The Pratt & Whitney geared turbofan engine, shown being readied for a test, may reduce aircraft noise at takeoff by 77 percent.

CHANGING THE GAME

POTENTIALLY RADICAL ADVANCES IN GAS TURBINES CAME IN ALL SHAPES AND SIZES IN 2007.

BY LEE S. LANGSTON

Air travel has traditionally been a symbol of freedom and limitless potential. But in recent years its image has changed for the worse. Part of the blame for that, to be sure, sits squarely with the experience of modern airports and airlines—from the intrusive security checkpoints to the low-frills operations aboard the planes.

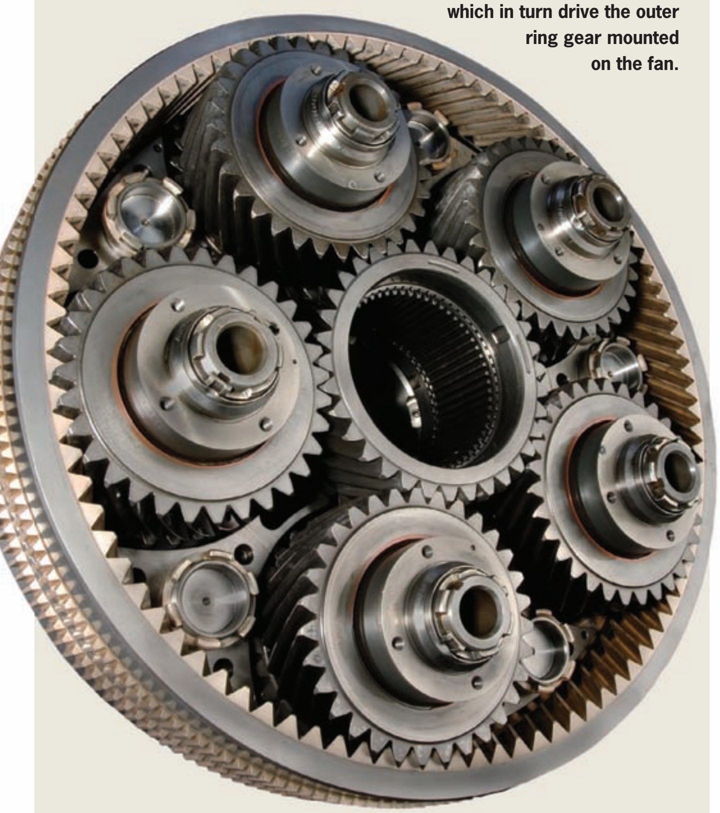
Some of the problem, however, is in the way airplanes and their engines

Lee S. Langston is Professor Emeritus of the mechanical engineering department at the University of Connecticut in Storrs. He is a member and a past chair of ASME's International Gas Turbine Institute.

interact with the world around us. Jets are loud enough to be considered nuisances to neighbors miles away from the airport. And their fuel consumption and carbon emissions have some people questioning whether air travel is even sustainable in the coming century.

Even without those sorts of concerns looming, Pratt & Whitney's introduction last year of its new commercial jet engine would have been remarkable. But the geared turbofan engine, which Pratt has been developing since the early 1990s, promises to be a game changer. It will significantly cut fuel use—by more than 12 percent—manifestly reduce jet engine noise and reduce NO_x emissions by use of an advanced combustor design and reduced fuel consumption.

Gas turbine production is now a $30 billion industry, one that has been dominated, except for a stretch in the late 1990s, by commercial and military aviation. That trend continued in 2007, and exciting developments like Pratt's GTF suggest why. The game is constantly changing, but every year provides breakthroughs and landmarks.


The gear system inside the GTF reduces the speed of the fan to optimal levels. The sun gear meshes with five fixed planet gears, which in turn drive the outer ring gear mounted on the fan.

In its 70-year history, the gas turbine has become one of society's most important and versatile energy-converting machines. And its impact can create a chain of energy conversion. Consider the Pentagon's recent award to Northrop Grumman and European Aeronautic Defence and Space Co. of a $35 billion contract for the KC-45 refueling tanker aircraft, which has made international news. The contract winner gets a lucrative jet engine order to power 179 tankers, whose job is to transport and deliver fuel to other jet aircraft in flight. Jet fuel in a tank is relatively inert; fuel converted to power through a gas turbine is as kinetic a substance as you can find, and one that can create great wealth.

One way to gauge the influence of the gas turbine industry is to look at its recent financial history. Analyst Bill Schmalzer of Forecast International in Newtown, Conn., tapped his company's computer models and extensive data base to provide a look at the values of gas turbine manufacturing production from 1990 to 2007. (Value of production is a more accurate indicator than sales figures.) Trade journals usually report separately on the gas turbine aviation market (jet engines and turboprop engines for manned aircraft) and the gas turbine non-aviation market (electric power generation, mechanical drives, and marine ship power), but FI's values of production allow us to view the entire gas turbine picture. The total worldwide value of production for gas turbines for 2007 was $32.3 billion, compared to an average of $26.2 billion over the previous 18 years. The business is definitely growing.

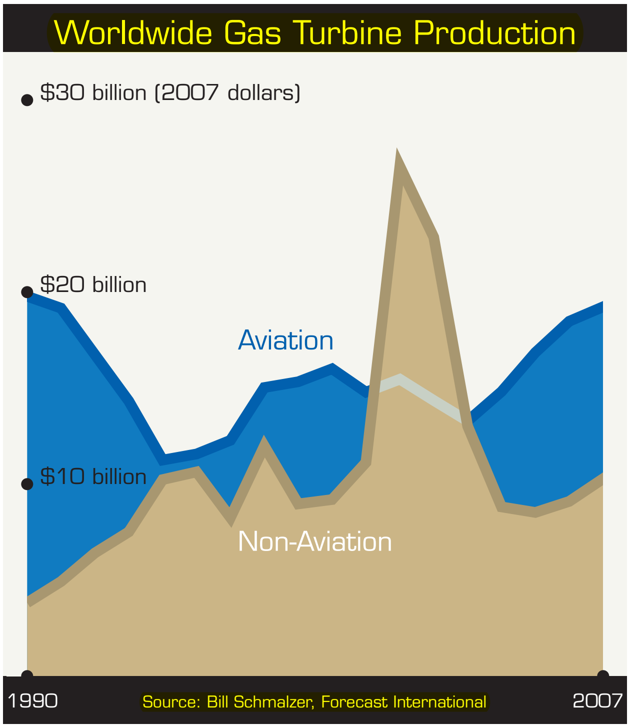
In the $21.8 billion aviation market, nearly 80 percent is for commercial aircraft engines, while the dominance of electrical generation in the $10.5 billion non-aviation market is even greater.

Even so, some of the highest-profile developments in the past year have been in the smaller market segments. Military jet engines account for only $4.5 billion of gas turbine production, but the technology developed there results in benefits for commercial aviation. Important programs in 2007 and the future include the Pentagon tanker award, and the F135 engine for the Joint Strike Fighter, which was discussed last year ("Fahrenheit 3,600," April 2007). The JSF program will hit another benchmark with the first flight of the JSF Lockheed Martin F-35B, scheduled for later this year. Unmanned aerial vehicles, which are increasingly used for reconnaissance and surveillance—and, in some instances, covert attack—are another growing market for military jet engines.

The market for commercial aircraft jet engines is still bouncing back from a decline in the 1990s. (The all-time record for value of production was set in 1990 at the tail end of the airline expansion of the 1980s.) Last year saw a 17 percent increase over 2006, and FI is predicting a steady rise in production to $23 billion—a 36 percent increase over 2006—by 2011.

As this is written, it also looks as if 2007 will be the first profitable year in the commercial airline industry since 2000, when it subsequently fell prey to both 9/11 and SARS. Posting a net profit is all the more remarkable, considering that the price of jet fuel climbed from about $1.60 per gallon in late 2006 to as much as $2.80 per gallon by late 2007. The industry's renewed strength has led to a record year of new aircraft orders for the big plane manufacturers—Boeing, which received more than 1,400 new orders in 2007 alone, and Airbus—and, of course, for the engine makers. Of the three big engine producers, General Electric led, followed by Rolls-Royce and Pratt & Whitney.

New commercial planes on order include the 555-pas-



Worldwide Gas Turbine Production

Source: Bill Schmalzer, Forecast International

The value of production for non-aviation gas turbines spiked in 2001. The industry on the whole has, however, shown consistent growth.

senger super-jumbo A380 from Airbus and the Boeing 787, a 296-passenger sub-jumbo. The first production A380 is now flying for Singapore Airlines. The 787, which has a truly innovative all-carbon fiber fuselage, will be first flown this year and is powered by two jet engines, either the new GE GEnx or the R-R Trent 1000. Airbus offers the A380 powered by either the R-R Trent 900 or the GE-P&W Alliance GP 7200.

New aircraft represent advances for commercial aviation, but commercial jet engines are themselves the key to future growth of the airline industry. Steven Udvar-Hazy, chief executive officer of International Lease Finance Corp. and much listened to as an expert on the airline industry, said, “More than any other new airplane design we’ve seen in the last 20 to 30 years, replacements [of existing aircraft] hinge more on engine technology than anything else.” His remarks, printed last August in *Aviation Week & Space Technology*, also called for the need for greater fuel economy and acknowledged the growing governmental and public pressure to reduce noise and emissions.

Pratt & Whitney’s formal introduction of its new geared turbofan engine meets the needs called out by Udvar-Hazy: It will be cleaner, quieter, and more efficient than almost anything else in the air.

Most large commercial turbofan engines are twin-spool gas turbines with two concentric shafts. A longer, lower-rpm shaft—connecting the front fan and low-pressure compressor to a low-pressure turbine—rotates inside a shorter, higher-rpm shaft that connects the high compressor to the high turbine. Indeed, Rolls-Royce engines have a third intermediate pressure spool. With a large frontal area, the commercial turbofan is designed to produce peak thrust at aircraft takeoff speeds, with most of the thrust produced by air drawn in by the fan that bypasses the engine itself. A typical bypass ratio is 6:1 with 6 pounds of air bypassing the engine for every one pound through the engine.

Engine compressors and turbines run most efficiently at higher rpm, while fans operate best at lower speeds. The unique feature of the geared turbofan engine is a fan hub-mounted epicyclic, or planetary, gearing system that drives the fan at lower speeds, permitting higher bypass ratios. By using a three-to-one gearing system, the GTF fan speed is cut by one-third, allowing for much less fan noise and higher bypass ratios—8:1 to 11:1. With such a high bypass ratio, fuel consumption goes down. A gearbox adds weight to the engine, but this is counterbalanced by the need for fewer engine airfoils, since engine components can now run at more efficient speeds that aren’t limited by fan aerodynamics or stress limits.

The gearing system in the GTF must be capable of transmitting on the order of 30,000 horsepower. That means any significant gearing inefficiencies must be eliminated to prevent damage to the gear lubricants and to prevent gearbox overheating. During the keynote discussion period at the ASME Turbo Expo in Reno in 2005, retired Rolls-Royce chairman Sir Ralph Robins and retired GE Aircraft Engines CEO Brian Rowe both remarked that as young apprentice jet engine engineers they had learned that gear systems were to be avoided. Louis Chenevert, then Pratt & Whitney’s president, retorted that the company’s successful engineering development of the GTF gear system showed that not to be the case. It should also be noted that a much smaller Honeywell geared fan has been in service since the 1970s.

WHOOSH INSTEAD OF A WHINE

Late in 2007 Pratt completed the first tests of the GTF demonstrator engine at test stands in Florida. “It doesn’t sound like a jet engine,” noted one P&W staffer, and another added that the characteristic turbofan whine is gone, replaced instead by a “whoosh.” Noise calculations show that the GTF could reduce the size of the noise footprint during takeoff by as much as 77 percent. A 30,000-pound thrust GTF demonstrator will be flight-tested on a Boeing 747SP later this year.

The GTF engine will power the new 70-to-90-passenger Mitsubishi MRJ regional jet, with a first flight in 2013. A larger version has been selected for the 110-to-130 passenger Bombardier CSeries commercial aircraft, projected to enter service in 2013.

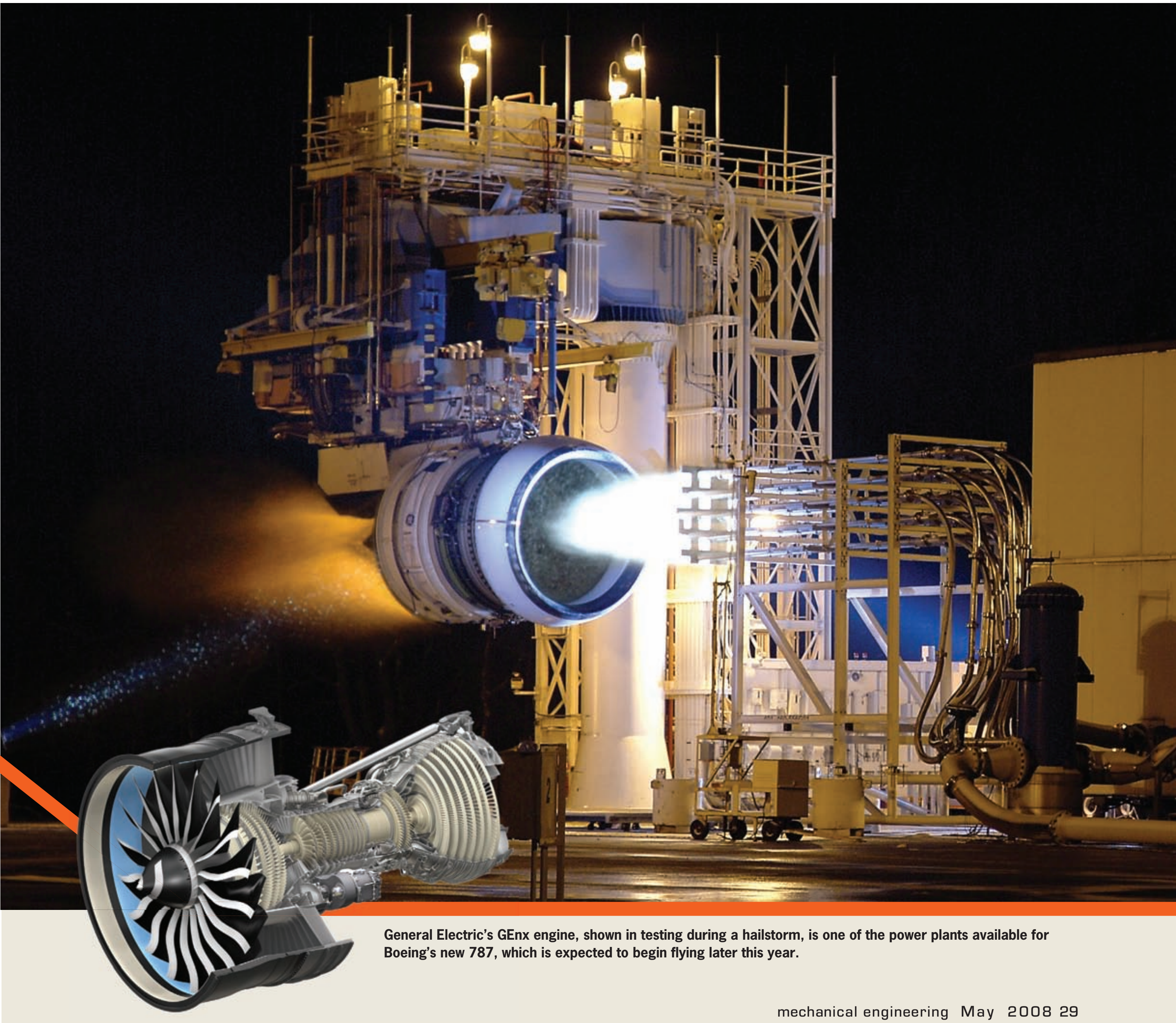
The smallest end of the passenger airplane market is still the scene of much activity. As many as 8,000 very light jets are forecast to be flying in U.S. airspace by 2025. The VLJs are twin-engine jets with a pilot and from three to eight passengers, providing point-to-point, on-demand air taxi service, typically for flights shorter than 500 miles.

Late in 2007, DayJet began offering air taxi flights within Florida on three-passenger Eclipse 500s, each powered by two Pratt & Whitney Canada PW610F engines. According to DayJet, one of the pioneers in this new air taxi service, fares will vary between $1 and $4 per mile. Williams International and a Honda/GE collaboration are also supplying engines for this market.

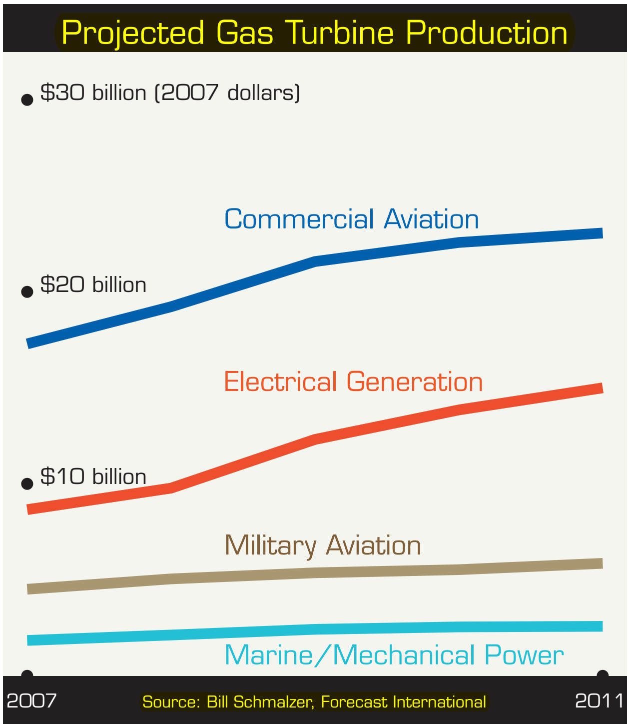
While the aviation market has seen steady growth over the past decade or so, the non-aviation market for gas turbines has a noticeable production spike. Indeed, it could be a case study of the market principles that Alan Greenspan discusses in his 2007 book, *The Age of Turbulence*. In 1990, the market for non-aviation gas turbines—again mostly for electrical power production—was $3.8 billion. As the efficiency and durability of these land-based units grew in the 1990s, the value of production figures increased. Combined-cycle plants based on gas turbines and steam turbines, with thermal efficiencies almost double that of conventional power plants, were coming on line.

By 2000, the value of production stood at $11.1 billion for non-aviation gas turbines and then the market took off, rising to $26.6 billion in 2001, overshadowing the aviation market at that point. This boom was part of a process Greenspan describes as "creative destruction": " . . . A market economy will incessantly revitalize itself from within by scrapping old and failing businesses and then reallocating resources to newer, more productive ones." During this period, for instance, four or five gas turbine combined-cycle plants were built near me, in southern New England, displacing older, operational, steam power plants.

Unfortunately, the gas turbine market had got caught up in another Greenspan coinage—"irrational exuberance." When the bubble popped, production plummeted to about $8.5 billion in 2005. It has been recovering slowly ever since, and Forecast International predicts growth continuing through 2011.



General Electric's GEnx engine, shown in testing during a hailstorm, is one of the power plants available for Boeing's new 787, which is expected to begin flying later this year.



Source: Bill Schmalzer, Forecast International

According to data from Forecast International, the prospects for commercial jet engines and gas turbines for electrical generation are bright.

Gas turbine electrical generation has much to recommend it. The capital costs of gas turbine electric power plants are the lowest of all. A light water nuclear power plant may cost as much as $4,000 per kilowatt. An installed kilowatt of a coal-fired steam turbine power plant might be $1,200 to $1,600. The latest gas turbine figures given by *Gas Turbine World* in its *2007-08 GTW Handbook* are as low as $200 per kilowatt for simple cycle and $400 per kilowatt for combined-cycle gas turbine power plants.

Although many units can burn fuel oil, natural gas is the fuel of choice for a gas turbine power plant. The price of natural gas had been relatively stable in the United States—around $2 per million Btu—but it now can soar above $10 per million Btu in winter months. The push to use coal as fuel for these turbines in integrated gasification combined-cycle plants has stalled due to the uncertain regulatory future of carbon emissions, the recent cancellation of the Department of Energy's FutureGen program, and the rising IGCC capital cost.

That leaves natural gas-fueled turbines as the most attractive power plant. To be sure, nuclear power is showing signs of a comeback, but these plants have a decade-long lead time for permitting and construction. There is much activity in developing new high-temperature nuclear gas turbine power plants (see "Pebbles Making Waves," February 2008).

One of the most innovative electric power turbines introduced in recent years is Solar's Mercury 50 unit, a 4.6-megawatt gas turbine suitable for industrial, hospital, or university cogeneration sites. A simple-cycle gas turbine of that size could be expected to have an efficiency of about 30 percent, but the Mercury 50 operates at 38.5 percent efficiency and has a very favorable emissions profile.

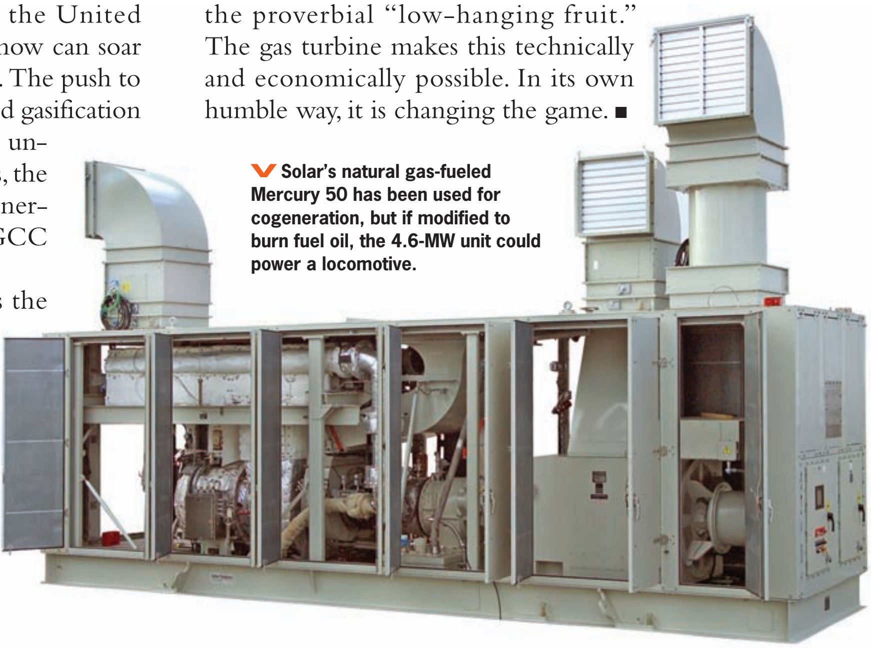
LOW-HANGING FRUIT

The Mercury 50 is the first commercial electric-power gas turbine to have been specifically designed around a recuperator, also called a regenerator by some. This is a heat exchanger that transfers heat from the turbine exhaust to air entering the combustor, helping to raise the thermal efficiency. With recuperators, the challenge is to design a long-life, air-to-air compact heat exchanger without introducing a significant pressure drop in the gas path flow of the unit.

According to Chris Lyons of Solar Turbines in San Diego, the company has sold 30 units in both the U.S. and Europe, since it was introduced commercially in 2004. Recently, I visited Fairfield University in Connecticut where a Mercury 50 unit has been installed and running as a cogeneration plant since January. Fairfield has about 8,000 students and, according to the university energy manager, Bill Auger, the 4.6-megawatt unit supplies all the campus electrical power and heat, using street-line natural gas to supply fuel.

A unique feature of the Mercury 50, which is an axial flow gas turbine, is its roughly "figure eight" gas path, necessary to accommodate the recuperator. The nearby University of Connecticut has a 25-megawatt cogeneration plant (described in "Campus Heat and Power," December 2006), and I am used to seeing a generator at one end of the gas turbines and the exhaust at the other end. With the Mercury 50, one end is the generator, but at the other end, one is looking at the combustor.

In our society's move to conserve high availability energy, such as natural gas, cogeneration is an easy first step—the proverbial "low-hanging fruit." The gas turbine makes this technically and economically possible. In its own humble way, it is changing the game. ■



Solar's natural gas-fueled Mercury 50 has been used for cogeneration, but if modified to burn fuel oil, the 4.6-MW unit could power a locomotive.