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GE LM1600

Outlook

- Production of the LM1600 has ceased
- Marine applications have proved very limited
- This report will be archived next year

Orientation

Description. The LM1600 is a 50/60-Hz simple-cycle, dual-rotor, axial-flow, aeroderivative industrial & marine gas turbine machine in the 13-15 MW class.

Sponsor. The U.S. Department of Defense, through the U.S. Navy, Naval Sea Systems Command (Washington, DC), has sponsored development of the LM3000 (formerly referred to as the LM1600 ICR) marine powerplant.

Power Class. The approximate power output of the GE LM1600 gas turbine machine is as follows:

Machine Use	Power Output
Power Generation	13.7 MW (LM1600PE)
Mechanical Drive	19,105 shp (14,246 kW)
Marine Propulsion	20,000 shp (14,914 kW)

Status. Out of production.

Total Produced. At the start of 2017, at least 160 LM1600s had been delivered.

Application. Applications include electrical generation, consisting of cogeneration and various mechanical load drives, plus compressor drives for pipeline, platform, and process operations.

A few LM1600s have been installed for marine propulsion/drive duty.

Price Range. Estimated in 2016 U.S. dollars at $6.6 million for an electrical generation-based package and $5.8 million for a gas turbine-based mechanical drive package.

For electrical generation (simple cycle), the genset price covers a single-fuel skid-mounted gas turbine, an electric generator, an air intake with basic filter and a silencer, an exhaust stack, a basic starter and controls, and a conventional combustion system.

For mechanical drive, the price covers a gas-fired gas turbine (without driven equipment) with a gearbox, a skid, an enclosure, inlet and exhaust ducts and an exhaust silencer, basic turbine controls, fire protection, starting systems, and a conventional combustion system.

Competition. In the electrical generation arena the LM1600PE competes with the Siemens SGT-400 and the Solar Titan 130.

In the mechanical load drive arena the LM1600 competes with the Rolls-Royce Avon 2648, Solar Titan 130, and Siemens SGT-400. In the marine propulsion arena, the 20,000-shp LM1600 competes with the Zorya-Mashproekt UGT-15000R and UGT-16000R.

GE LM1600

Contractors

Prime

GE Power	http://www.gepower.com, 4200 Wildwood Pkwy, Atlanta, GA 30339 United States, Tel: + 1 (770) 859-6000, Fax: + 1 (678) 844-6690, Prime

Subcontractor

Alden O Sherman Co Inc	27 Lois St, Norwalk, CT 06851 United States, Tel: + 1 (203) 847-5775, Fax: + 1 (203) 847-0131, Email: jsherman_aosherman@snet.net (Compressor Section Components)
Dollinger Corp	http://www.dollinger-usa.com, 2499 S W 60th St, Ocala, FL 34474 United States, Tel: + 1 (352) 861-7873, Fax: + 1 (352) 873-5783 (Oil Mist Eliminator)
Hilliard Corp	http://www.hilliardcorp.com, 100 W Fourth St, Elmira, NY 14902 United States, Tel: + 1 (607) 733-7121, Fax: + 1 (607) 733-3009 (TC Series Starter)
Maag Gear Co Ltd, a member of the FLSmidth Group	http://www.maag-gear.com, Hardstr 219, Zurich, Switzerland, Tel: + 41 01 2787878, Fax: + 41 01 2787880 (Load Gear System - Epicyclic Gearbox GPF3-27)
Precision Castparts Corp	http://www.precast.com, 4650 SW Macadam Ave, Ste 440, Portland, OR 97239-4262 United States, Tel: + 1 (503) 417-4800, Fax: + 1 (503) 417-4817, Email: info@precastcorp.com (Structural Casting)
The Kahn Companies	http://www.kahn.com, 885 Wells Rd, Wethersfield, CT 06109 United States, Tel: + 1 (860) 529-8643, Fax: + 1 (860) 529-1895, Email: info@kahn.com (Dynamometer)
VT Group plc	Woolston Shipyard, Victoria Rd, Woolston, Southampton, United Kingdom (Control)
Wood Group Fuel Systems	http://www.woodgroup.com, 66 Prospect Hill Rd, East Windsor, CT 06088 United States, Tel: + 1 (860) 292-3115, Fax: + 1 (860) 292-1305 (Fuel Nozzle)
Zurn Mechanical Drives Division	1801 Pittsburgh Ave, Erie, PA 16514-3801 United States, Tel: + 1 (814) 453-5891 (Ameriflex Coupling)

Contractors are invited to submit updated information to Editor, International Contractors, Forecast International, 22 Commerce Road, Newtown, CT 06470, USA; rich.pettibone@forecast1.com

Technical Data

Dimensions.

	Metric Units	U.S. Units
Length	15.24 m	50 ft
Width	3.65 m	12 ft
Height	4.57 m	15 ft
Weight	86.18 tonnes	95 tons

Performance.

	ELECTRICAL GENERATION		MECHANICAL LOAD DRIVE	MARINE PROPULSION
	LM1600PE (50 Hz)	LM1600PE (60 Hz)	LM1600PE	LM1600
ISO Base Rating	13,748 kW	13,769 kW	19,105 shp	20,000 shp (a)
Heat Rate	9,749 Btu/kWh	9,735 Btu/kWh	7,016 Btu/shp-hr	6,928 Btu/shp-hr
	10,286 kJ/kWh	10,271 kJ/kWh	9,924 kJ/kWh	9,801 kJ/kWh
Efficiency	35.0%	35.1%	36.3%	$\leq$ 36.3%
Pressure Ratio	20.2:1	20.2:1	20.2:1	21.4:1
Flow	104.3 lb/sec	104.3 lb/sec	104.3 lb/sec	102.0 lb/sec
	47.3 kg/sec	47.3 kg/sec	47.3 kg/sec	46.3 kg/sec

GE LM1600

	ELECTRICAL GENERATION		MECHANICAL LOAD DRIVE	MARINE PROPULSION
	LM1600PE (50 Hz)	LM1600PE (60 Hz)	LM1600PE	LM1600
Turbine Speed	7,900 rpm	7,900 rpm	7,900 rpm	7,000 rpm
Exhaust Temp.	915ºF	894ºF	915ºF	939ºF
	491ºC	479ºC	491ºC	504ºC

(a) ISO maximum rating. ISO continuous rating is 19,200 shp.

Design Features The aeroderivative industrial and marine LM1600 is a simple-cycle gas generator developed for gas turbine applications in the 12,000-20,000-shp range. The LM1600 gas turbine is a three-shaft machine with a two-shaft gas generator and a single-shaft, aerodynamically coupled power turbine. The power turbine speed is 7,900 rpm, which results in an excellent speed match for the direct drive of compressors in this power range. A load gear is required for electrical generators.

The LM1600 is derived from the GE Aircraft Engines F404 turbofan engine with only minor modifications. The three fan stages of the LPC are clipped, thereby reducing the flow path diameter by approximately 4 inches (101mm). In addition, the bypass duct, which is redundant in the gas generator versions, is eliminated. A new front frame assembly was introduced, industrializing the aero engine. A bellmouth and a stationary forward center body were added to guide the inlet air into the engine.

Inlet Section. The inlet section has a bellmouth and stationary forward centerbody for straightening and guiding the airflow. The aluminum bellmouth contains a water wash manifold and forms the outer flowpath contour into the front frame.

Low-Pressure Compressor. The three-stage, axial-flow LPC is driven through a concentric drive shaft by a single-stage, air-cooled, low-pressure turbine. Variable inlet guide vanes are standard. The front frame incorporates 24 such vanes; the LPC rotor is a three-stage titanium rotor consisting of three discs and an aft shaft bolted together. Pressure ratio is 4:1.

High-Pressure Compressor. The HPC is a seven-stage, axial-flow, variable-geometry (Stages 1-3 only) type driven by a single-stage, air-cooled, high-pressure turbine. The HPC rotor consists of a forward shaft, Stages 1-2 spool pieces, and a Stage 3 disc of titanium. Stages 4-7 are steel. Stages 1-2 blades have axial dovetails secured by retaining rings. Stages 3-7 blades are retained by circumferential dovetails. Overall pressure ratio is 20.1:1-21.3:1.

The HPC stator case assembly is horizontally split and consists of two sections. The forward casing is titanium, with the rear casing being a high-temperature nickel-base alloy.

Combustor. The combustor is an annular through-flow multifuel type utilizing machined-ring construction. Metered fuel is distributed and introduced through 18 individually replaceable fuel nozzles.

High-Pressure Turbine. The HPT consists of a nozzle, rotor, and shroud. It is a single-stage, air-cooled design; blade and vane coating have been improved for protection from salt and sulfur corrosion. The HPT nozzle is a segmented assembly that is fully cooled by a combination of convection, impingement, and film cooling using inner and outer combustor flowpath air. Turbine inlet temperature is 2,265°F (1,241°C).

The HPT rotor is a rigid, bolted assembly that drives the HPC through a bolted joint on the forward shaft. The HPT shroud assembly, which restricts hot gas leakage at the blade tips, is made up of 16 segments.

Low-Pressure Turbine. A single-stage low-pressure turbine that is fully air-cooled. The LPT case is a one-piece iron and nickel alloy shell. The LPT nozzles and blades are cooled by fourth-stage HPC bleed air. The LPT exhaust frame provides the main structural support for the LM1600 gas generator. It is a one-piece, eight-strut, nickel-base alloy casting. Overall power shaft speed is 7,900 rpm.

Power Turbine Unit. The GE-specified industrial power turbine consists of a two-stage, high-speed unit that has been specifically designed to match both the LM1600 gas generator and the load equipment normally used in its horsepower range. The operating range is 4,200-7,900 rpm at a nominal 1,370°F (743°C) PT inlet temperature with uncooled blading. The overhung rotor is supported by two bearings: one roller bearing and one ball bearing, with the latter a combined thrust/journal bearing.

The transition casing is a 360° casting in IN718, and the transition duct inner and outer walls are one piece formed from Hastelloy X. Overall EGT is 491°C.

Gas Generator Shafting and Bearings. The LM1600 is a two-rotor system consisting of low-pressure and high-pressure rotors. The two rotor systems are supported by five main bearings. The LP rotor is aided by bearing Nos. 1, 2, 4, and 5, and the HP rotor is supported by bearing Nos. 3 and 4. All main bearings are made from M50 material.

GE LM1600

Maintainability Features. Borescope ports are located at LPC Stages 1, 2, and 3, mid-frame, and at the HPC discharge port, combustor case, HPT, and LPT to permit inspection.

Horizontally split HP and LP compressor casings are incorporated for easy access to the compressor rotors and stators. All compressor blades, with the exception of LPC Stage 1, are removable and individually replaceable with the compressor casings removed. All compressor vanes are removable and replaceable individually or in sections with the compressor casings removed.

Control Compartment. The LM1600 uses the advanced Speedtronic Mk IV distributed microcomputer-based electronic control system, which increases gas turbine reliability standards significantly. It features redundant computer sections, with on-line diagnostics.

Fuel System. Dual fuel using either natural gas or liquid distillate oil, thus allowing one fuel to be changed to another at any power level. Simultaneous operation on both fuels is possible across all power ranges and in varying mixture percentages.

Operational Characteristics. The aeroderivative industrial and marine LM1600 is a simple-cycle gas generator developed for gas turbine applications in the 12,000-20,000-shp range. The LM1600 gas turbine is a three-shaft machine with a two-shaft gas generator and a single-shaft, aerodynamically coupled power turbine. The power turbine speed is 7,900 rpm, which results in an excellent speed match for the direct drive of compressors in this power range. A load gear is required for electrical generators.

The LM1600 combines the features of high power-to-weight ratio, compact design, ease of maintenance, and ease of operation. It also offers a high degree of commonality with the aero engine – a plus for the powerplant in the marine marketplace. Given the experience of the F404, the LM1600 is one of the few turbines to enter service with a lengthy track record behind it. From a family-of-engines perspective, the LM1600 industrial machine is the middle sibling, nestled between GE's LM500 and LM2500 engines.

For cogeneration applications, the gas turbine system delivers both shaft power for the generator and useful thermal energy for process use. In the most simple gas turbine cogeneration cycle, exhaust energy is used to generate steam at conditions suitable for a process steam header, in an arrangement commonly used when applying a gas turbine heat recovery steam generator system to an existing process plant. The HRSG steam partially or totally displaces steam generated in ambient air-fired process boilers. Because steam is generated at higher steam conditions than those required in process plants, steam turbines can be used in addition to the gas turbine in the cogeneration cycle.

An additional possible feature is a dual-pressure-level (DPL) HRSG, an arrangement common for unfired HRSG systems. An advantage of DPL HRSGs is that more gas turbine exhaust energy can be recovered, thereby contributing significantly to the thermal performance associated with this cycle.

Variants/Upgrades

LM1600PA. The designation LM1600PA still applies to the LM1600 manufactured by IHI in Japan; that model is simple-cycle rated at 13.9 MW. Other parameters are as follows: pressure ratio, 22.3:1; exhaust flow, slightly more than 46.99 kg/sec; power shaft speed, 7,000 rpm; exhaust temperature, 490°C.

LM1600PD. The LM1600PD is a DLE-equipped LM1600.

LM1600PE. The LM1600PE is the basic gas turbine model in the series.

LM3000. The LM3000 is the designation of the formerly designated LM1600 ICR; it is an intercooled regenerative-cycle LM1600 arrangement.

PGT16. GE documentation has included a PGT16 aeroderivative gas turbine. The PGT16 gas turbine machine consists of an LM1600 gas generator coupled with an industrial power turbine designed by GE Oil & Gas (here referring to the Nuovo Pignone entity). The PGT16 has a power turbine shaft speed of 7,900 rpm.

LM1600 Steam Injection. The former Gas Research Institute (GRI) of the U.S. and GE have worked on a steam-injected (STIG) version of the LM1600 rated at 17-17.6 MW with full steam injection. In a STIG configuration, steam generated from the LM1600 is injected back into the LM1600 to increase power output. Operating parameters are as follows: HP steam, 201.1 kg/sec (steam conditions 500 psia, 770°F [3,445 kPa, 410°C]); LP steam, 179.1 kg/sec (steam conditions 190 psia, 730°F [1,310 kPa, 388°C]).

The LM1600 demonstrated average NOx emission levels with the standard dual-fuel combustion system of 144 ppm on natural gas and 236 ppm on distillate (referenced to 15 percent oxygen) at full ISO baseload output (with 4-in inlet and 8-in exhaust duct losses). Using STIG for NOx suppression, levels can be reduced

to a guaranteed 25 ppm on natural gas and 42 ppm on distillate fuel. These levels meet virtually all environmental requirements without involving selective catalytic reduction (SCR) systems. The ability to change the steam injection rate rapidly is another STIG feature well suited to cogeneration applications with varying process demands. STIG can be used in combined-cycle cogeneration plants.

Affiliates/Licensees

Dresser-Rand Company. The Dresser-Rand company Turbo Products Division has offered the LM1600 gas generator mated to a Dresser two-stage power turbine to create the DR-60G mechanical drive package for powering pumps and compressors. The DR-60G is ISO-rated at 14,500 kW (19,445 hp).

DR-60Gs have been ordered by such customers as Alberta Natural Gas (2), Great Lakes Gas Transmission Company (3), NAM in the Netherlands (1), Nova (4), Pacific Gas Transmission Company (1), TransCanada Pipelines Company (5), Transgas in the Czech Republic (4), and Westcoast Energy (2). Overall, D-R installed at least 23 LM1600s on its power turbines. Dresser-Rand's relationship with GE as a packager was discontinued in 1999.

MTU. In June 1989, MTU (Motoren- und Turbinen-Union) signed an agreement for the joint development of a marine propulsion package powered by the LM1600. GE supplies the gas turbine engine, while MTU supplies the balance of the plant, including resilient mounting on the base plate, plenums, acoustic enclosures, lube skids, couplings, and control and monitoring equipment. The first modules were delivered in 1990. MTU has installed at least three LM1600s for marine power.

GE Oil & Gas (Nuovo Pignone Entity). GE had intended to build its own power turbine for the LM1600 gas generator, based on its popular MS3002 power turbine but incorporating an added stage, advanced aerodynamically designed rotor and stator airfoils, higher temperature materials, fixed (as opposed to variable geometry) nozzles, and modular construction for ease of removal of the power turbine. While in the early stages of power turbine design, GE learned that one of its longtime business associates, then-Nuovo Pignone of Italy (now a part of GE's Oil & Gas business unit), was developing a variant of its PGT25 (LM2500-based) power turbine for its new PGT16 turbine machine.

The Nuovo Pignone two-stage design is rated at 92 percent isentropic efficiency. It features adjustable Stage 1 nozzles and has a 7,900-rpm output/power shaft speed. For 50-Hz or 60-Hz electrical generation systems, the PGT16 is rated at 13,870 kW ISO baseload. For mechanical drive service, the power turbine's output shaft speed of 7,900 rpm is well suited to drive the most current line of centrifugal compressors.

Nuovo Pignone reportedly delivered six machines to TransCanada Pipelines Company in 1991-1992 for gas compression duty, two machines to Cascades Paper Company in 1992 for cogeneration duty, and one additional machine to Phillips Petroleum for gas compression duty. Nuovo Pignone installed at least nine LM1600s.

S&S Energy Products (Stewart & Stevenson). This Houston-based firm has incorporated the LM1600 in its units under the designations TG1600 and TMD1600. Under the old Thomassen Stewart & Stevenson International (TSSI) designation, at least two machines were delivered to customers. In 1997, Stewart & Stevenson sold its Gas Turbine Division to GE.

Thomassen International. In a system developed and executed by Thomassen International BV, gas and steam turbines drive both ends of a single generator, with the configuration providing optimal system flexibility. The LM1600's combined-cycle efficiency is reported by Thomassen as being as high as 88 percent, and a maximum net electric power of approximately 18 MW is typical of its configuration. Thomassen installed at least nine LM1600s for generation duty.

IHI Corp. IHI Corp in Japan offered the LM1600 in a gas turbine generator package featuring a wide variety of standard equipment and optional equipment; in a combined-cycle arrangement, the IHI unit carries the designation LM1600PA. It delivered one unit in 1993 to the Tokyo metropolitan government for peaking power duty in Tokyo. IHI has installed at least two LM1600s.

European Gas Turbines Ltd/Alstom. EGT (and later Alstom) installed 21 LM1600s for electrical generation and 17 for mechanical drive duty. European Gas Turbines was subsequently incorporated into Alstom. This company was later absorbed by GE.

Kvaerner Eureka. Kvaerner Eureka installed at least 15 LM1600s, including 10 for marine power, four for mechanical load drives, and one machine for power generation. Kvaerner Eureka later became Kvaerner Energie. Kvaerner Energie is now a part of GE Energy.

GE LM1600

Program Review

GE's aeroderivative industrial and marine LM1600 is the first third-generation aero-derived gas turbine, being a derivative of the GE Aircraft Engines F404 aviation turbofan, which powers the McDonnell Douglas F/A-18C/D multirole fighter. Design and development of the 13.7-MWe machine were influenced by the operating experience of the LM2500 as well as the heavy-duty GE units. The LM2500 reportedly offers the highest quoted simple-cycle efficiency in its power class.

Beyond the Ingersoll-Rand unit installed in 1986, GE is believed to have installed two LM1600-powered cogeneration sets: one for use by Lynn, Massachusetts, utilities and the other for use by Evendale, Ohio, utilities. These units, which are believed to have gone on line in 1988, serve as showcases for potential customers, as well as providing power to the two utility operations.

In 1989, Thomassen International received a contract from Hoogovens Groep BV in the Netherlands for the supply and installation of an LM1600 cogeneration facility at a steel mill in Ijmuiden. It was the first cogeneration order involving the LM1600.

LM1600 Marine Engine. In 1986, the U.S. Navy awarded GE a $2.75 million contract for the development of a new propulsion system for next-generation warships. Using the F404-based LM1600, an intercooler and regenerator have been added to the LM1600 core to produce the LM3000 engine (formerly referred to as the LM1600 ICR). The intercooler aids in the heat removal process between the LP compressor and the HP compressor. Preheating combustion air with a regenerator is considered an excellent method of decreasing fuel consumption. The ICR machine was expected to burn 30 percent less fuel during typical ship missions than comparably powered gas turbines.

The first LM1600 marine gas turbine was installed in a 75-meter high-speed yacht in the summer of 1990. A second application, the 67.6-meter Fincantieri-built *Destriero*, uses three LM1600s.

Kvaerner Eureka ordered two LM1600s and two LM2500s in August 1993 from GE Marine & Industrial for Stena AB's High-speed Sea Service (HSS 1500) ferry, which entered service in 1995. The 125-meter ferry carries 1,500 passengers and 375 cars at speeds of up to 40 knots across the Irish Sea between Holyhead, Wales and Dublin Bay, Ireland. The LM2500s are rated approximately 27,100 shp (20,208 kW) each, while the LM1600s are rated approximately 17,500 shp (13,050 kW) each, for a maximum total output of 89,200 shp (66,516 kW). The powertrain arrangement is COGAG (combined gas turbine and gas turbine). Kvaerner later placed orders for four more LM1600s (and four more LM2500s) for two additional 125-meter Sea Service ferries.

In 1995, Kvaerner placed orders for four LM1600s to power two 71-meter Seajet 250 high-speed catamaran ferries built by Danyard of Denmark for service in Denmark. The ferries accommodated 450 passengers and 120 cars. The LM1600s produce 24.8 MW for two Kamewa waterjets transmitted via a single-input / twin-output Maag gear. The gear splits the power (12.4 MW at 7,000 rpm) to the two 6.2-MW/580-rpm jets.

Funding

Early funding for the LM3000 (LM1600 ICR) was provided under U.S. Navy PE#63508N, Ship Propulsion System (Advanced) (now PE#0603508N, Surface Ship & Submarine HM&E Advanced Technology). This program element covers the development of advanced gas turbine propulsion and auxiliary power systems for U.S. naval combatants. The LM3000 was the progenitor of the GE LM2500, Allison (now Rolls-Royce) 501-KF, Garrett (now Honeywell) IE 831, Pratt & Whitney (now UTC Pratt & Whitney Power Systems) FT9, and Solar Turbines Rankine Cycle Energy Recovery System. Later, emphasis was placed on improvements to the LM2500 propulsion systems and 501-KF generating systems, on the RACER project, and on the LM3000 intercooled recuperated (or regenerative) cycle (ICR) gas turbine.

Contracts/Orders & Options

No contractual data for the GE LM1600 gas turbine is currently available.

Timetable

Month	Year	Major Development
	1986	First release of an LM1600
Mid-	1987	Ruston joins program
Late	1987	First LM1600 installed
	1988	First LM1600 begins service
Late	1988	Dresser-Rand ships first two DR-60Gs
	1990	First marine installation
	1990	First EGTL-IP and Thomassen machines shipped
	1991	First Nuovo Pignone machines delivered
	1991	Initial in-service date of marine gas turbines
	1992	First TSSI machine delivered
	1993	First IHI machine delivered
	1996	S&S/TSSI fills order for one machine for Syria Petroleum Company
Apr	1996	Stena *Explorer* begins commercial service
Jul	1996	Seajet 250 begins commercial service
Dec	1996	GE supplies IHI with LM1600 with DLE combustion system; first LM1600 with DLE enters commercial service
	1999	Alstom ceases to be an LM1600 packager
Late	1999	Dresser-Rand ceases to be a packager for GE
Q2	2005	Volvo Aero signs maintenance agreement with UBE Chemical Europe

Worldwide Distribution/Inventories

At the start of 2017, at least 160 LM1600s were in service. Forecast International's **Industrial & Marine Gas Turbine Installations Database** identifies 160 of these machines in 17 countries.

Forecast Rationale

The LM1600, a derivative of the GE F404, has been available since the mid-1980s and has been used in both industrial and marine applications. The LM1600 comes in two varieties: the LM1600 SAC, which is the standard version, and the LM1600 DLE, which is used in applications that benefit from use of an emissions reduction engine.

The LM1600 was once heralded as a machine with considerable sales potential, but orders for this machine have faded away and GE has confirmed that production of the gas turbine has ceased. It is possible that, should a demand resurface, its production status could be restored, but this appears improbable at this time. Therefore, this report will be archived next year.

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