted on a large scale will likely be those that will work in existing aircraft. On February 24, 2008, a Virgin Atlantic Boeing 747 flew from London to Amsterdam; one of its four engines was powered by a fuel blend that included a synthetic manufactured from oils derived from coconuts and seeds of babassu palm trees. A key to this flight was that no modifications to the airliner or its General Electric engines were required, though the biofuel accounted for less than 10% of the total propellant load.

Heralded as a breakthrough by Virgin president Sir Richard Branson, the overall environmental benefit of such biofuels was immediately the subject of debate. As some environmentalists noted, dedicating the amount of arable land required to grow enough coconut and babassu would cause its own environmental hazards. However, the fact that bio-derived fuels could be burned in an unmodified gas turbine engine suggests that other renewable sources of hydrocarbons might offer environmental benefits. But it is one thing to run an engine for a single flight on a new fuel; operating that engine for years with no damage may be a harder challenge.

The Air Force had entered the synthetic fuel arena eight months earlier. Maj. Gen. Curtis Bedke, then-commander of the USAF Flight Test Center at Edwards AFB, piloted a B-52 that burned a coal-derived synthetic fuel

More than 100 people at Edwards AFB attend a ceremony with Secretary of the Air Force Michael W. Wynne certifying F-T synthetic fuel blends for use in the B-52H.



blend in two of its eight engines over the skies of California. This was the first step in a systematic plan to certify the entire USAF fleet on synthetics, championed by then-Air Force Secretary Michael Wynne. The long-term goal began with a plan to derive 50% of the Air Force's domestic fuel from sources other than traditional crude oil by 2016. The effort is looking not only at the performance of synthetic fuels, but their effect on emissions and the long-term health of the engines.

This idea of powering the Air Force on synthetics was certainly not new; a study by the RAND Corporation in 1976 concluded that "uncertainties in the future availability and economics of crude-oil-based jet fuels pose a particular challenge to the Air Force....[To] meet this challenge the Air Force will be obliged to undertake measures to conserve jet fuel in the short term and to develop a future capability for using jet fuels derived from alternatives to crude oil."

Two years later in another RAND report, *Future Sources of Military Jet Fuels*, William Stanley recommended that the DOD begin a research program into alternate hydrocarbon fuels. Thirty years later, the Air Force's first candidate fuel was a hydrocarbon blend of conventional JP-8 jet fuel with a synthetic fuel first produced in Germany in the 1920s.

The Fischer-Tropsch (FT) process was used by Germany and Japan during WW II to produce fuel from coal. FT synthesis uses a catalyst to convert hydrogen and carbon monoxide into heavier hydrocarbons more suitable for combustion in conventional engines. The original synthesis gas can be derived from coal, natural gas, or other carbon feedstock such as biomass. In choosing the FT product, Air Force planners were careful to keep the door open for other alternatives.

The Air Force began flight qualification of its fleet with a B-52, and was steadily expanding the range of aircraft certified to use FT fuels to include transports, bombers, and fighters. In doing so, the service was emulating the experience of South Africa's Sasol, which has been manufacturing an FT blend since 1999 and has made it available to airlines refueling at the Tambo Airport in Johannesburg for over a decade. Sasol received approval to use a 100% synthetic in the spring of 2008.

FT synthesis, especially with coal feedstock, has been criticized as being environmentally unfriendly, with a total CO₂ output possibly twice that of the conventional fuels it replaces. That is only partly true, and depends not only on the feedstock but also on the de-

tails of the process. Proponents argue that if excess carbon is sequestered and returned to the ground, the end result is a fuel environmentally superior to oil-derived hydrocarbons.

In fact, the synthetic fuels produced by FT have many environmental benefits, including minimal sulfur content, few aromatics, and a higher combustion temperature—thus more thermal efficiency and less sooty exhaust. However, the jury is still out as to whether that higher overall efficiency, and resulting smaller fuel consumption, is counteracted by the slightly higher production of ozone-destroying nitrogen compounds associated with higher combustion temperatures.

Since FT products lack some of the complex molecules that protect engine seals, there is also still debate as to how much fossil-derived fuel, if any, should be mixed in with the synthetic for long-term engine health, or whether so-called aromatics can be added directly in the manufacturing process.

Extensive research into synthetics continues at the AFRL, now commanded by the same Maj. Gen. Bedke. Others are also working in this area in academia and industry, with support from government agencies such as NASA, FAA, DOE, and DARPA.

The latter's efforts are specifically aimed at a process that efficiently uses organic living sources to produce a surrogate for JP-8 jet fuel, incorporating both its combustion and physical properties, including melting and freezing points.

The Air Force is now looking beyond F-T fuels, to include biofuels, with a keen focus on environmental impact. As the Air Mobility Command Chief Scientist Don Erbschloe explains, "The synthetic blend certification was an important first step, but ultimately as consumers of jet fuel, the USAF is agnostic to the feedstock. We need something that looks like, performs like, and is priced competitively with JP-8." The Air Force Certification Office is planning to test both a fighter and a C-17 transport with a biofuel sometime in 2010.

On the commercial side, the FAA is leading the Commercial Aviation Alternative Fuels Initiative (CAAIFI), which was established "to enhance energy security and environmental sustainability for aviation" through the use of alternative fuels. CAAIFI is a forum for partners to interact, share data, and champion research on alternative fuels.

"[Flight certifications with F-T] allowed the USAF to develop a thorough, structured set of procedures to validate and test the efficacy of any alternative fuel—not just Fischer-Tropsch—in Air Force systems."

Don Erbschloe, Air Mobility Command chief scientist

INCREASING ENGINE EFFICIENCY

Just as the producers of greener aviation fuels will have a difficult time surpassing, or even matching, the performance of existing fossil fuels, so too will the designers of new engines have a hard time beating existing propulsion

technology. A modern gas turbine engine is among the most efficient machines ever built, converting nearly 60% of the available fuel energy to useful work, more than twice the efficiency of a typical automobile engine. The individual components of a gas turbine engine have efficiencies that are pushing the theoretical limits for such devices.

How can we make something that efficient even better? Several engine programs aim to do just that.

One approach is variability—building an engine that has a wider range of efficient operating modes because its flowpath can be varied. A modern gas turbine engine is typically most efficient in a very narrow range of flight conditions; outside that range, efficiency or performance suffers. For instance, an engine designed for efficient subsonic cruise will not be a particularly good supersonic thruster. Conversely, one designed to deliver very high thrust for bursts of supersonic speed or short takeoff will generally not be efficient for cruise. A variable engine might be good at both by changing the way it operates. This is analogous to adding a transmission to an auto powertrain, enabling an engine with a narrow operating range that can supply high torque at low speeds but also drive the wheels at high speed when torque is not needed.

The ADVENT (adaptive versatile engine technology) program, funded by the AFRL Propulsion Directorate, is looking at technologies that will explore various approaches to variability. Originally begun in 2006 as a program to improve engine performance, it was soon realized that ADVENT held the promise of increased fuel efficiency as well. Both Gen-

eral Electric and Rolls-Royce Liberty Works are working under ADVENT, each with its own approaches to variable cycles.

A key technique involves using adaptability to change the bypass ratio, varying the amount of air passing around the core engine. Especially promising is an auxiliary fan bypass flowpath, with a pressure ratio that can be controlled independently of the core engine. Coupled with concepts for varying the core flow, such ADVENT concepts could result in 30% fuel savings on a typical subsonic cruise mission and even greater savings for supersonic platforms.

More conventional concepts are also being pursued. For instance, those same companies are also involved with AFRL's highly efficient embedded turbine engine effort. HEETE is aiming to produce compressors with dramatically higher compression ratios than the current state-of-the-art, with correspondingly higher engine efficiencies. Ultimately, HEETE technology could be combined with ADVENT to produce even greener engines.

GE, working with Snecma, has also resurrected "unducted fan" concepts—essentially high-speed turboprops—building on engine programs from the late 1980s. Turbofans become more efficient as their bypass ratio is increased, but then as fan diameter grows, so do the weight and drag of the outer nacelle. Now referred to as open rotor engines, these unducted engines would solve this problem by eliminating the outer nacelle entirely. Fuel savings of up to 30% may be possible, though the 1980s versions of these engines had significant noise problems that were never completely resolved before dropping fuel prices ended their development.

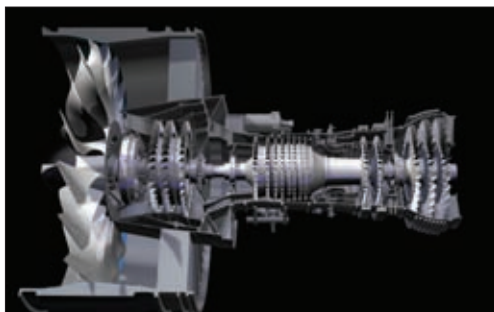
Pratt & Whitney, under its PurePower effort, is developing a geared turbofan engine in which each stage can operate at its own optimum speed. A conventional gas turbine engine tends to compromise performance by running each stage on a spool at the same speed, but it would be more desirable to run the forward fan stages at lower speeds and the high-pressure stages at higher ones. A lower speed fan could also be larger, and thus have a larger bypass ratio compared to a gearless counterpart. It would also be quieter.

In-flight tests on a Boeing 747 and Airbus 340 have demonstrated the concept, which P&W claims could save 12% in fuel consumption. Critics claim the addition of gears adds weight and mechanical complexity. But running stages at optimum speeds also means weight could be saved because fewer stages

"Without a doubt this is the high point of my 29-year Air Force career. ADVENT has energized the entire Air Force and contractor propulsion community to work together with the weapon system folks to examine many innovative applications for the future."

Jeffrey Stricker, chief engineer, Turbine Div.
AFRL Propulsion Directorate

PurePower is an effort to develop a geared turbofan engine in which each stage can operate at its own optimum speed.



may be needed, and thus far the engines have proven very reliable in over 120 flight hours.

DESIGNING ADVANCED AIRFRAMES

Advanced airframes are also being studied for their ability to improve overall efficiency. In cruise, an aircraft's range is proportional to the ratio of lift and drag forces. A Boeing 747 has a lift/drag ratio of about 18; a B-52 ratio is over 21. Though some gliders can reach values of up to 70, commercial jets have seen very little increase in lift-over-drag performance since the start of the jet age, an average of 15% since the introduction of the 707.

Changes to existing aircraft can improve aerodynamic performance. For example, the 2004 Scientific Advisory Board study on fuel efficiency concluded that adding winglets on certain aircraft could increase lift/drag ratios by up to 7%, though installation costs would not be recuperated until about 20 years of fleet operations. The USAF Air Mobility Command has undertaken a study of winglets for the military transportation fleet. And a National Research Academy Report in 2005 reached the conclusion that relatively simple modifications such as adding aerodynamic strakes, smooth laminar flow engine nacelles, and proper aileron trimming could have considerable savings over a large airfleet.

But more dramatic improvements will require a new approach to airframe design. Lightweight materials are one answer—the lighter an aircraft, the farther it will go on a tank of gas. The introduction of composites holds considerable promise in reducing airframe weight, thus reducing required fuel. Boeing's 787 will use an all-composite airframe, an example the military is following. Under the sponsorship of the AFRL, Lockheed-Martin Skunkworks, working with Aurora Flight Sciences, has built a smaller scale advanced composite cargo airplane, based on an existing aluminum-body Fairchild-Dornier 328JET. This one-of-a-kind aircraft began flying in June, and is meant to pave the way for other lightweight composite aircraft.

Standard composites are not the only promising material for fuel-efficient airframes. The Airbus A-380 uses a hybrid composite material in its upper fuselage, formed from alternating sandwich layers of aluminum and glass fiber. This material, originally developed at Delft University in the Netherlands, is not only much more crack resistant than pure aluminum, it is stronger and lighter than aluminum as well. It is also more easily repairable than a pure composite. Studies have shown

that replacing key aluminum parts on existing aircraft with hybrid composites would offer significant weight savings, which could translate directly into increased range or reduced fuel consumption. One immediate candidate for hybrid composites is the C-130 cargo fleet. An important added benefit is that the reduction in required maintenance inspections alone would easily pay for the replacement materials over the life of the fleet.

Ultimately, exotic aerodynamic shapes may offer the best improvements in aircraft efficiency. The performance of traditional tube-and-wing designs will improve only so far. To realize more dramatic improvements in lift/drag ratio may require a whole new approach: blended wing-body aircraft.



Although winglets are being considered for future aircraft, retrofitting would not be cost-effective.



The Advanced Composite Cargo Aircraft is a proof of concept technology demonstrator for advanced composite manufacturing processes in a full-scale, certified aircraft. It was developed by AFRL and Lockheed Martin officials.

In a blended-wing shape, wing and fuselage are smoothly merged so that the entire aircraft is producing lift. The idea is not new; the German Junkers G.38 introduced elements of a blended design in the late 1920s, and various aircraft, from the Northrop Flying Wing to the B-2 bomber, have used the same basic principle. NASA is presently testing a 7-m subscale radio-controlled blended-wing demonstrator, designated X-48 at its Dryden facility. This aircraft may be the prototype of a next generation of fuel-efficient airliners, cargo haulers, or military transports.



Finding alternative fuels that are friendly to both the pocket and the environment, developing even more efficient engines, and dramatically broadening our notions of what an aircraft should be made of and how it should look will all contribute to reducing fuel consumption. And coupled with finding ways to fly less, these efforts will leave our military just as strong but a lot more green. ▲