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GE Aeroderivative Gas Turbines - Design and Operating Features

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Abstract

Aeroderivative gas turbines possess certain technical features inherent in their design heritage which offer operational and economic advantages to the end user. This paper presents an overall description of GE's current LM series of aeroderivative gas turbines with power output ranging from 13 to 47 MW. It discusses operational and economic considerations resulting from GE's aeroderivative gas turbine design philosophies, and the value of these considerations in a customer's gas turbine selection process.

GE's total research and development budget for aircraft engine technology is approximately one billion dollars a year. Today's entire GE gas turbine product line continues to benefit from this constant infusion research and development funding. Advances are constantly being made which improve GE's gas turbine benefits to the customer.

Introduction

Headquartered in Cincinnati, OH, GE's Industrial Aeroderivative Gas Turbine Division (GE-IAD) manufactures aeroderivative gas turbines for industrial and marine applications. GE Power Systems sells and services the current gas turbine products, which include the LM1600, LM2500, LM2500+ and LM6000. In addition, the LM2000 is offered as an integrated packaged product including an LM2500 gas turbine at reduced rating.

Figure 1 presents the performance characteristics for power generation applications, while *Figure 2* presents the product line's performance characteristics for mechanical drive applications.

GE's aeroderivative industrial products are produced in two configurations:

- Gas turbine, made up of a GE-supplied gas generator and power turbine
- Gas generator, which may be matched to an OEM-supplied power turbine.

These turbines are utilized in simple cycle, STIG™ (Steam Injected Gas Turbine) applications for power enhancement, or integrated into cogeneration or combined-cycle arrangements. GE also produces a variety of engine-mounted, emissions control technologies, described in *Figure 3*.

Selection of Aeroderivative Engines

Prior to commencing production of a new aeroderivative gas turbine based on the current

GE INDUSTRIAL AERODERIVATIVE GAS TURBINE PERFORMANCE CHARACTERISTICS									
GENERATOR DRIVE GAS TURBINE RATINGS									
		OUTPUT	HEAT RATE		EXHAUST FLOW		EXHAUST TEMP.		FREQUENCY
MODEL	FUEL	kWe	Btu/kWhr	kJ/kWhr	lb/s	kg/s	deg F	deg C	Hz
LM1600PA	G	13750	9624	10153	103	46.7	910	488	50/60
	D	13750	9692	10225	103	46.7	928	498	50/60
LM2000	G	18000	9377	9892	139	63	886	474	60
LM2500PE	G	22800	9273	9783	152	69	974	523	60
	D	22800	9349	9863	152	69	994	534	60
LM2500PK	G	30700	8815	9300	192	87.2	959	515	50/60
	D	29600	8925	9415	189	85.8	965	518	50/60
LM2500PV	G	30240	8598	9071	186	84.3	931	499	60
	D	28850	8748	9229	182	82.5	941	505	60
LM6000PC	G	43315	8198	8648	277	126	845	451	60
	D	42111	8293	8748	276	125	851	455	60
	G	42665	8323	8779	277	126	845	451	50
	D	41479	8419	8881	276	125	851	455	50
LM6000PD	G	42227	8246	8698	275	125	841	449	60
	D	41505	8331	8787	273	124	854	457	60
	G	41594	8372	8830	275	125	841	449	50
	D	40882	8458	8921	273	124	854	457	50

Figure 1. GE aeroderivative product line: generator drive gas turbine performance characteristics

GE INDUSTRIAL AERODERIVATIVE GAS TURBINE PERFORMANCE CHARACTERISTICS										
MECHANICAL DRIVE GAS TURBINE RATINGS*										
		OUTPUT		HEAT RATE		EXHAUST FLOW		EXHAUST TEMP.		
MODEL	FUEL	sHP	kWs	Btu/HPhr	kJ/kWhr	lb/s	kg/s	deg F	deg C	
LM1600PA	G	19200	14320	6892	9750	103	46.7	910	488	
	D	19200	14320	6941	9820	103	46.7	928	498	
LM2500PE	G	31200	23270	6777	9587	152	69	974	523	
	D	31200	23270	6832	9665	152	69	994	534	
LM2500PK	G	42000	31320	6442	9114	192	87.2	959	515	
	D	40500	30200	6522	9227	189	85.8	965	518	
LM2500PV	G	42000	31320	6189	8756	186	84.3	931	499	
	D	40100	29900	6297	8909	182	82.5	941	505	
LM6000PC	G	58932	43946	6002	8490	277	126	845	451	
	D	56937	42458	6095	8621	276	125	851	455	
LM6000PD	G	57783	43089	6026	8524	275	125	841	449	
	D	56795	42352	6088	8611	273	124	854	457	
*ISO (15C, 60% RH, SEA LEVEL, NO LOSSES), BASE LOAD, AVERAGE NEW ENGINE										

Figure 2. GE aeroderivative product line: mechanical drive gas turbine performance characteristics

						ENGINE MOUNTED NOx ABATEMENT METHODS		
MODEL	GAS GENERATOR	GAS TURBINE	SIMPLE CYCLE	COMBINED CYCLE	STIG	WATER INJECTION	STEAM INJECTION	DLE
LM1600	X	X	X	X	X	X	X	X
LM2000	X	X	X	X	X	X	X	X
LM2500	X	X	X	X	X	X	X	X
LM2500+	X	X	X	X		X	X	X
LM6000	X		X	X		X	X	X

Figure 3. GE aeroderivative product line: available equipment arrangements

line of aircraft engines, GE considers the following factors:

- Market forecast for marine and industrial engines
- Projected performance and price competitiveness of the new line of aeroderivative engines
- Degree of difficulty involved in converting the aircraft engines design into the new, aeroderivative configuration.

The last point is extremely important. In order to keep a new aeroderivative product's overall cost as low as possible, the aircraft engine chosen as the basis for this line must be convertible from aircraft to marine and industrial usage:

- With very few changes to its original design
- Using parts which are mass-produced for the aircraft application.

Figure 4 shows the operating hours accrued for each of the GE parent engines in flight applications and their derivative engines in industrial and marine service. For example, the LM2500 and its parent aircraft engine have over 63 million hours of operating experience and have

	AIRCRAFT		AERODERIVATIVE	
	QUANTITY	OPERATING HOURS	QUANTITY	OPERATING HOURS
LM1600 (F404)	3400	7,000,000	146	3,500,000
LM2500 (TF39/CF6-6)	1130	32,300,000	1767	31,200,000
LM6000 (CF6-80C2)	2806	58,700,000	300	3,200,000
Data as of February, 2000				

Figure 4. Aircraft and aeroderivative engine operating experience as of February 2000

demonstrated excellent reliability. All GE AeroDerivative engines benefit from this combined experience.

The following sections will introduce and summarize the key characteristics of each of the individual LM model gas turbines. Configuration terminology and arrangement options are defined in *Figure 5*.

compressor. The low-pressure rotor consists of the low-pressure turbine (LPT), which drives the low-pressure compressor (LPC) via a concentric drive shaft through the high-pressure rotor. The high-pressure rotor is formed by the high-pressure turbine driving the high-pressure compressor (HPC). The LM2000, LM2500 and LM2500+ are single-rotor machines that have

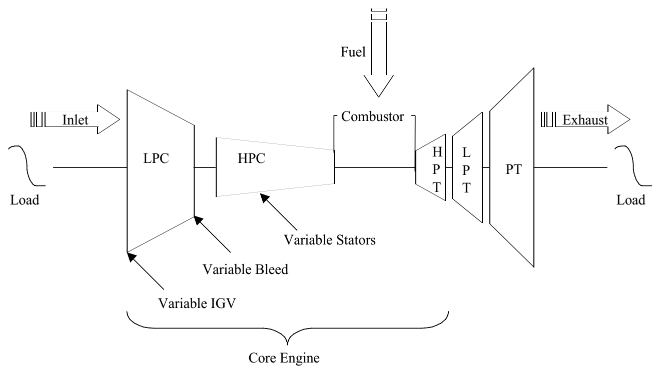

Figure 5. Gas turbine terminology and arrangement

The following features are common to all LM model gas turbines:

- A core engine (compressor, combustor, and turbine)
- Variable-geometry for inlet guide and stator vanes
- Coated combustor dome and liner
- Air-cooled, coated, high-pressure turbine (HPT) blading
- Uncooled power turbine blading
- Fully tip-shrouded power turbine rotor blading
- Engine-mounted accessory gearbox driven by a radial drive shaft.

The LM1600 and LM6000 are dual-rotor units. A rotor consists of a turbine, drive shaft, and one axial-flow compressor, and an aerodynamically coupled power turbine.

The LM1600, and LM6000 employ electronically operated, variable-bleed valves arranged in the flow passage between the low- and high-pressure compressors to match the LPC discharge airflow to the HPC. These valves are fully open at idle and progressively close to zero bleed at approximately 50% power. The position of these variable-geometry controls is a function of the LP rotor speed, HP rotor speed and inlet air temperature.

Aeroderivative engines incorporate variable geometry in the form of compressor inlet guide vanes that direct air at the optimum flow angle, and variable stator vanes to ensure ease of starting and smooth, efficient operation over the entire engine operating range.

Aeroderivative turbines are available with two types of annular combustors. Similar to those used in flight applications, the single annular combustor features a through-flow, venturi swirler to provide a uniform exit temperature profile and distribution. This combustor configuration features individually replaceable fuel nozzles, a full-machined-ring liner for long life, and an yttrium-stabilized zirconium thermal barrier coating to improve hot corrosive resistance. In 1995, a dry, low emissions (DLE) combustor was introduced to achieve low emissions without the use of fuel diluents, such as water or steam.

The LM1600, LM2000, LM2500, and LM2500+ all include an aerodynamically coupled, high-efficiency power turbine. All power turbines are fully tip-shrouded. The LM1600 PT and LM2500+ High Speed Power Turbine (HSPT) feature a cantilever-supported rotor. The power turbine is attached to the gas generator by a transition duct that also serves to direct the exhaust gases from the gas generator into the stage one turbine nozzles. Output power is transmitted to the load by means of a coupling adapter on the aft end of the power turbine rotor shaft. Turbine rotation is clockwise when viewed from the coupling adapter looking forward. Power turbines are designed for frequent thermal cycling and can operate at constant speed for generator drive applications, and over a cubic load curve for mechanical drive applications. The LM6000 power turbine drives both the LPC and the load device. This feature facilitates driving the load from either the front or aft end of the gas turbine shaft.

All of the models have an engine-mounted, accessory drive gearbox for starting the unit and supplying power for critical accessories. Power is extracted through a radial drive shaft at the forward end of the compressor. Drive pads are provided for accessories, including the lube and scavenge pump, the starter, the variable-geometry control, and the liquid fuel pump.

LM1600 Gas Turbine

The LM1600 gas turbine consists of a dual-rotor gas generator and an aerodynamically coupled power turbine. The LM1600 is shown in *Figure 6*, and consists of a three-stage, low-pressure compressor; a seven-stage, variable-geometry, high-pressure compressor; an annular combustor with 18 individually replaceable fuel nozzles; a single-stage, high-pressure turbine; and a single-stage, low-pressure turbine. The gas generator operates at a compression ratio of 22:1.

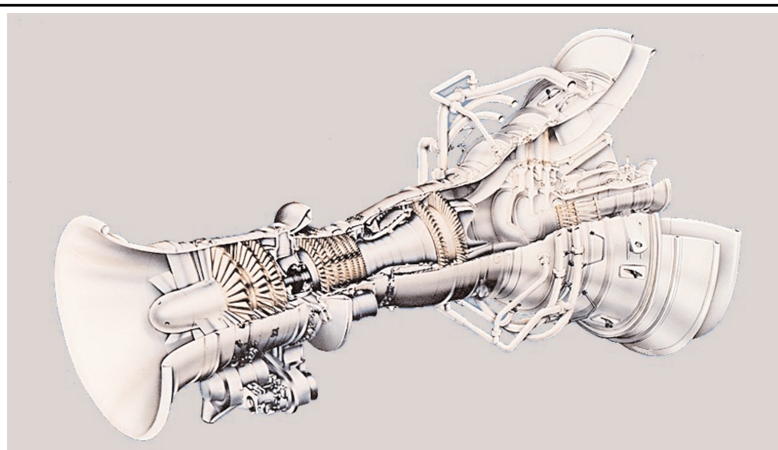

Figure 6. LM1600 gas turbine

The LM1600 incorporates variable-geometry in its LPC inlet guide vanes and HPC stator vanes. Four electronically operated, variable-geometry bleed valves match the discharge airflow between the LPC and HPC. In industrial applications, the nozzles and blades of both the HPT and LPT are air-cooled and coated with “CODEP,” a nickel-aluminide-based coating, to improve resistance to oxidation, erosion, and corrosion. For marine applications, HPT nozzles are coated with a thermal barrier coating, LPT nozzles are coated with CODEP and the blades of both the HPT and LPT are coated with PBC22. The two-stage power turbine operates at a constant speed of 7,000 rpm over the engine operating range for generator drive applications, and over a cubic load curve for mechanical drive applications.

LM2500 Gas Turbine

The LM2500 gas turbine consists of a single-rotor gas turbine and an aerodynamically coupled power turbine. The LM2500 (*Figure 7*) consists of a six-stage, axial-flow design compressor, an annular combustor with 30 individually replaceable fuel nozzles, a two-stage, high-pressure turbine, and a six-stage, high-efficiency power turbine. The gas generator operates at a compression ratio of 18:1.

The inlet guide vanes and the first six-stages of stator vanes are variable. In both stages of the high-pressure turbine, the nozzles and blades are air-cooled. For industrial applications, the nozzles are coated with CODEP and the blades are coated with platinum-aluminide to improve resistance to erosion, corrosion and oxidation.

The six-stage power turbine operates at a nominal speed of 3,600 rpm, making it ideal for 60 Hz generating service. Alternatively, it can be used in 50 Hz service without the need to add a speed reduction gear. The LM2500 can also operate efficiently over a cubic load curve for mechanical drive applications.

The LM2500 gas turbine is also offered at an 18MW ISO rating as an integrated packaged product called the LM2000 with an extended hot-section life for the gas turbine.

LM2500+ Gas Turbine

The first LM2500+, a design based on the very successful heritage of the LM2500 gas turbine, rolled off the production line in December 1996. The LM2500+ was originally rated at 27.6 MW, for a nominal 37.5% thermal efficiency at ISO, no losses and 60 Hz. Since that time, its rating has continually increased to reach its current level of 31.3 MW and 41% thermal efficiency. An isometric view of the LM2500+ gas turbine, including the single annular combustor (SAC), is shown in *Figure 8*.

The LM2500+ has a revised and upgraded com-

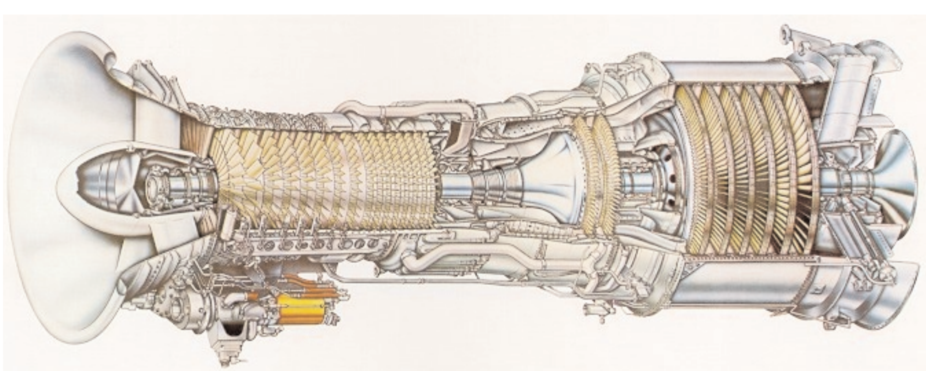

Figure 7. LM2500 gas turbine

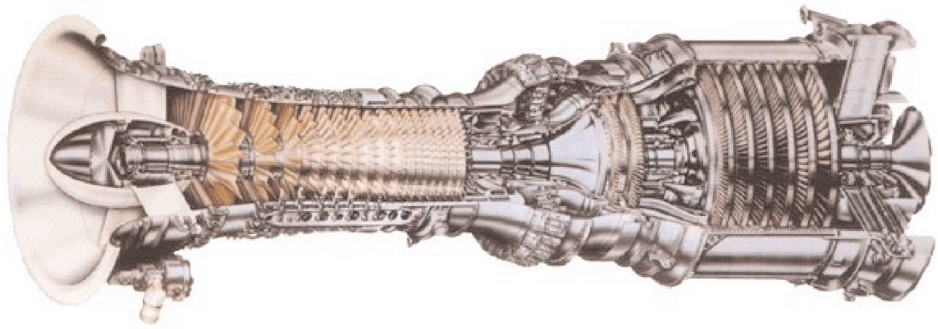

Figure 8. LM2500+ gas turbine

pressor section with an added zero stage for increased flow and pressure ratio, and revised materials and design in the HP and power turbines. The gas generator operates at a compression ratio of 22:1. The inlet end of the LM2500+ design is approximately 13 inches/330 mm longer than the current LM2500, allowing for retrofit with only slight inlet plenum modifications. In addition to the hanging support found on the LM2500, the front frame of the LM2500+ has been modified to provide additional mount link pads on the side. This allows engine mounting on supports in the base skid.

The LM2500+ is offered with two types of power turbines: a six-stage, low speed model, with a nominal speed of 3600 rpm; or a two-stage high speed power turbine (HSPT).

The LM2500+ six-stage power turbine displays several subtle improvements over the L2500 model from which it was derived:

- Flow function was increased by 9%, in order to match that of the HPC.
- Stage 1, 5 and 6 blades as well as the stage 1 nozzle were redesigned.
- Disc sizing was increased for all of the stages.
- Spline/shaft torque capability was increased.
- Casing isolation from flow path gases by use of liners stages 1-3.

The LM2500+ two-stage HSPT has a design speed of 6100 rpm, with an operating speed range of 3050 to 6400 rpm. It is sold for mechanical drive and other applications where continuous shaft output speeds of 6400 rpm are desirable. When the HSPT is used at 6,100 rpm to drive an electric generator through a speed reduction gear, it provides one of the best options available for power generation applications at 50 Hz.

Both the six-stage and two-stage power turbine options can be operated over a cubic load curve for mechanical drive applications.

In 1998, a version of LM2500+ was introduced to commercial marine application. The only differences between the marine and industrial versions to address the harsher environment are as follows:

- Stage 1 HPT nozzle coating
- Stage 1 HPT shroud material and coating.

LM6000 Gas Turbine

The LM6000 turbine (*Figure 9*) consists of a five-stage LPC; a 14-stage HPC, which includes six variable-geometry stages; an annular combustor with 30 individually replaceable fuel nozzles; a

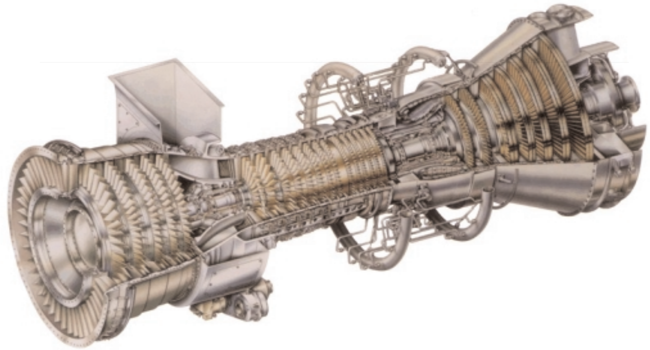

Figure 9. LM6000 gas turbine

two-stage, air-cooled HPT; and a five-stage LPT. The overall compression ratio is 29:1. The LM6000 does not have an aerodynamically coupled power turbine.

The LM6000 is a dual-rotor, "direct drive" gas turbine, derived from the CF6-80C2, high-bypass, turbofan aircraft engine. The LM6000 takes advantage of its parent aircraft engine's low-pressure rotor operating speed of approximately 3,600 rpm. The low-pressure rotor is the driven-equipment driver, providing for direct coupling of the gas turbine low-pressure system to the load, as well as the option of either cold end or hot end drive arrangements.

The LM6000 maintains an extraordinarily high degree of commonality with its parent aircraft engine, as illustrated in *Figure 10*. This is unlike the conventional aeroderivative approach which maintains commonality in the gas generator only, and adds a unique power turbine. By maintaining high commonality, the LM6000 offers reduced parts cost and demonstrated reliability.

The status of the LM6000 program, as of February 2000, includes:

- 300 units produced since introduction in 1991
- 208 units in commercial operation
- First DLE combustor in commercial operation producing less than 25 ppm NO_x - 1995
- High time engine =50,829 hours
- 12 month rolling average engine availability = 96.8%
- Engine reliability = 98.8%
- Exceeded 3.1 million operating hours

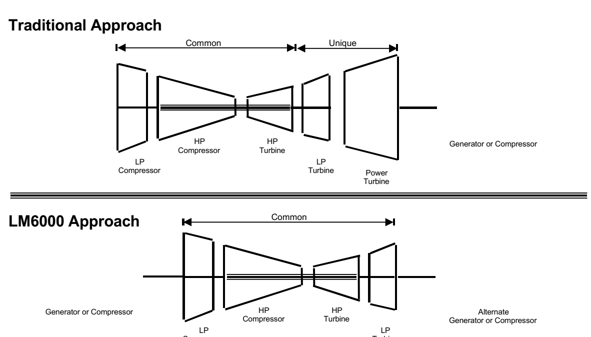

Figure 10. LM6000 concept

- Variable speed mechanical drive capability – 1998
- Dual fuel DLE in commercial operation – 1998
- LM6000 PC Sprint™ System in commercial operation - 1998

In mid-1995, GE committed to a major product improvement initiative for the LM6000. New models designated as LM6000 PC/PD were first produced in 1997, and included a significant increase in power output (to more than 43 MW) and thermal efficiency (to more than 42%); dual fuel DLE; and other improvements to further enhance product reliability.

LM6000 Sprint™ System

Unlike most gas turbines, the LM6000 is primarily controlled by the compressor discharge temperature (T3) in lieu of the turbine inlet temperature. Some of the compressor discharge air is then used to cool HPT components. SPRINT™ (Spray Inter-cooled Turbine) reduces compressor discharge temperature, thereby allowing advancement of the throttle to significantly enhance power by 12% at ISO, and greater than 30% at 90°F (32°C) ambient temperatures.

The LM6000 Sprint™ System is composed of atomized water injection at both LPC and HPC inlet plenums. This is accomplished by using a high-pressure compressor, eighth-stage bleed air to feed two air manifolds, water-injection manifolds, and sets of spray nozzles, where the water droplets are sufficiently atomized before injection at both LPC and HPC inlet plenums. *Figure 11* displays a cross-section of the LM6000 Sprint™ System. *Figure 12* provides the Sprint™ Gas Turbine expected performance enhancement, relative to the LM6000-PC.

Since June 1998, when the first two Sprint™units began commercial operation, ten other installations have gone into service. As of February 2000, LM6000 Sprint™ Gas Turbine (*Figure 13*) operating experience exceeds 20,000 hours. Sprint™ System conversion kits for LM6000 PC models are now available for those considering a potential retrofit.

STIG™ Systems

STIG™ (Steam Injected Gas Turbine) systems operate with an enhanced cycle, which uses large volumes of steam to increase power and improve efficiency. See *Figure 14* for STIG™ system performance enhancements at ISO base load conditions.

In the STIG™ cycle, steam is typically produced in a heat recovery steam generator (HRSG) and

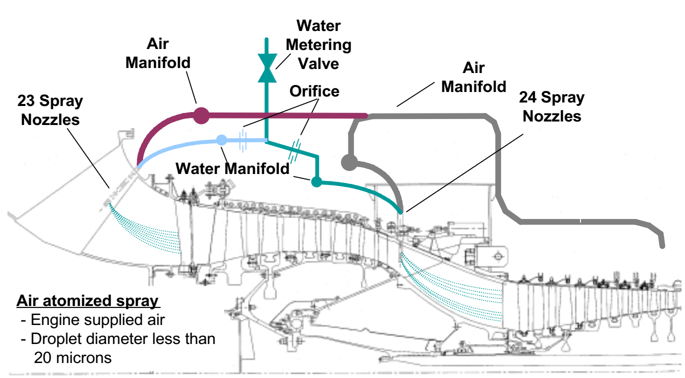

Figure 11. LM6000 Sprint™ flow cross section

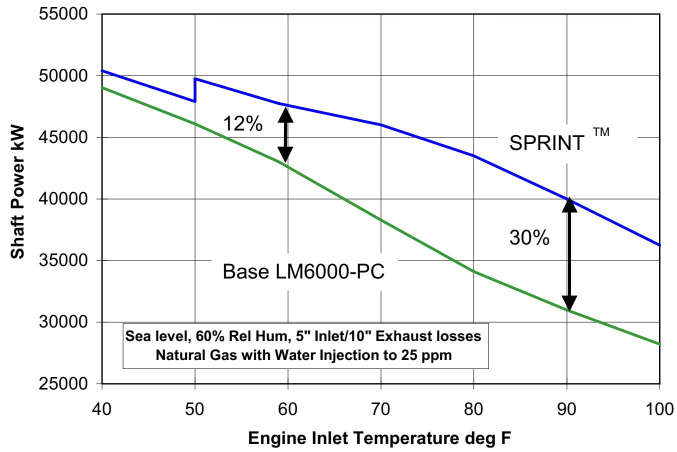

Figure 12. LM6000 Sprint™ gas turbine performance enhancement

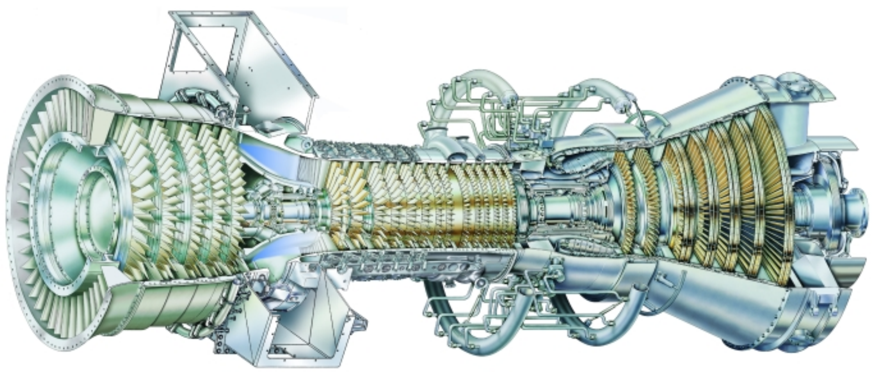

Figure 13. LM6000 Sprint™ gas turbine

Standard Base Load, Sea Level, 60% RH, - Natural Gas - 60 Hertz -
4 in. (102mm) Inlet/10 in. (254mm) Exhaust Loss - Average Engine at the Generator Terminals*

Model	Dry Rating (MWe)	%Thermal Efficiency (LHV)	STIG Rating (MWe)	%Thermal Efficiency (LHV)
LM1600	13.3	35	16	37
LM2000	18	35	23.2	39
LM2500	22.2	35	27.4	39

*3% margin on Eff. Included

Figure 14. STIG™ system performance enhancement – generator drive gas turbine performance

is then injected into the gas turbine. The STIG™ system offers a fully flexible operating cycle, since the amount of steam injected can vary with load requirements and steam availability. Also, steam can be injected with the gas turbine operating from 50% power to full load.

A typical STIG™ cycle is shown in *Figure 15*. The installation includes a steam-injected gas turbine, coupled with an HRSG which can be supplementally fired. The control system regulates the amount of steam sent to process and, typically, the excess steam is available for injection. *Figure 16* shows the steam injection capability for the various models.

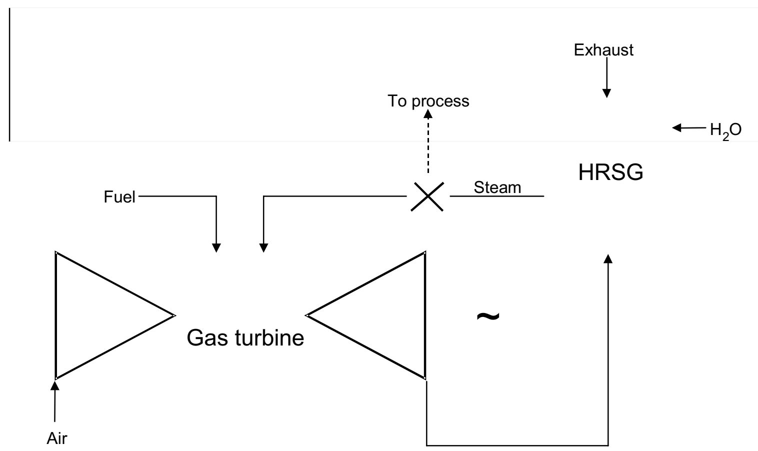

Figure 15. Typical STIG™ cycle

Standard Base Load, Sea Level, 60% RH, - Natural Gas - 60 Hertz -
4 in. (102mm) Inlet/10 in. (254mm) Exhaust Loss - 25 PPM NOx

			Steam Flows -lb/hr (kg/hr)	
Model	Rating (MWe)*	%Thermal Efficiency*	Fuel Nozzle	Compressor Discharge
LM1600	16	37	11540 (5235)	9840 (4463)
LM2000	23.2	39	14558 (6604)	15442 (7005)
LM2500	27.4	39	18300 (8301)	31700 (14379)
LM2500+	32.5	40	23700 (10750)	
LM6000	42.3	41.1	28720 (13027)	

* Average Engine at generator terminals
(2.5% on LM1600 Gen, 2.0% on all others Gen, 1.5% GB included)

Figure 16. STIG™ steam flow capability – generator drive gas turbine performance

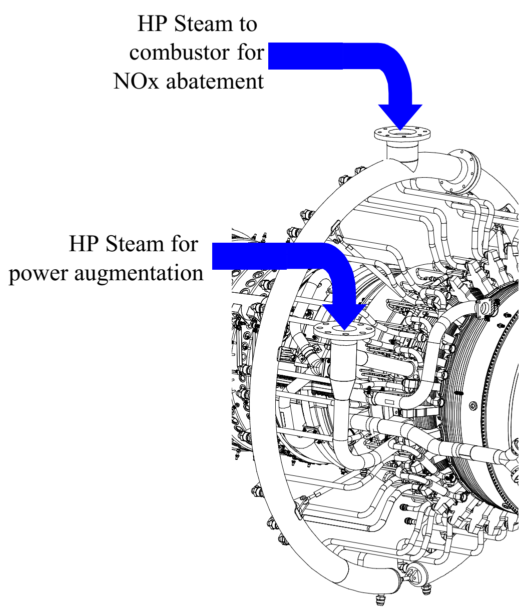

Figure 17. STIG™ system steam injection ports

The site at which steam is injected into the gas turbine differs according to the design of the particular model. For instance, in both the LM1600, LM2000 and LM2500, steam is injected into the high-pressure section via the combustor fuel nozzles and compressor discharge plenum. See *Figure 17* for the location of steam injection ports on an LM2500 gas turbine. A STIG™ system is not planned for the LM6000, beyond that steam injected through the fuel nozzles for NO_x abatement.

Emissions

NO_x emissions from the LM1600, LM2000, LM2500, LM2500+ and LM6000 can be reduced using on-engine water or steam injection arrangements, or by the incorporation of DLE combustion system hardware. The introduction of steam or water into the combustion system:

- Reduces NO_x production rate
- Impacts the gas turbine performance
- Increases other emissions, such as CO and UHC
- Increases combustion system dynamic activity which impacts flame stability
- The last item results in a practical limitation on the amount of steam or water which can be used for NO_x suppression.

Figure 18 lists the unabated NO_x emission levels for the GE Aeroderivative gas turbines when burning either natural gas or distillate oil. Depending on the applicable federal, state, country and local regulations, it may be necessary to reduce the unabated NO_x emissions.

ISO - Base Load - SAC Combustor		
	Unabated NOx Emissions (ppmvd ref.15% O2)	
Model	Natural Gas	Distillate Oil
LM1600	127	209
LM2000	129	240
LM2500	179	316
LM2500+	229	346
LM6000	205	403

Figure 18. GE aeroderivative gas turbine unabated NO_x emissions

Figure 19 shows GE's current, guaranteed minimum NO_x emission levels for various control options. With steam or water-injection and single fuel natural gas, the LM2500 can guarantee NO_x emissions as low as 15 ppm. For applications requiring even lower NO_x levels, other means, such as selective catalytic reduction (SCR), must be used.

In 1990, GE launched a Dry Low Emissions Combustor Development program for its aeroderivative gas turbines. A premixed combustor configuration (*Figure 20*), was chosen to achieve uniform mixing of fuel and air. This premixing produces a reduced heating value gas, which will then burn at lower flame temperatures required to achieve low NO_x levels. Increased combustor dome volume is used to increase combustor residence time for complete reaction of CO and UHC. DLE combustors feature replaceable premixer/nozzles and multiple burner modes to match low demand.

NOx Emission Capabilities (NOx ppmvd, ref. 15% O2)								
Fuel System	SAC	SAC	SAC	SAC	SAC	SAC	DLE	DLE
Fuel	Natural Gas	Natural Gas	Natural Gas	Distillate	Distillate	Distillate		Distillate
	Dry-unabated	Water	Steam	Dry-unabated	Water	Steam	None	None
LM1600	127	25	25	209	42	75	25	NA
LM2000	129	25	25	240	42	42	25	NA
LM2500	179	15	15	316	42	42	25	NA
LM2500+	229	25	25	346	42	42	25	NA
LM6000	205	25	25	403	42	NA	25	125

Figure 19. Minimum NO_x emission guarantee levels – wet and dry emissions control options

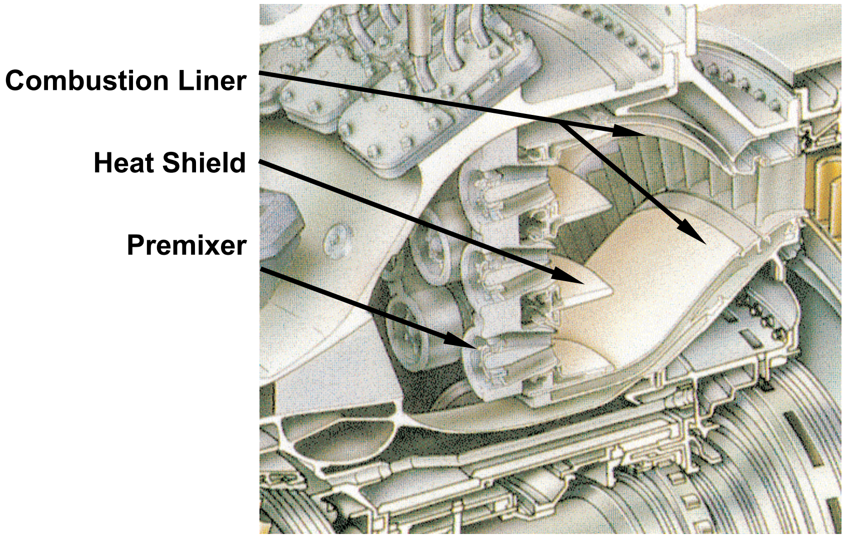

Figure 20. DLE combustor

In order to achieve low emissions throughout the operating range, fuel is staged through the use of multiple annuli. The LM1600 uses a double annular configuration, while all other models use a triple annular construction.

Factory testing of components and engine assembly on an LM6000 gas turbine was completed in 1994. These tests demonstrated less than 15 ppm NO_x, 10 ppm CO and 2 ppm UHC at a firing temperature of 2350°F/1288°C at rated power of 41 MW.

The Ghent power station in Belgium became the first commercial operator to use the LM6000 fitted with the new DLE combustor system. A milestone was reached in January 1995 when the station achieved full power at 43 MW with low emissions of 16 ppm NO_x, 6 ppm CO and 1 ppm UHC. As of today, the high time LM6000 engine has accumulated over 34,000 hours.

By the end of 1999, there were 3 LM1600, 58 LM2500, 27 LM2500+, and 30 LM6000 gas turbines equipped with the DLE combustion system in service worldwide.

Today, GE continues its DLE technology development on the Dual Fuel DLE front. Completely dry operation has been achieved on gas and distillate fuels on two LM6000 engines in the United Kingdom. Operating on liquid fuel, NO_x and CO emission levels have been less than 125 ppm and 25 ppm, respectively. GE continues to do research on reducing liquid fuel to NO_x levels below 65 ppm , with the goal of achieving this by the end of the year 2000. By early 2001, GE plans to release a Dual Fuel DLE system on the LM2000, LM2500 and LM2500+ gas turbines.

Design and Operation of GE Aeroderivative Gas Turbines

Design Features

GE Aeroderivative gas turbines combine high temperature technology and high pressure ratios with the latest metallurgy to achieve simple-cycle efficiencies above 40%, the highest available in the industry.

It is essential to GE's aeroderivative design philosophy that an industrial or marine aeroderivative gas turbine retain the highest possible degree of commonality with the flight engine on which the aeroderivative is based. This results in a unique and highly successful approach to on-site preventive and corrective maintenance, including partial disassembly of the engine and replacement of components such as blades, vanes and bearings. On-site component removal and replacement can be accomplished in less than 100 manhours. Complete gas generators and gas turbines can be made available within 72 hours (guaranteed), with the complete unit replaced and back on-line within 48 hours. The hot-section repair interval for the aeroderivative meets the industrial demand of 25,000 hours on natural gas. The LM engines have been adapted to meet the important industrial standards of ASME, API, NEC, ISO9001, etc., consistent with their aircraft engine parentage.

Other advantages related to the evolution from the flight application are the technical requirements of reduced size and low weight. The aeroderivatives' rotor speeds (between 3,000 and 16,500 rpm) and casing pressure (20 to 30 atmospheres) may appear high when compared with other types of gas turbines. However, the high strength materials specified for the aircraft engine are capable of handling these pressures and rotor speeds with significant stress margins. For example, cast Inconel 718, commonly used for aircraft engine casing material, has a yield strength of 104 ksi (717 kN/m^2) at 1200°F/649°C, while cast iron commonly used in other types of gas turbine casings has a yield strength of 40 ksi at 650°F (276 kN/m^2 at 343°C).

The aeroderivative design, with its low supported-weight rotors – for example, the LM2500 HP rotor weighs 971 lbs/441 kg – incorporates roller bearings throughout. These do not require the large lube oil reservoirs, coolers and pumps or the pre-and post-lube cycle associated with other bearing designs. Roller bearings have proven to be extremely rugged and have demonstrated excellent life in industrial service. Although bearings generally provide reliable service for over 100,000 hours, in practice, it is advisable to replace them when they are exposed during major repairs, or, at an estimated 50,000 hours for gas generators and 100,000 hours for power turbines.

The high-efficiency aeroderivative is an excellent choice for simple-cycle power generation and cyclic applications such as peaking power, which parallels aircraft engine use. With start times in the one-minute range, the aeroderivative is ideal for emergency power applications of any sort.

With its inherently low rotor inertias, and the variety of pneumatic and hydraulic starting options available, the GE Aeroderivative engine has excellent "black start capability," meaning the ability to bring a "cold iron" machine online when a source of outside electrical power is unavailable. An additional benefit of having low rotor inertias is that starting torques and power requirements are relatively low, which in turn reduces the size and installed cost of either the pneumatic media storage system or the diesel or gasoline engine driven hydraulic systems. For example, the LM2500 starting torque is less than 750 ft-lbs (1,017 N-m), and its air consumption during a typical start cycle is between 2,000 and 2,600 SCFM (56,600 and 73,600 l/min).

Fuels

Natural gas and distillate oil are the fuels most frequently utilized by aeroderivatives. These engines can burn gaseous fuels with heating values as low as 6,500 Btu/lb (15,120 kJ/kg). Recently, an LM6000 with a single, annular combustor was modified to operate on medium Btu (8,000-8,600 Btu/lb ~ 18,600-20,000 kJ/kg) fuel. It demonstrated that it could operate with lower NO_x emissions without requiring flame-quenching diluents such as water or steam.

As part of GE's Research and Development Program, an LM2500 combustor, modified to utilize low heating value biomass fuel, has been operated in a full annular configuration at atmospheric pressure. A sector of the annular combustor design was then tested at gas turbine operating pressures. Ignition, operability, gas temperature radial profiles, temperature variations and fuel switching were in acceptable ranges when operated on simulated biomass fuel. Low NO_x is a by-product since low heating value fuel is essentially the same as operating in a lean premix mode like the DLE combustor.

Operating Conditions

The climatological and environmental operating conditions for aeroderivatives are the same as for other types of gas turbines. Inlet filtration is necessary for gas turbines located in areas where sand, salt and other airborne contaminants may be present.

At the extreme ends of the ambient temperature spectrum, the aeroderivative exhibits a less attractive lapse rate (power reduction at off-ambient temperatures) than other types of gas turbines. However, the LM aeroderivative does have a "constant power" performance option which can be applied in areas where the extremes are encountered for extended periods of time.

Ratings Flexibility

All turbines, including aeroderivatives, have "base ratings". In the case of GE's aeroderivatives, when natural gas is used as the fuel and the engine is operated at the base power turbine inlet temperature control setting, its base rating corresponds to a hot-section repair interval of approximately 25,000 hours. The LM2000 is an exception; at its base rating the hot-section repair interval is approximately 50,000 hours.

Aeroderivatives utilize the same basic hardware as aircraft engines, which are designed to operate reliably at firing temperatures much higher than the corresponding aeroderivative base rating temperatures. By taking advantage of the extensively air cooled hot-gas-path components typically found in aircraft engines, aeroderivative models can operate at higher temperatures and power levels than their base rating.

The LM2500 will be used as an example, with the other LM products having similar characteristics. *Figure 21* illustrates the full capability of the LM2500 as a function of ambient temperature. In the ambient temperature region above 55°F/13°C, the LM2500's maximum capability is limited by the maximum allowable temperature at the power turbine inlet. *Figure 21* also shows the availability of additional power above the ISO base rating of the unit.

In order to achieve this increased power, operation at increased cycle temperature is necessary. As with any gas turbine, the hot-gas-path section repair interval (HSRI) of the LM2500 is related to the cycle temperature. *Figure 22* presents the relationship between output power, power tur-

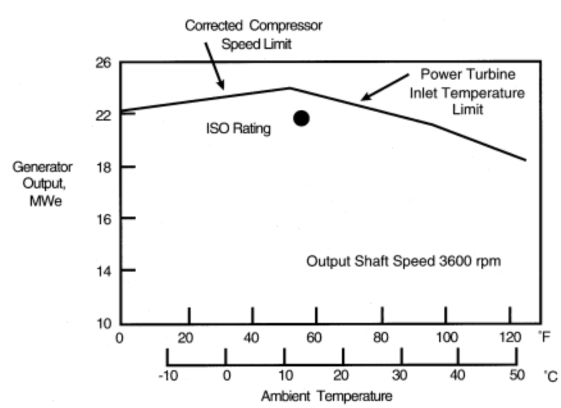

Figure 21. LM2500 maximum power capability

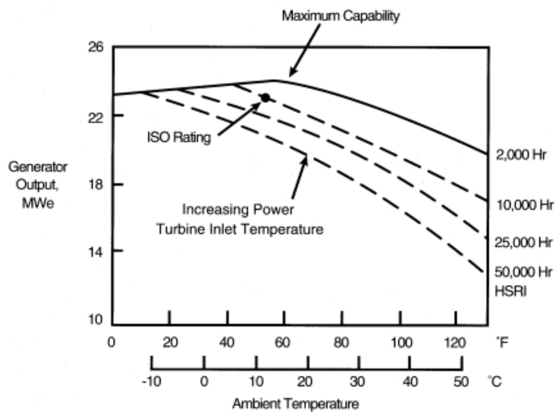

Figure 22. Effect of increased power rating on LM2500 hot-section repair interval

bine inlet temperature and estimated time between hot-section repairs. The ISO rating temperature corresponds to the curve for an estimated 25,000 hours between hot-section repairs when burning natural gas fuel. *Figure 22* also shows that power is available for applications requiring more power than is available when limiting the temperature to that associated with the 25,000 hours curve. However, those LM2500s utilizing this additional power will require more frequent hot-section repair intervals.

The LM2500, like any gas turbine operating at a constant cycle temperature, has more power available at lower ambient temperatures than at higher ambient temperatures. This is shown in *Figure 22* by the sloping lines of constant hot-section repair intervals (constant power turbine inlet temperature). There are, however, many applications in the industrial market that cannot use all of the power that is available at the lower ambient temperatures. In these cases, the operating characteristic of "constant power," regardless of the ambient temperature, is more consistent with the actual requirements of the installation.

Figure 23 shows an example of an application where constant power, rather than variable power, is required over a specific ambient temperature range. This figure clearly shows that the LM2500 is capable of producing this power over the full ambient temperature range. However, the estimated hot-section repair interval for this type of operation is not apparent in *Figure 23*, since when operating during high ambient temperature conditions, the power turbine inlet temperature corresponds to shorter intervals than when operating at lower ambient temperatures.

An ambient temperature profile for the particular site is needed to determine the duration of operation at the various power turbine inlet temperatures. Once this ambient temperature information is available, an estimate of the hot-section repair interval for this power level and particular site can be made. If the operator does not provide duty cycle estimates, it is generally assumed that a unit operates continuously for 8,600 hours per year for any given site.

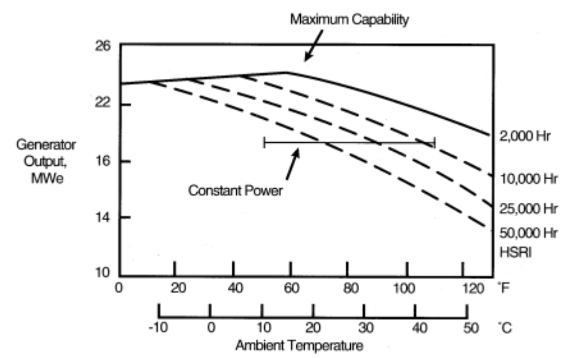

Figure 23. LM2500 constant power rating

To carry this example further, assume the ambient temperature profile for this particular site results in an estimated hot-section repair interval of 25,000 hours for this power level.

Comparison of operation at constant temperature and constant power level is shown in *Figure 24*. Since both curves result in an estimated hot-section repair interval of 25,000 hours, potential power at low ambient temperatures has been traded for more potential power at higher ambient temperatures. Again, for an application where the required power is independent of the ambient temperature, a constant power rating results in trading off the higher power at low ambient temperatures for extended constant power at higher ambient temperatures.

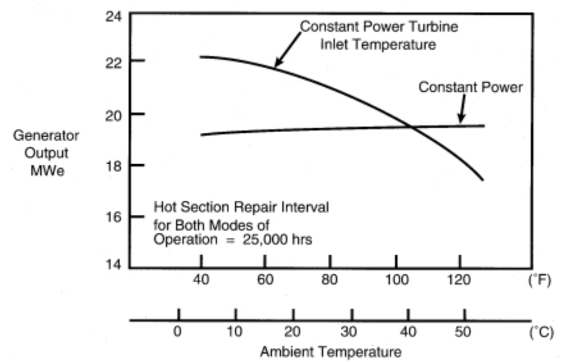

Figure 24. LM2500 constant PT inlet temperature and constant power operation

Performance Deterioration and Recovery

Deterioration of performance in GE Aeroderivative (LM) industrial gas turbines has proven to be consistent over various engine lines and applications. Total performance loss is attributable to a combination of "recoverable" (by washing) and "non-recoverable" (recoverable only by component replacement or repair) losses.

Recoverable performance loss is caused by fouling of airfoil surfaces by airborne contaminants. The magnitude of recoverable performance loss is determined by site environment and character of operations. Generally, compressor fouling is the predominant cause of this type of loss. Periodic washing of the gas turbine, either by on-line wash or crank-soak wash procedures, will recover 98% to 100% of these losses. The severity of the local environment and operational profile of the site determine the frequency of washing.

Studies of representative engines in various applications show a predictable, nonrecoverable performance loss over long-term use. Deterioration experience is summarized in *Figure 25* for power and heat rate for an LM aeroderivative gas turbine operating on natural gas fuel.

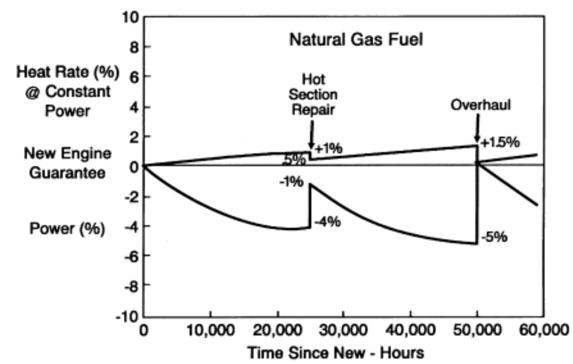

Figure 25. LM2500 field trends – power and heat rate deterioration

This figure illustrates long-term, non-recoverable deterioration, not losses recoverable by washing. Power deterioration at the 25,000-hour operating point is on the order of 4%; heat rate is within 1% of "new and clean" guarantee. These deterioration patterns are referenced to the "new and clean" base rating guarantee, although actual as-shipped engine performance is generally better than the guarantee level.

Generally, HPT components are replaced at 25,000 hour intervals for reasons of blade life and performance restoration. The result of replacement of the HPT components is 60% or more restoration of the non-recoverable performance loss, depending on the extent of work accomplished. Over 80% recovery can be achieved if limited high-pressure compressor repairs are performed at the same time. General overhauls at about 50,000-hour intervals entail more comprehensive component restorations throughout the engine, and may result in nearly 100% restoration of the non-recoverable performance.

When using liquid fuel, which is more corrosive than natural gas, a similar but more rapid pattern of deterioration occurs, resulting in approximately the same 3% to 5% level at the typical 12,500-hour liquid-fuel HPT repair interval.

Maintenance Features

In an operator's life cycle cost equation, the most important factors are engine availability and maintenance cost. To enhance these considerations in regard to its aeroderivative engines, GE has invested considerable effort in developing features to optimize the result of this equation. GE's aeroderivatives' unique designs allow for maintenance plans with the following features:

- Borescope inspection capability. This feature allows on-station, internal inspections to determine the condition of internal components, thereby increasing the interval between scheduled, periodic removals of engines. When the condition of the internal components of the affected module has deteriorated to such an extent that continued operation is not practical, the maintenance program calls for exchange of that module.
- Modular design. Using their flight heritage to maximum advantage, aeroderivative engines are designed to allow for on-site, rapid exchange of major modules within the gas turbine. The elapsed time for a typical HPT and combustion module replacement is 72 hours. This exchange allows the gas turbine to operate for an additional 25,000 hours.
- Compactness. The GE AeroDerivative engines have inherited modest dimensions and lightweight construction that generally allows for on-site replacement in less than 48 hours.
- Monitoring and Diagnostics Services are made available by establishing direct phone connections from the control system at the customers' sites to computers in GE's LM monitoring center. These services link the expertise at the factory with the operations in the field to improve availability, reliability, operating performance, and maintenance effectiveness. Monitoring of key parameters by factory experts allows early diagnosis of equipment problems and avoidance of expensive secondary damage. The ability for service engineers to view real-time operations in many cases results in accelerated troubleshooting without requiring a site visit (*Figure 26*).

Figure 26. Monitoring and Diagnostic services: GE engineer remotely monitoring a unit

The integration of all of the features noted above enables the operator to monitor the condition of the engine, maximize uptime, and conduct quick maintenance action. To learn in greater depth about the maintenance of the GE Aeroderivative gas turbines, refer to GER-3694, "Aeroderivative Gas Turbine Operating and Maintenance Considerations."

Advances in Aircraft Engine Technology

GE Aircraft Engines invests over $1 billion annually in research and development, much of which is directly applicable to all of GE's aeroderivative gas turbines. In particular, consistent and significant improvement has been made in design methodologies, advanced materials and high-temperature technologies. Areas of current focus are presented in *Figure 27*. As these technological advances are applied to industrial uses, GE's aeroderivative engines benefit from continual enhancement to attain greater power, efficiency, reliability, maintainability and reduced operating costs.

In 1993, GE Aircraft Engines began testing the new, ultra-high thrust, GE90, high bypass fan engine (*Figure 28*). The thrust level demonstrated at initial certification was 87,400 pounds (376,764 N), and since then, has reached a thrust level of 110,000 pounds.

- Components
  - Multi-Hole Combustion Liner
  - Dual Annular Combustors
  - Aspirating Seals
  - Counter Rotating Turbines
  - Fiber Optic Controls
  - High Temperature Disks
  - MMC Frames/Struts
  - Model Based Controls
  - Composite Wide Chord Fan Blades
  - Swept Airfoils
  - Lightweight Containment
  - High Torque Shafts
  - Magnetic Bearings
- Metals
  - High temperature Alloys
    - N5. N6, R88DT, MX4
  - Intermetallic Alloys
    - NiAl, TiAl, Orthorhombic Ti
  - Structural Ti Castings
- Non-metals
  - Polymeric Composites
    - PMR 15 Case
    - Composite Fan Blade
  - High Temperature Polymerics (700°F/371°C)
  - Thermal Barrier Coatings
- Advanced Materials
  - Metal Matrix Composites (MMC)
  - Ceramic Matrix Composites
- Advanced Processes
  - Dual Alloy Disks
  - Spray Forming
  - Laser Shock Peening
  - Translational friction Weld
  - Braiding
  - Resin Transfer Molding
  - Waterjet Machining
  - Superplastic Forming/Diffusion Bonding
  - Robust Material Processes
- Technology Aids
  - Six Sigma Processes
  - Remote Monitoring & Diagnostics
  - Concurrent Engineering/Manufacturing
  - Design Engineering Workstations
  - Computational Fluid Dynamics
  - Process
  - Modeling
  - Stereolithography Apparatus
  - Virtual Reality
  - Advanced Instrumentation
  - New Product Introduction Methods

Figure 27. New processes and technologies

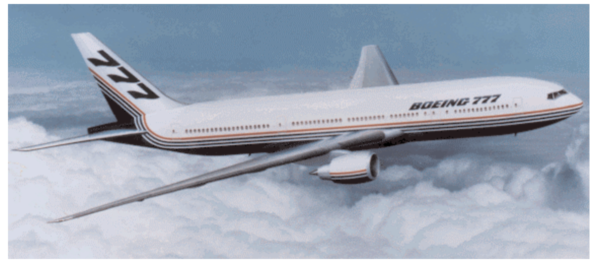

Figure 28. GE90 high-bypass fan engine on Boeing 777

The advanced technologies proven in the GE90 engine include wide-chord composite fan blades, short durable 10-stage HPC, composite compressor blades and nacelles, and a dual-dome annular combustor. These attributes contribute to delivering economic advantages of low fuel consumption, low noise and emissions, reliability of a mature engine, and growth capability to over 100,000 pounds thrust.

In 1995, the GE90 engine entered commercial service on a Boeing 777 aircraft operated by British Airways. One year later, a growth version of this engine, rated at 90,000 pounds of thrust, was certified and delivered. By 2000, GE90 engines had realized a major landmark, having accumulated more than one million flight hours since entry into service. After logging one million flight hours, and fueled by strong market interest and customer commitments, the Boeing Company and GE introduced two new, longer range models, powered by the newly introduced, growth derivative GE90-115B engine.

Summary

GE's continued investment in R&D aircraft engine technology enables the LM series of gas turbines to maintain their leadership position in technology, performance, operational flexibility, and value to the customer. Offered in power output from 13 to 47 MW, and having the ability to operate with a variety of fuels and emission control technologies, GE's aeroderivative gas turbines have gained the widest acceptance in the industry, with total operating experience in excess of 41million hours. These turbines have been selected for a multitude of applications, from power generation to mechanical drive, for the exploration, production and transmission of oil and gas, as well as marine propulsion systems including transport, ferryboat, and cruise ship installations.

List of Figures