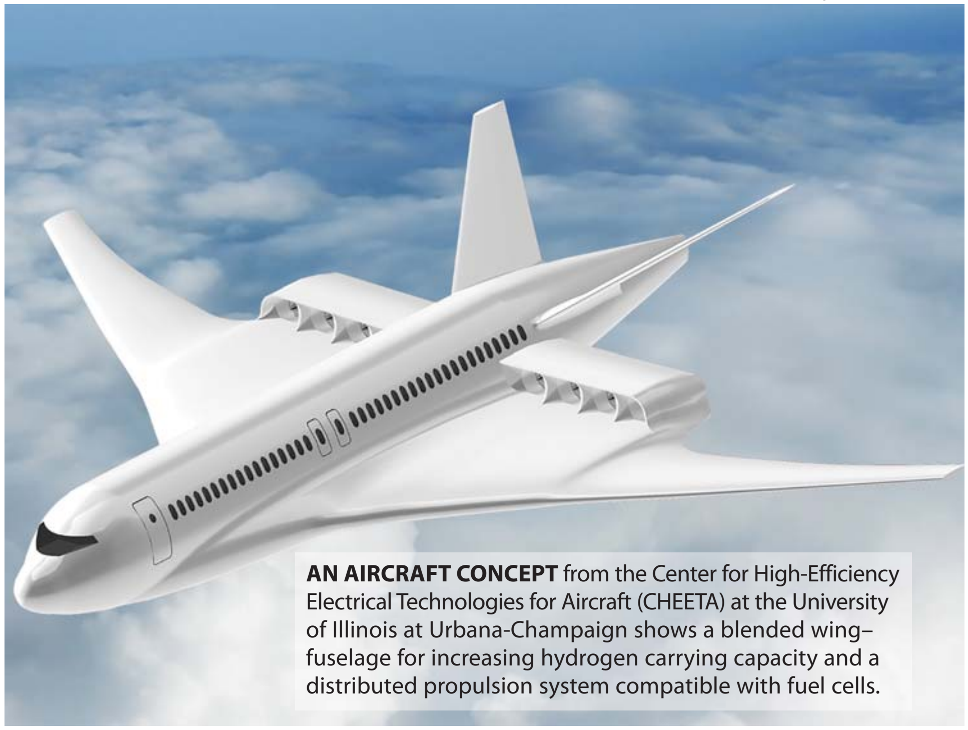
Hydrogen-powered aircraft may be getting a lift

Cutting the weight of fuel tanks and continuing advances in fuel-cell technologies are key to making hydrogen competitive in aviation.

CHEETA



AN AIRCRAFT CONCEPT from the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) at the University of Illinois at Urbana-Champaign shows a blended wing–fuselage for increasing hydrogen carrying capacity and a distributed propulsion system compatible with fuel cells.

As nations work toward achieving net-zero carbon economies, commercial aviation will be one of the most difficult sectors to decarbonize. Fossil fuel's energy-density advantage is too tough to beat, the argument goes, and rather than try to confront that, it might make more sense to continue the use of petroleum in airliners and to aim at offsetting their emissions using some negative carbon emissions technology.

Nonetheless, plenty of research is underway on lower-carbon aircraft propulsion. Some early-adopter airlines routinely blend biofuels into their aviation fuel, for example, and in 2018 Boeing flew a commercial airliner on 100% biofuel for the first time. But biofuels have their own drawbacks: The growing, gathering, and conversion of crops to liquid fuels is carbon-intensive. And biofuels' potential is limited by agricultural and other competing land uses.

Another option is hydrogen-powered flight. To be carbon-neutral, the hydrogen must be produced either with renewable energy or with natural gas equipped with carbon capture and storage. Both of the world's major airliner manufacturers are looking at the lightest element as one option for reducing their customers' carbon footprint. Amanda Simpson, vice president for research and technology at Airbus Americas, says Airbus will decide by 2025 whether the market can support hydrogen-fueled airliners. Assuming that it can, the company projects its first hydrogen airliners will enter service in 2035.

In 2008 Boeing built and operated the first aircraft ever to fly solely on hydrogen power. The fuel cells on the single-person plane were supplemented with power from lithium ion batteries during takeoff and ascent. Four years later, the company unveiled the Phantom Eye, a liquid-hydrogen-powered unmanned aerial vehicle (UAV). It was designed to fly reconnaissance missions of up to four days at an altitude of 20 000 meters. Boeing was unable to sell the UAV to the military, however, and it is now a museum piece.

Chris Raymond, Boeing's chief sustainability officer, says the company is looking at hydrogen for commercial aviation, but notes that the more immediate focus is on sustainable aviation fuels. "The reality is we have to do something now. But our view is that there will be a mix of solutions," with hydrogen power more likely to fill the short-haul, smaller end of the sector.

Although Boeing has shown that hydrogen will work as aviation fuel, more effort is required to determine whether an aircraft's structure and fuel tanks can be built to operate as safely as today's airliners, says Mike Sinnett, vice president of product development for Boeing's commercial airplanes division. He estimates it will be two decades or more before hydrogen could be introduced in Boeing aircraft, and he says engines that will power aircraft a decade from now are being designed today.

The small company ZeroAvia has set its sights on manufacturing a 10- to 20-passenger aircraft powered by hydrogen fuel cells by 2023. The California startup, according to its founder and CEO Val Miftakhov, has received $5 million in grants from three UK government programs and has attracted interest from 12 regional carriers in the UK, US, and European Union.

Weight and energy density

The biggest impediment to hydrogen-powered flight is the extra weight required for fuel storage, be it in gaseous or liquid form. For liquid hydrogen, the challenge will be making lightweight vacuum-insulated tanks that maintain the fuel below its 20 K boiling point. Gas carries a greater weight penalty, since the tanks must be built to withstand high pressures of 250–350 bar.

Measured by megajoules per kilogram, liquid hydrogen offers 2.8 times the energy density of aviation fuel. But in terms of combined fuel and tank weight, aviation fuel has the advantage over hydrogen by a factor of 1.6, says Rajesh Ahluwalia, a hydrogen and fuel-cell researcher at Argonne National Laboratory. Whereas aviation fuel constitutes about 78% of the combined weight of tank and fuel, liquid hydrogen accounts for just 18% of the total in current storage designs. To compete with fossil fuels, the fuel weight fraction has to reach at least 28%, he says.

Compared to hydrocarbons, liquid hydrogen has a much lower energy per unit volume. But Phillip Ansell, director of the NASA-funded Center for High-Efficiency Electrical Technologies for Aircraft at the University of Illinois at Urbana-Champaign, says that the added external surface area required to accommodate larger hydrogen tanks, and the resulting increase in aerodynamic drag, can be minimized by carefully tailoring other parts of the aircraft. One potential solution is a blended wing–fuselage design (see illustration, page 27).

ZeroAvia will use hydrogen compressed to 350 bar on the fuel-cell-powered aircraft that it plans to fly on short hops of 500 nautical miles (roughly 900 km) or less. Gaseous hydrogen could also find a niche in unmanned aerial vehicles, Ahluwalia says. But for large airliners carrying 150 or more people on longer flights, "gaseous hydrogen won't cut it," says Ansell. A pressurized storage system requires a much more robust tank and would occupy about twice as much space as tanks containing liquid hydrogen, he says.

By the end of the decade, ZeroAvia expects to debut 50- to 100-passenger fuel-cell aircraft powered by liquid hydrogen. The tanks would be made from combinations of existing composites and resins. No new materials development is needed, Miftakhov says. ZeroAvia's current fuel-to-tank weight ratio is 11–12% for gaseous hydrogen. The company is currently testing liquid hydrogen tanks that have ratios greater than 50%, he says.

Fuel cells or combustion?

Subsonic jetliners such as the Boeing 737 are powered by turbofans, which use mechanical energy derived from a gas turbine to accelerate air rearward by means of a ducted fan. Today's gas turbines could burn hydrogen with relatively few modifications. "You can almost just drop hydrogen into today's engines," says Ansell. Simpson compares the conversion process to adapting a propane grill to operate with natural gas. But though it would produce no CO_2 or soot, hydrogen will produce pollutant nitrogen oxides (due to nitrogen's presence in air) and water vapor. A greenhouse gas, water vapor at high altitudes remains in the atmosphere longer than at lower elevations, where it precipitates as rain.

Hydrogen-fueled proton exchange membrane (PEM) fuel cells are emissions-free if the hydrogen comes from carbon-free sources, and their exhaust water can be condensed before release. PEMs, though, provide only half the 3.7 kW/kg power per unit weight of modern gas turbines burning conventional fuel, says Ansell, not including the weight of the fuel or the tank. Still, that's an order of magnitude improvement from the 0.3 kW/kg of 15 years ago, and continued advances are likely.

Today's PEM fuel cells should compete with piston aircraft engines in powering four- to six-passenger aircraft, says Ahluwalia. But their energy-to-weight ratio is far below that of turboprops and turbines.

The fan of a turbofan provides about 80% of the engine's total thrust, with the remainder delivered by combustion. It's hoped that fuel-cell systems can be developed to deliver the entire thrust of a turbofan by electric power. Alternatively, fuel cells could be supplemented with battery power during takeoff and ascent.

"We'll probably never compete with the specific power of a gas turbine," says Dave Tew, a program manager for electric flight systems at the Department of Energy's Advanced Research Projects Agency–Energy (ARPA–E). But the hope is that the efficiency of fuel cells and electric drive systems can be improved enough to match or exceed the energy-to-weight ratios of the turbine and fuel combined.

Airbus has produced three concepts for hydrogen-fueled airliners with capacities of up to 200 passengers and ranges of 2000 nautical miles (3700 km) or more. Each is proposed to be powered by a hybrid system of combustion turbines and fuel-cell-driven motors. In a turboelectric configuration, a hydrogen-fueled gas turbine drives an electric generator, and the fan is driven by an electric motor.

"We think that at the 1000- to 2000-mile ranges, turbines will be required, but we will see as we go through the pencil sharp-

ZEROAVIA

ZEROAVIA's six-seat fuel-cell-powered aircraft made its maiden flight in September 2020 in Cranfield, UK. The company claims it is the world's largest hydrogen-powered aircraft.

AIRBUS

THREE CONCEPTUAL HYDROGEN-FUELED airliners from Airbus all combine hydrogen-burning gas turbines with hydrogen fuel cells that generate electrical power. The turboprop (bottom) would carry up to 100 passengers and have a range of 1000 nautical miles. The others would carry up to 200 passengers, with a range of 2000 nautical miles.

ening," Simpson says. "We've already seen some countries in Europe saying that aircraft within their borders will have to be zero [carbon] emission. Whether [those requirements] will be enough to launch a larger aircraft like we are talking about remains to be seen in interest from our customers," she says.

Airbus envisions synthetic fuels produced from renewable sources, not hydrogen, powering its future long-range 300- to 400-seat airliners. Though the company already is familiar with hydrogen in aerospace applications, adapting the fuel to aircraft that will be emptied and filled multiple times a day will be a new challenge, Simpson says.

R&D needed

Whereas PEM fuel cells rely on a liquid electrolyte to shuttle protons between electrodes, solid oxide fuel cells (SOFCs) use an oxide material, usually yttria-stabilized zirconia, as the electrolyte to produce electricity by oxidizing a fuel. The cells can be fueled by liquid hydrocarbons or ammonia. SOFCs offer higher efficiencies than PEMs. But they weigh significantly more, and heavier hydrocarbon fuels such as gasoline or kerosene must first be reacted by steam or air to form simpler molecules such as hydrogen and methane. For very long flights, the higher efficiency of SOFCs may make up for their greater weight, says Ansell.

In August ARPA–E awarded $13.1 million in grants to six companies to develop different SOFC technologies for aviation. Tew says weight reduction is a major thrust of the R&D. Other DOE programs support PEM research, so ARPA–E's program specifically excluded them.

Thermal management at altitude will be an issue for any type of fuel cell, notes Ansell, since the lower air density diminishes capacity to shed waste heat. "The question is how efficiently you can reject the heat, and SOFCs are actually quite good at this." The high operating temperatures of SOFCs—around 800 °C, compared with PEMs' 100 °C—actually improve heat removal due to the wider differential between fuel-cell and ambient temperatures. Moreover, the waste heat from an SOFC might be directed to drive a gas turbine, in a manner analogous to an automobile turbocharger, he says.

To obtain oxygen, fuel cells require a sufficient airflow that may not be achievable at high cruising altitudes. That problem could be overcome by compressing air, albeit at the expense of power available for propulsion.

Hydrogen-fueled aircraft will need to meet the same levels of safety and integrity as those fueled with kerosene. "How do you inert a fuel tank with hydrogen?" says Boeing's Sinnett, using industry language for reducing the risk of fuel-tank flammability. "How do you fuel the airplane? How do you avoid electrostatics in the fueling process? How do you ensure the structural integrity of the fuel tank?" If solutions can be found to those questions, the next step is determining whether that aircraft can be efficient. "Almost anything is achievable from an engineering and technology standpoint, but you have to ask if the result will be practical," he says. Finally, the plane must be built to hydrogen-specific safety and regulatory standards that don't yet exist.

The infrastructure

Adoption of hydrogen fuel will be impossible without a fueling infrastructure. But the challenge should be less daunting for airlines than it is for car owners. If demand warranted, hydrogen could be produced on site, thereby eliminating distribution costs. ZeroAvia plans to do just that, using nearby renewable energy sources to power electrolyzers. In the company's scheme, a single airport hub could service multiple round-trip routes of its aircraft, so long as flights are 250 nautical miles (about 460 km) or less each way, Miftakhov says. That's suitable for flights between London and Paris or between New York and Boston.

Miftakhov predicts that the cost of fuel cells and electrolyzers should follow a similar trajectory as photovoltaics, whose costs have fallen more than 80% in the past 10 years. "In three years we will get to half of today's cost for hydrogen at the point of consumption, partly through improvements in scale." Even small airports could produce and dispense multiple tons of hydrogen per day, he says; a typical vehicle fueling station, for comparison, sells 200 kg a day. The high aviation volume should drive down the price from its uncompetitive level of $12–$15/kg at filling stations. The efficiency of electrolyzers also continues to improve markedly (see PHYSICS TODAY, August 2020, page 20).

Several interested parties have already approached Airbus about providing fuel to airports should the company decide to move forward on hydrogen, says Simpson. "The International Energy Agency has said we can expect to see green hydrogen capacity of 40 gigawatts in Europe by 2030, and we expect the rest of the world will have to jump on."

David Kramer PT