CLEAR SKIES AHEAD

THE MARKET FOR GAS TURBINES SEEMS TO HAVE AN UNLIMITED CEILING.

BY LEE S. LANGSTON

The latest-generation Boeing 737 MAX, powered by a pair of advanced LEAP-1B engines, made its maiden flight in January.

By any measure, the commercial aircraft business is booming. Airbus delivered 635 commercial aircraft in 2015, while Boeing topped that at 762. The two giant airframe manufacturers netted more than 1,800 orders last year, leaving them with a backlog of more than 12,000 aircraft, according to *Aviation Week & Space Technology*.

Together with last year's deliveries, the aircraft orders in the pipeline are the equivalent of replacing about two-thirds of the estimated worldwide air transport fleet. It will take roughly ten years to clear that backlog at today's rate of production. Considering that airframes can last decades—the U.S. Air Force is flying B-52s built in the early 1960s—it is fair to ask what's driving this rush to replace the world's commercial fleet.

One hint comes from Steven Udvar-Hazy, who gave an interview to *AW&ST* in 2007, while he was still CEO of International Lease Finance Corporation, a leader in leasing commercial jet aircraft to airlines. Udvar-Hazy, whose $65 million donation financed an annex to the Smithsonian Air and Space Museum at Washington's Dulles Airport, made clear that replacement of existing commercial aircraft hinged more on engine technology than anything else. If new engine technology could deliver a double-digit improvement in direct operating costs over what airlines were paying, that would be a compelling reason to upgrade.

The commercial jet engine industry has met Udvar-Hazy's challenge. The new engines being produced and marketed are quieter and more fuel efficient than previous generations. They will reduce fuel consumption, a major airline direct operating cost, by more than 15 percent (with 20 percent reductions promised in the near future), thereby clearing the bar of double-digit percentage improvements.

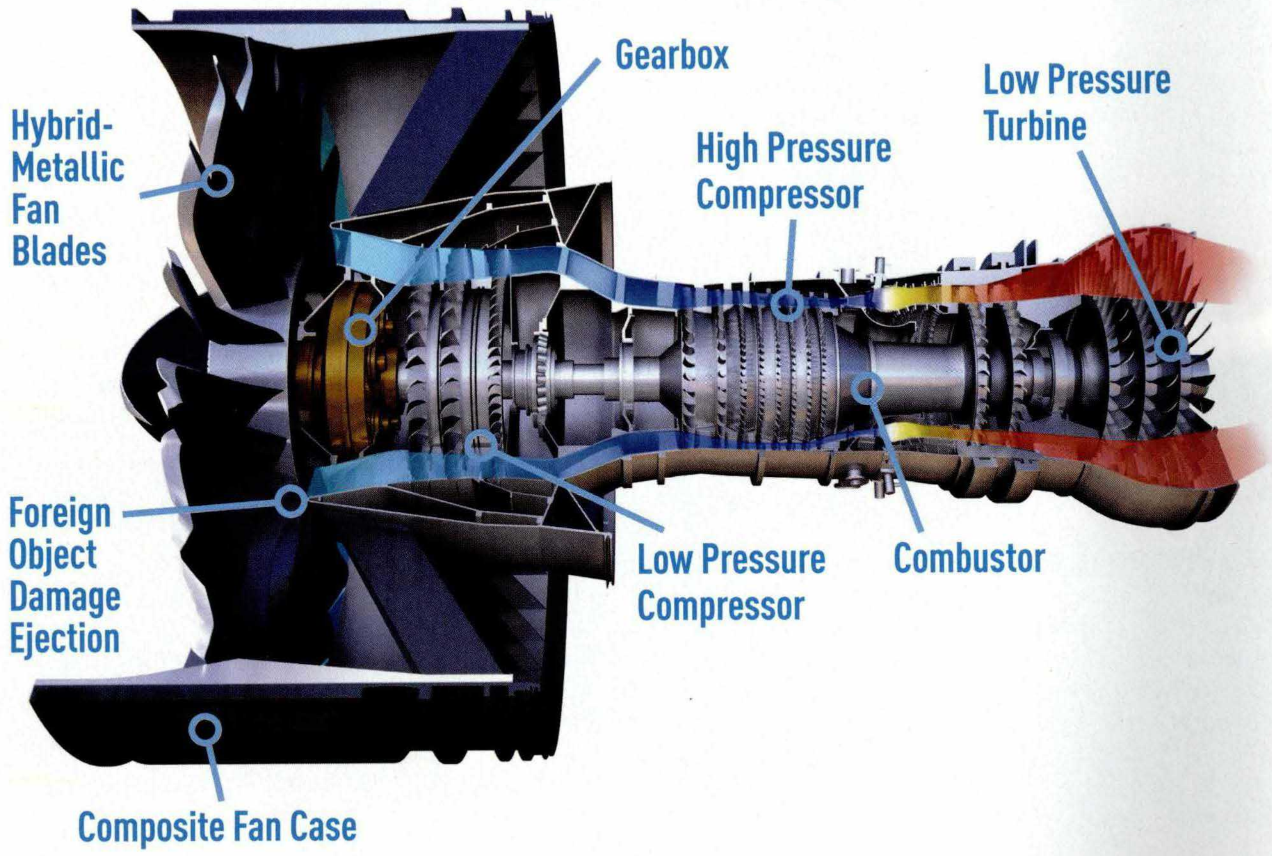
It is quite an accomplishment to see a disruptive advance in what might seem like a mature technology.

GOLDEN ENGINES

Building engines for commercial jetliners is the largest market segment for the gas turbine industry, but it is far from the only one. To get a complete view of the industry and how it has evolved, I turn each year to Forecast International of Newtown, Conn., which uses computer models and an extensive database to calculate the financial picture for both the aviation and non-aviation markets. FI has computed the value of production of gas turbine manufacturing, which the company considers more accurate than reported sales, from 1990 to 2015 and has predicted values to 2030.

Those numbers tell quite a story. FI's financial report shows that the worldwide value of production for gas turbines was $83.5 billion in 2015, up from $81.4 billion in 2014. Aviation gas turbines had a value of production of $63 billion in 2015; that market was split between military jet engines, with a value of production of $8.1 billion, and engines for commercial aviation, of which $54.9 billion worth were produced. All told, aviation accounted for more than three-quar-

THE PRATT & WHITNEY PW1100-G GEARED TURBOFAN



ters of the gas turbine market. (The rest of the market is made up of non-aviation gas turbines—those produced to provide electrical power, mechanical drive in uses such as natural gas pipeline compression, and marine power.)

FI's value of production history and predictions show a steady monotonic growth for the aviation segment beginning about 2003 and running through 2030.

The engine market for single-aisle aircraft such as Boeing's 737 and Airbus's A320 families has been the most lucrative. Each aircraft in that class is powered by two 20,000-to-30,000 pound thrust engines produced by either CFM International (a joint venture between General Electric and Snecma) or International Aero Engines (a partnership led by Pratt & Whitney).

Both GE and P&W have new high-efficiency engines in the single-aisle market. CFM International's new single-aisle engine is a high-bypass turbofan GE calls LEAP, short for Leading Edge Aviation Propulsion. Compared to the company's CFM56, the current market leader, LEAP has a higher bypass ratio, a larger diameter carbon fiber composite fan, and a higher compression ratio. LEAP had its first model certified last year and there now are roughly 10,000 on order.

LEAP will be the first production engine using ceramic matrix composites in its gas path. Those CMCs are a composite of fine intertwined ceramic silicon carbon fibers embedded in and reinforcing a continuous silicon carbon-carbon ceramic matrix. About one-third the weight of high temperature alloys, CMCs are just as strong and can withstand higher temperatures than the metals they replace. The LEAP will use CMCs in the shroud of its first stage high pressure turbine. (I wrote about this use of CMCs in the March 2016 issue.)

GE is expanding the application of CMCs to its 100,000 pound thrust GE9X engine, now under development for Boeing's 777X airframe and scheduled to enter service in 2020. It will feature CMC combustion liners, high-pressure turbine stators, and first stage shrouds.

Meanwhile, Pratt & Whitney has been developing a new single-aisle engine since the 1980s. Now on the market, the PW1000G series is a geared turbofan. It has a hub-mounted planetary gearing system that drives the fan at lower speeds, resulting in much less engine noise and permitting greater fuel economy.

The first customer for Pratt's geared turbofan is Lufthansa, which is flying the Airbus A320neo passenger aircraft powered by PW1100-G engines between German cities. Initial reports indicate the geared fan engines are not only meeting fuel requirements but also are notably quieter. The characteristic jet engine whine has been replaced with the geared fan's whoosh, and passengers report not hearing engine noise once the cabin doors are closed before takeoff.

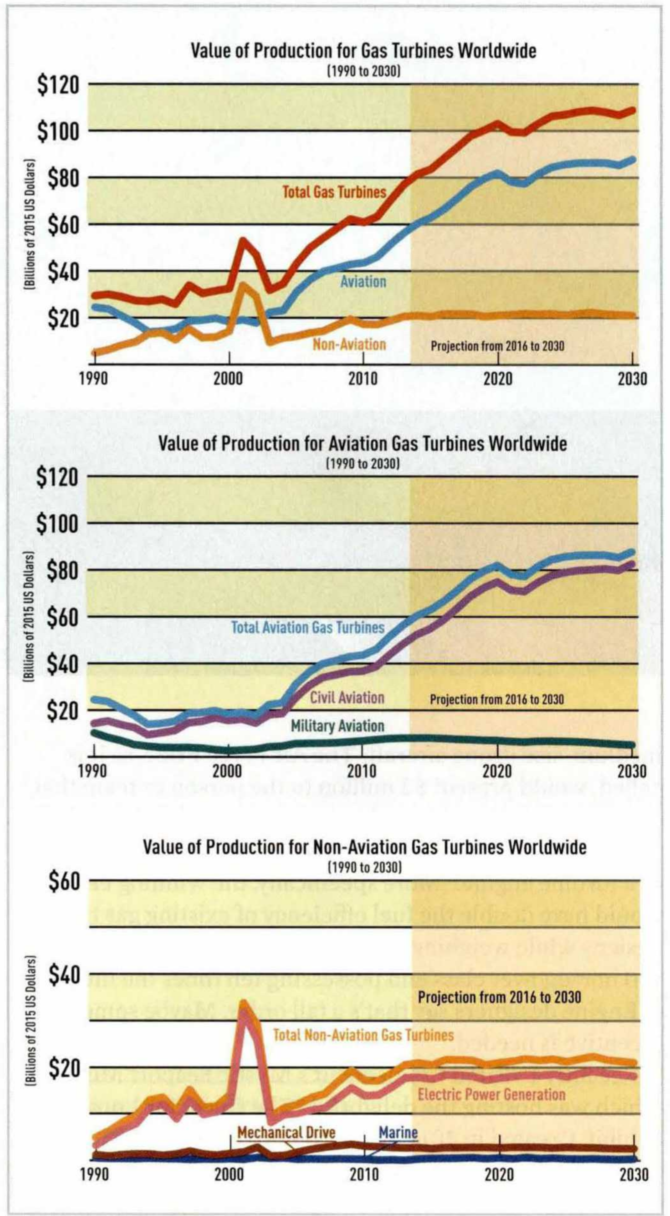
Decades ago, Pratt & Whitney (known then as Pratt & Whitney Aircraft, to avoid confusion with the older Connecticut machine tool company of the same name) had a so-called golden engine that dominated the single-aisle aircraft market. Over time, however, Pratt's JT8D was superseded by GE-Snecma's CFM56, which has seen more than 25,000 in service since 1974. Pratt has invested more than $1 billion over two decades to develop gear technology on the gamble that the geared turbofan would develop into its next golden engine. To date, Pratt reports that it has more than 7,000 orders for its PW1000G series engines.

EXTRA INCENTIVES

The other segment of the aviation market, those jet engines produced for military aircraft, is a key part of the industry in spite of its relatively small value of production. Advanced technology developed for military programs—historically, this includes film cooling and single crystal turbine blades—have filtered into other gas turbine areas.

In 2015, the Pratt & Whitney F135 engine program for the Lockheed Martin F-35 Joint Strike Fighter dominated the military segment. Now in production, the F135 is a 3,600 °F (1,982 °C) class engine, whose high temperature technology should lead to more efficient commercial engines in the future. Pratt delivered 50 F135s in 2015, with plans for 58 in 2016. Production of the JSF is occurring at assembly sites in the U.S., Italy, and Japan, reflecting the international partnership for the F-35 fighter.

One other 2015 military gas turbine program of note was the announcement of an U.S. Air Force competition for an innovative design of a small turbine engine, suitable for a



Data courtesy: Forecast International.


Littoral combat ships, such as the USS *Independence* of the U.S. Navy, use General Electric LM2500 gas turbines.

Photo: U.S. Navy

medium-size drone aircraft. The Air Force Prize, as it is called, would present $2 million to the person or team that can develop "a new kind of turbine engine with the fuel efficiency of a piston engine and the low weight and durability of a turbine engine." More specifically, the winning engine would have double the fuel efficiency of existing gas turbine designs while weighing a fraction of a piston engine in the 100 horsepower class and possessing ten times the life span.

Engine designers say that's a tall order. Maybe some extra incentive is needed.

Recently I visited Connecticut's Mystic Seaport Museum, which was hosting the delightful "The Quest for Longitude" exhibit. Created in 2014 by the National Maritime Museum in London, the exhibit commemorates the 300th anniversary of the British government's Longitude Act of 1714, which offered a prize of £20,000 to the person who could accurately measure longitude from a vessel. The act eventually brought forth precision timepieces—the best from clockmaker John Harrison—that were capable of producing accurate longitude measurements.

More than 300 years later, the U.S. government is trying the same approach to spur gas turbine development. But the $2 million prize doesn't seem adequate. When adjusted for inflation the £20,000 Longitude prize is worth $45 million today. That seems more in line with the challenge.

WARRANTED OPTIMISM

Slightly less than a quarter of the gas turbine market is in the non-aviation segment, which had a value of production in 2015 of $20.5 billion, according to Forecast International. That segment can be subdivided further: Mechanical drive gas turbines, usually installed to drive compressors in liquefied national gas plants and to boost pressure along natural gas pipelines, amounted to $2.6 billion for 2015; while marine gas turbines, used to drive shipboard generators for propulsion and electricity, accounted for $400 million.

That leaves $17.5 billion for the major non-aviation segment, electric power gas turbines. Those are used in simple cycle or combined cycle (possessing both gas turbines and steam turbines) power plants, using gas turbines with output up to 510 MW and thermal efficiency up to 44 percent. Combined cycle plants with a single gas turbine and steam turbine currently can have an output as high as 764 MW and a current proven efficiency of up to 60.75 percent.

The electrical power gas turbine market experienced a sharp boom and bust from 2000 to 2002 as a result of the deregulation of many electric utilities. Since then, however, the electric power gas turbine market has shown a steady increase, right up to present times.

Forecast International projects the value of production for electrical power gas turbines to flatten out over the next 15 years, but I think there is a compelling case for a sustained increase.

To start with, about 40 percent of the world's electricity is generated in Rankine cycle, steam-powered coal-fired power plants. In the United States, those plants operate with a thermal efficiency of about 30 percent, and that's probably typical elsewhere. Modern combined cycle gas turbine plants, burning natural gas, now have a thermal efficiency of 60 percent. At the same time, the amount of carbon dioxide per unit of energy produced by combusting coal is about twice that of natural gas. Thus, replacing a coal power plant with a new, more efficient natural gas CCGT power plant reduces CO_2 by a factor of almost four, resulting in a substantial 75 percent reduction in CO_2 greenhouse gas production.

To the emissions argument, one can add an economic one: The capital cost of a CCGT plant is between $700 and $1,200 per kW. That compares favorably to a new Rankine-cycle steam component, which is in the $2,000 per kW range, let alone a nuclear power plant that can run well more than $5,000 per kW. And in the United States at least, natural gas is plentiful and currently competitive with coal in price. (In countries that must import their gas, the price can be much higher.)

Thus my forecast is that over time, gas turbine plants will push out coal-fired plants. Since the coal-fired segment is so large, I would argue for a growing future market for gas turbines.

In that, the world would follow the lead of New England, a region that has an electrical load demand as high as 30,000 MW and no fossil fuel resources. Coal-fired plants now supply less than 5 percent of the electrical load, having been largely replaced by new natural gas-fired gas turbine power plants.

Working in tandem with renewable energy power facilities, the new fleet of gas turbines will provide reliable, on-demand electrical power at a reasonable cost.

Forecast International projects the entire gas turbine industry will have a value of production by 2030 of $108.9 billion. That is a 31 percent increase over 2015—quite an increase. But since FI predicts that almost all that growth will be due to commercial aviation, I believe that optimistic forecast should be considered a minimum.

As a global growth industry, gas turbines look to have clear skies ahead. **ME**

LEE S. LANGSTON is an ASME Fellow and professor emeritus of the mechanical engineering department at the University of Connecticut in Storrs.


The 550-MW Rhode Island State Energy Center in Johnston is one of the efficient combined cycle gas turbine power plants that replaced coal power in New England.

REFERENCES

1. Flottau, J., and Norris, G., "Building Volume," *Aviation Week and Space Technology*, January 18-31, 2016, pp. 24-26.

2. "Straight Talk," *Aviation Week and Space Technology*, August 6, 2007, pp. 58-60.

3. Norris, G., "Boom Time for Civil Engine Makers," *Aviation Week and Space Technology*, December 24, 2015.

4. Langston, L.S., "Hot Plates", *Mechanical Engineering* magazine, March 2016, pp. 42-27.

5. Langston, L.S., "Gas Turbines-Major Greenhouse Gas Inhibitors," *Global Gas Turbine News*, in *Mechanical Engineering* magazine, December 2015, pp. 54-55.