Fahrenheit 3,600

Everywhere you look, the gas turbine industry is running hot.

by Lee S. Langston

One of the basic rules of gas turbines is that the hotter the gas that enters the work-producing turbine from the combustor, the greater the thermal efficiency and output. Still, there are limits. Turbine inlet temperatures in the gas path of modern high-performance jet engines usually don't exceed 3,000°F, while non-aviation gas turbines operate at 2,700°F or lower.

But 3,600°F? That temperature exceeds the melting point of iron and the boiling point of molten silver. And yet the turbine airfoils in the new F135 jet engine that powers the Joint Strike Fighter Lightning II are capable of operating at these extreme temperatures. The F135 gas turbine is the first production jet engine in this new 3,600°F class, designed to withstand these highest, record-breaking turbine inlet temperatures.

There have been, in fact, quite a few accomplishments in the gas turbine industry over the last year. GE put into operation a
simple-cycle 100 MW turbine that runs at 46 percent efficiency. Pratt & Whitney ramped up production of engines for a new class of aircraft, the very light jet. And construction of the first pebble bed nuclear reactor, set to be built in South Africa, was placed on the schedule.

But 3,600°F? That's hot. The JSF engine represents a bold—and necessary—step forward. This 40,000-pound thrust engine will power all three variants of the JSF: an Air Force fighter that takes off conventionally, a carrier-based Navy jet, and a short takeoff/vertical landing aircraft for the Marines. The STOVL version is the first aircraft to be able to do the "Hat Trick"—take off in a short distance, go into supersonic flight, then hover and land vertically. These varied missions require a very high thrust-to-weight ratio, and thus high turbine inlet temperatures.

*The powerful engine for the new Joint Strike Fighter on its test platform in Florida (above) will develop 40,000 lbs. of thrust. The jet engine will come in Navy, Marine, and Air Force versions (below).*
Last December, at Pratt & Whitney's Middletown, Conn., plant, Ed Crow, retired senior vice president and head of engineering at Pratt, took a few of us from the University of Connecticut Mechanical Engineering Department to view a F135 engine disassembled after 600 to 800 hours of operation. The blades and vanes of the high turbine, clad with ceramic thermal barrier coatings, are made of single crystal superalloys, which soften and melt at temperatures between 2,200 and 2,600°F. (Single crystal alloys were the subject of an article, "Crown Jewels," in ME magazine in February 2006.) Turbine airfoils closest to the combustor operate in a gas stream that can exceed their superalloy melting point by 1,000°F.
So how do turbine airfoils survive running conditions in this 3,600°F class engine? The vanes and blades are cooled to maintain acceptable service temperatures, some eight-tenths to nine-tenths of their melting temperature. Each high-temperature turbine airfoil is formed from an elaborate investment casting to accommodate the intricate internal passages and surface hole patterns necessary to channel and direct cooling air (bled from the compressor) within and over external surfaces of the airfoil structure. An error in airfoil cooling hole location or in
cooling air pressure ratios could cause airfoil gas path inhalation rather than film cooling exhalation, which at the JSF's high turbine gas path temperatures would induce airfoil expiration. The JSF turbine film cooling design is based on some 30 years of gas turbine industry film cooling research and development, and unequivocally pushes forward the state-of-the-art of turbine performance and durability.

The JSF engine is just one product in the $3.7 billion military gas turbine market, which includes jet engine production for the world's fighter aircraft—such as the F15, F16, F22, F35, and Typhoon—military cargo, transport, refueling, and special-purpose aircraft. And that's just a fraction of the total worldwide gas turbine market.

**A Steep Climb**

David Franus of Forecast International in Newton, Conn., has again this year provided me with values of gas turbine manufacturing production, based on FI's proprietary databases and computer models. FI's values of production of gas turbines are unique in that they are for both aviation and non-aviation, the two disparate parts of the industry, usually reported on separately in trade journals. Worldwide gas turbine production for 2006 amounted to $27.6 billion, up significantly from $22 billion in 2005, but still below the 10-year average of $28.5 billion.

The aviation portion, all for manned aircraft jet and turboprop engines, amounted to $18.5 billion, two-thirds of the 2005 total value of gas turbine production.
The value of gas turbine production for commercial aviation is three to four times that of military, $14.8 billion in 2006. There is a prediction of $16.9 billion in 2010 (a 14 percent increase). This upward trend reflects the growth of the airline industry, evidenced by increased passenger loads (especially for Asian travel) since 9/11 and SARS, and an increase in the number of new airlines. Sales of existing models of Boeing and Airbus aircraft, using a variety of General Electric, Pratt & Whitney, Rolls-Royce, and Snecma engines, are strong, and both airframe companies are developing new models. Boeing has the new subjumbo 787, designed to serve what the company sees as the future demand of air travel, as well as a "new" superjumbo 747-8 family. (The 747 is an incredibly long-lived product line. I remember working on the first JT9D 747 jet engines, back in the 1960s at Pratt & Whitney Aircraft.). Airbus is developing its trouble-plagued superjumbo A380.

The air cargo market is strong and orders for new jet engine-powered freighters are high. Jet engine demand is also strong in regional airline and business aircraft markets.
The Siemens SGT-8000H gas turbine, shown here in a cutaway diagram, is the world's largest, rated at 340 MW.

A booming area for new jet engines is the very light jet, or "air taxi" market (the subject of the article "Very Light and Fast" in January). A VLJ twin-engine aircraft with a pilot and from five to eight passengers, could provide point-to-point, on-demand air taxi service to some of the 5,000 local airports in North America. For flights shorter than 500 miles, VLJ aircraft use could enable air travelers to circumvent the bottleneck created by airport security and could eliminate layovers caused by the existing hub-and-spoke airline system.

Eclipse Aviation, Honda Aircraft Co., Cessna Aircraft Co., Citation, Embraer, and Adam Aircraft have entered the VLJ market, and Eclipse reports orders for 2,500 of its jets. Pratt & Whitney Canada is in full production for several thousand of the VLJ engines, in the 1,000- to 3,000-pound thrust range. Other VLJ engine OEMs are Williams International and Honda/GE.
In contrast with the steadily climbing aircraft market, the value of production for non-aviation gas turbines shows a boom-and-bust quality, rising to a peak of nearly $26 billion in 2001 before dropping back to around $8 billion a few years later. That behavior is caused by the rapid growth in—and sometimes speculative nature of—the electric power market, during this recent era of piecemeal utility deregulation.

Non-aviation gas turbines consist of electrical power generation, mechanical drive (mostly used to drive natural gas pipeline compressors), and marine (Navy, cruise ships, and ferry propulsion). The largest segment of that market by far is electrical power generation, in simple cycle (gas turbine only), combined cycle (gas turbine with its exhaust producing steam for steam turbine generation), and cogeneration (gas turbine, with its exhaust producing steam for heat, as described, for instance, in "Campus Heat and Power," Dec. 2006).

Forecast International predicts significant growth in coming years in demand for gas turbine electrical power generation, rising from $8.6 billion in 2006 to a projected $13.5 billion in 2008, a 60 percent increase. Based on a small sample of OEMs that I interviewed at the big Power-Gen conference and exhibit in Orlando last December, I agree with FI's predictions. In particular, two U.S. OEMs said that the cogeneration market for gas turbines was much stronger in Europe than in the U.S. In the words of one OEM exhibitor, "The sales are strong in those countries that signed the [Kyoto] treaty." Such an observation would seem to be at odds with assertions made by U.S. officials that signing the Kyoto treaty on greenhouse gas emissions would put the U.S.
at an economic disadvantage.

**Cleaning Coal**

In many countries, such as the United States, South Africa, and China, coal is the major energy source, and it is used to produce electricity in steam Rankine cycle plants. At the Sino-American Technology and Engineering Conference I attended in Beijing last October, Xu Kuangdi, the president of the Chinese Academy of Engineering, remarked that of every three power plants currently being built in the world, two were in China, where the major fuel is coal.

Companies and government have been launching projects to design and develop integrated gasification combined-cycle power plants. These IGCC plants convert coal into syngas, a low calorific value gas composed of carbon monoxide and hydrogen; the syngas is then used as fuel for a gas turbine, whose exhaust provides heat to generate steam to run a steam turbine. Using the same fuel twice, in essence, a combined-cycle power plant can have thermal efficiencies as high as 60 percent. There are now only two IGCC plants in operation in the United States, compared with 1,100 pulverized coal steam power plants, all with thermal efficiencies much, much lower than 60 percent. If IGCCs prove to have reasonable capital costs per kilowatt, the market for gas turbines could be very promising.

The first standardized commercial IGCC plants are being built by GE Energy and Bechtel, for American Electric Power, the
U.S.'s largest electrical generator. Also, the U.S. Department of Energy has initiated FutureGen, a program to build the first integrated sequestration and hydrogen production plant. This is to be a zero-emissions fossil fuel plant using, of course, gas turbines.

The very largest electric power gas turbines are identified as H class, a designation that has lightheartedly been interpreted as an abbreviation for "humongous" (see "A Year of Turbulence," ME magazine's Power & Energy, June 2004). A General Electric GE Energy 9H gas turbine weighs in at 405 tons (367,900 kg), and the first one went into natural gas fuel operation at Baglan Bay, Wales, in 2003. In combined-cycle operation this unit can input 520 MW into the U.K.'s electric power grid, at a plant thermal efficiency of just under 60 percent.

Siemens' first H class gas turbine combined-cycle plant is now under construction in Frechting, Germany. It's also slated to have a thermal efficiency over 60 percent, and a plant output of 530 MW. The Siemens SGT-8000H gas turbine itself is rated at 340 MW, making it the world's largest.

The two companies differ in their design philosophy on turbine cooling systems. GE Energy H units are steam cooled—closely tying together the steam (Rankine) and gas turbine (Brayton) cycles—while the Siemens H gas turbine will be cooled by air bled from the compressor.
Wild animals graze along the road to the Koeberg nuclear power station (below). The site, home to a 1,800 MW conventional nuclear power station, will see construction of the world’s first pebble bed nuclear reactor in 2008. The new reactor will have an output of 165 MW.

While H machines are designed mainly for base load electric power markets, General Electric’s new LMS100 gas turbine is aimed at the mid-merit and daily cycling segments—the difficult-to-predict, must-be-ready-to-start electric peak power providers. The LMS100 is rated at 100 MW and, at 46 percent, has the highest efficiency of any simple cycle gas turbine. It is the first
modern production electric power gas
turbine that has an intercooler. This is a
water-cooled, shell-and-tube heat exchanger
through which gas path flow between the
high and low compressor is cooled, making
for less compressor work. The resulting
heated intercooler water can then be used
for some other purposes, but more
importantly, the net gas turbine output is
increased and colder turbine cooling air is
made available, boosting thermal efficiency.

The LMS100 is an aeroderivative, based on
GE's CF6-80C1 jet engine, but perhaps
should be called a hybrid aeroderivative
since the machine's low compressor is
derived from GE's heavy-frame MS6001FA
gas turbine. The first production unit of this
innovative, intercooled gas turbine went into
operation at Groton, S.D., last year.

This past February, while in Cape Town,
South Africa, I visited what will be the site of
the world's first nuclear-powered gas
turbine electric power plant. The consortium
Pebble Bed Modular Reactor (Pty) Ltd. will
begin construction by May 2008, and
Westinghouse of the U.S., Mitsubishi Heavy
Industries of Japan, Nukem of Germany, and
South Africa's utility, Eskom, are all
participating.

This first PBMR unit will have an output of
165 MW provided by a closed-cycle gas
turbine designed and developed by
Mitsubishi and operating with helium gas.
The helium is heated in a nuclear graphite-
modulated, high-temperature reactor,
approximately 88 feet high and 20 feet in
diameter. The reactor is filled with 450,000
fuel "pebbles," managed in such a way that
the reactor need not be shut down for
refueling. Each 6 cm diameter graphite
pebble (about the size of a tennis ball) is heated by nuclear reactions going on in some 15,000 kernels of uranium dioxide, each about 0.5 mm diameter, dispersed in the pebble, and individually encased in protective layers of carbon and silicon carbide.

The helium enters the pebble bed at 500°C and 9 Mpa, and is heated to about 900°C before it enters the turbine, then on to a recuperator, compressor, intercooler, recuperator, and then back into the pebble bed reactor, thus producing a nuclear-heated, Brayton thermodynamic closed cycle. In a closed-cycle operation, electric load variation is accomplished by varying the amount of helium in the system (A book on the subject, Closed-Cycle Gas Turbines, by Hans Frutschi is available from ASME Press). The PBMR is designed to have a relatively high thermal efficiency: 41 percent, compared to 33 percent for a conventional light water reactor using a Rankine cycle.

One selling point of the design is that any loss of coolant will shut down the nuclear reactions. This first PBMR unit, in fact, will be built right next to Eskom's Koeberg 1,800 MW Rankine cycle nuclear power plant. That facility is located on 7,500 acres of the Koeberg Nature Reserve, on the Atlantic coast less than 20 miles north of Cape Town. It's a very picturesque location for a generating station of any sort, and probably the only nuclear power plant in the world patrolled by wild springboks and zebras.

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