Gas Turbines for Cogeneration & Combined-Cycle ©

An introduction to the industrial gas turbine generator engine: both heavy-duty frame and aero-derivative, the package and auxiliaries, for the cogeneration or combined-cycle power plant .

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GAS TURBINE CONCEPTS

The Basic Gas Turbine Cycle

The basic gas turbine thermodynamic cycle is an open Brayton Cycle, using air as the working fluid. Air at ambient state 1 is compressed to a high pressure at state 2; fuel is added and continuously burnt to the firing temperature (state 3); and the resultant high-pressure, high-temperature air is expanded through a turbine to atmosphere (4).

The expander turbine physically drives the compressor section, and the excess power available on the turbine shaft is used to drive a load.

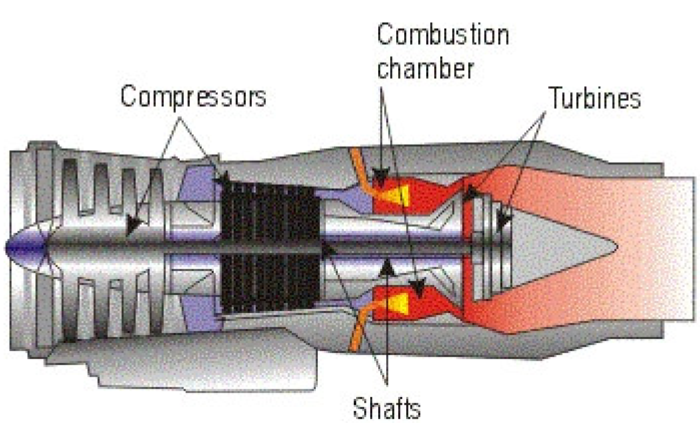
The higher the turbine inlet temperature T3, for a given pressure ratio, the higher the power output and efficiency of the unit.

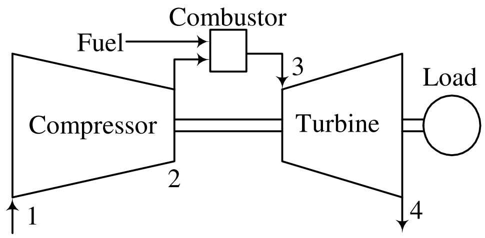
As gas turbine materials have developed, turbine “firing” temperatures have steadily climbed from the 1400 deg F region, through 2000~2200 deg F, and now up to 2600 deg F in the newest units being offered.

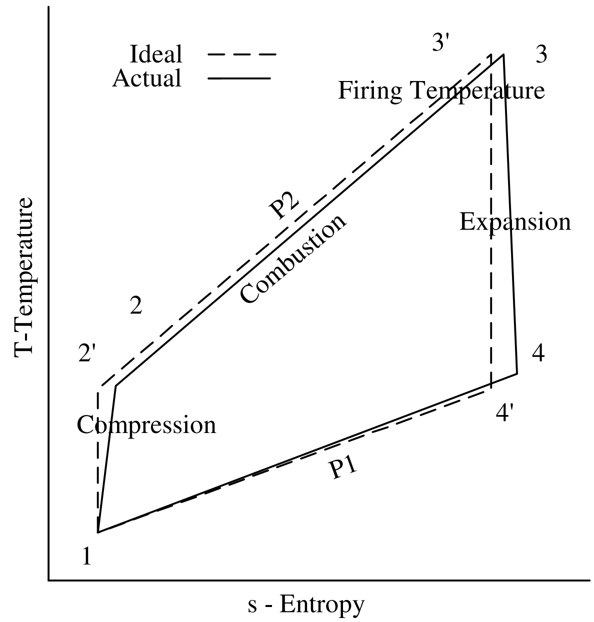
The higher the pressure ratio P2/P1, the higher the unit’s efficiency (for higher firing temperatures), and the higher the specific power output of the engine (hp/lb/sec).

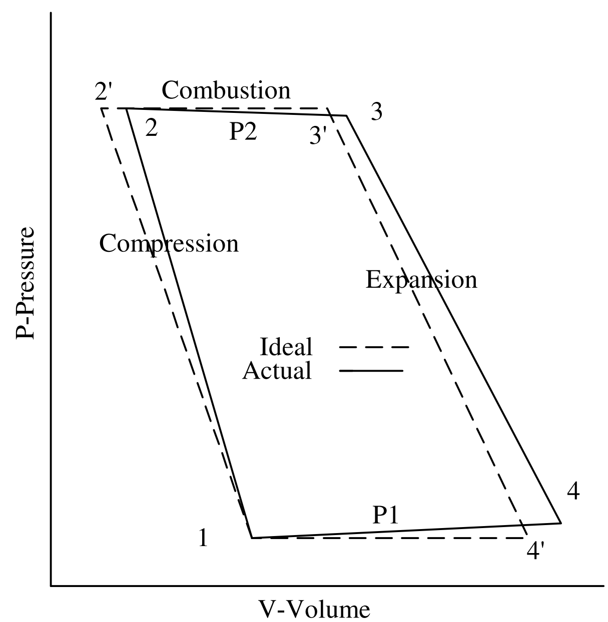
Accordingly, most aircraft gas turbines (jet engines, turboprops and turbofans) use high pressure ratio, high firing temperature designs to minimize weight and frontal area. Thus, the resultant aero-derivative GT shares a high-pressure ratio design.

Gas turbine design pressure ratios vary from 7.5:1 for the smaller and older technology GT’s, up to 35:1 for the recent, most advanced GT’s.





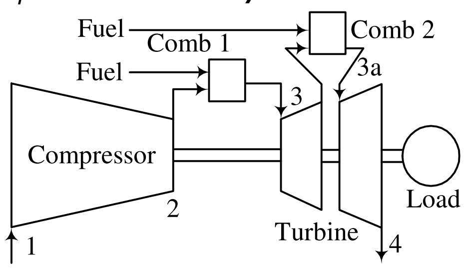


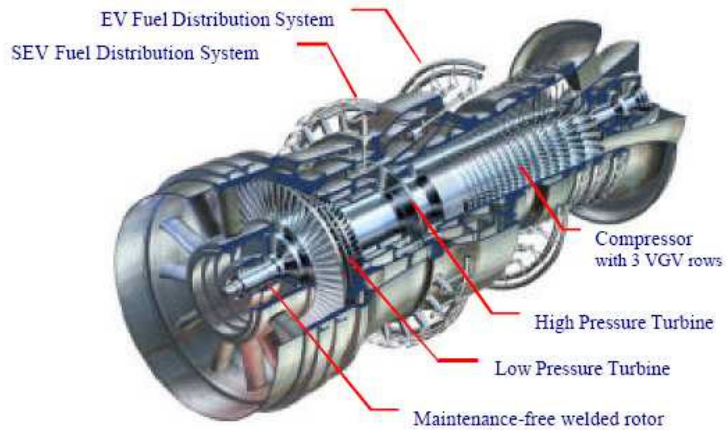


Turbine Cycle Variations

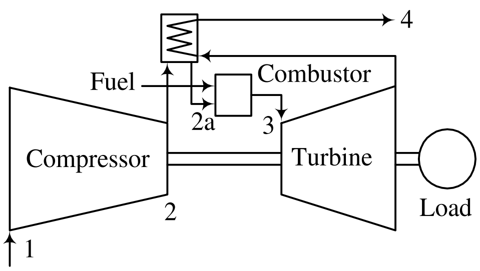
There are several major **variations** of the basic gas turbine Brayton cycle, including:

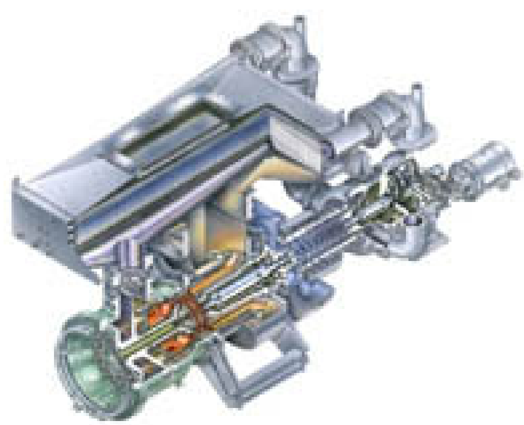
a) **Reheat or sequential combustion** – typically employed in high-pressure ratio GT's. The hot gases leaving the HP turbine section, are reheated by the combustion of additional fuel prior to entry into the LP turbine section. Reheat increases the output of the LP turbine, and raises the turbine's exhaust temperature, resulting in increases in simple-cycle and combined-cycle power output. *Example:* ***Alstom GT24/26***.



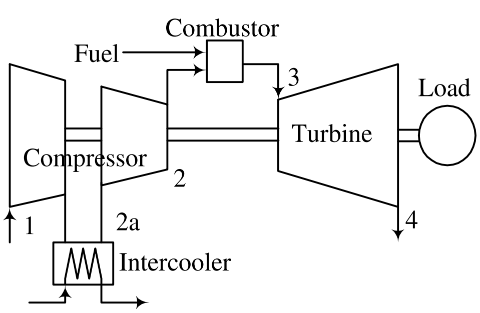


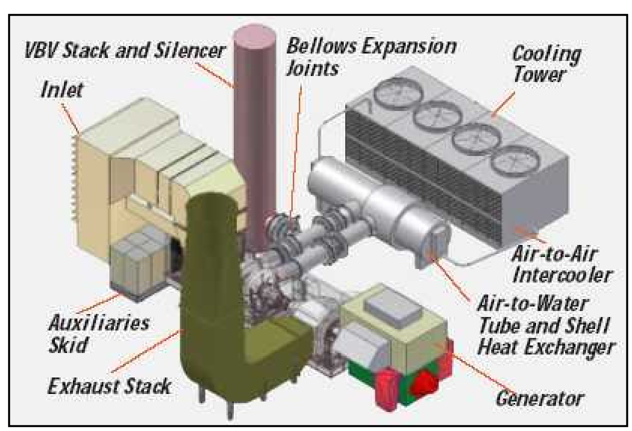
b) **Recuperated or regenerated GT's**, typically employed in low-pressure ratio units with high firing temperatures. An external regenerative heat exchanger is used to transfer heat from the exhaust to the air leaving the compressor, before it enters the combustor. This saves fuel and increases thermal efficiency, with a slight decrease in power output. Because of the high-flow, high-temperature nature of the process, these heat exchangers are very large and expensive. *Example:* ***Solar Mercury***.



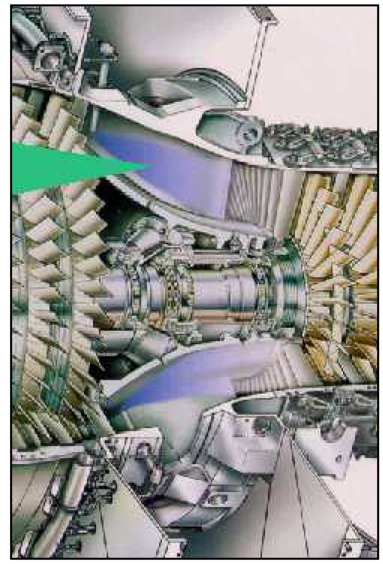


c) **Inter-cooled GT's** – typically employed in high-pressure ratio multi-shaft units. Compressed air from the LP compressor is directed through an external heat exchanger, and a cooling medium (e.g. cooling water, or a process fluid) is used to decrease the air temperature (hopefully close to ambient conditions) prior to entry into the HP compressor. This process decreases the required HP compressor power, thus improving the efficiency and specific output of the unit. Again, because of the external heat exchanger and modifications to the "standard" unit, this process tends to be large and expensive; plus an external cooling system of some form is required. Example: the new 100 MW ***GE LMS100***, with either air or water cooling.

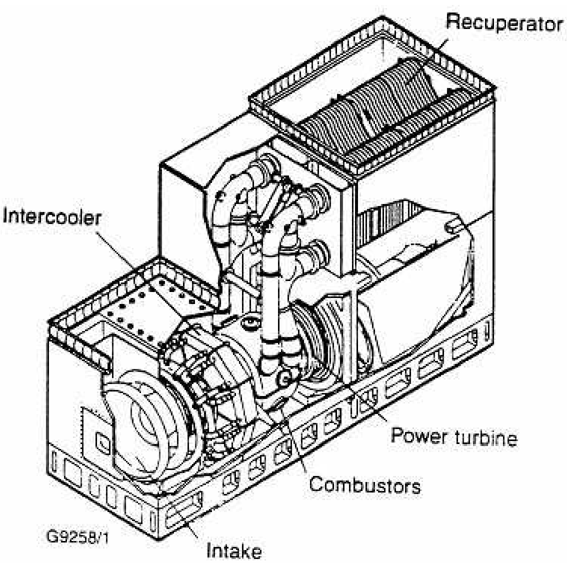


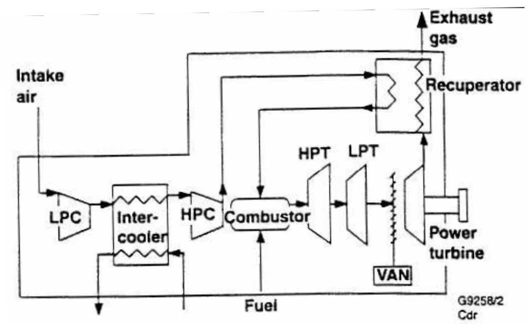


d) **Spraywater Cooling** – an intercooling version where clean water is introduced between the LP and HP compressor of the multi-shaft aero-derivative ***GE LM6000 Sprint*** that is controlled to a fixed compressor discharge temperature T2. Cooling the HP compressor inlet air allows increased HPC mass flow (for the same T2 setpoint), resulting in an increased pressure ratio, increased unit power output and improved efficiency, especially at higher ambients.



Further enhancements can be achieved by spray cooling / fogging the inlet to the LP compressor, at high ambients.



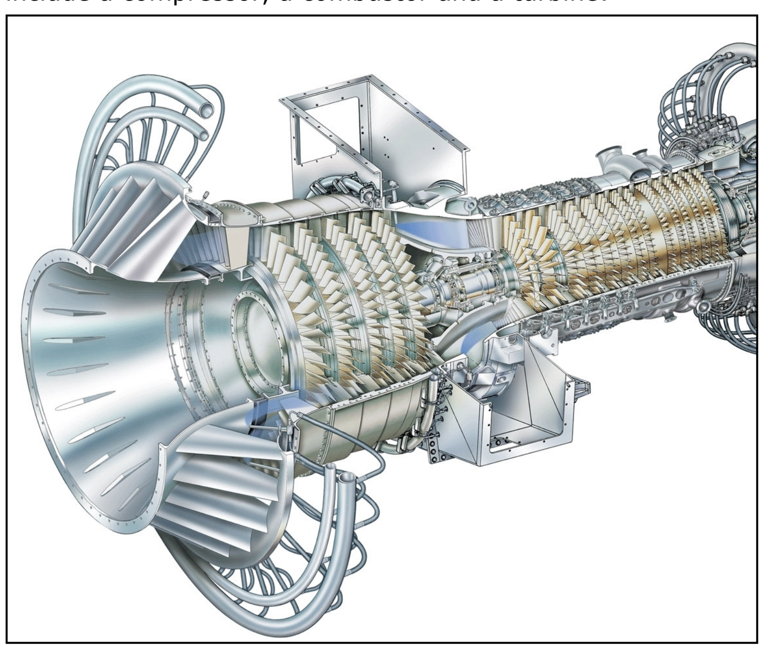


e) **Intercooled & Recuperated GT** – for interest only, the ***Rolls-Royce WR-21*** marine drive unit is a special high-efficiency configuration that employs both an exhaust recuperator and a sea-water cooled intercooler (there are no land applications)

Basic Components of the Gas Turbine

The major components of the gas turbine engine include a compressor, a combustor and a turbine:

a) **Compressor Section** – most frequently a multi-stage axial design. In each stage, a row of stationary blades (stators) acts on the air to impart the correct angle for the succeeding rotating blades. A final set of outlet guide vanes and a diffuser straighten and slow the air stream prior to entry into the combustor section.



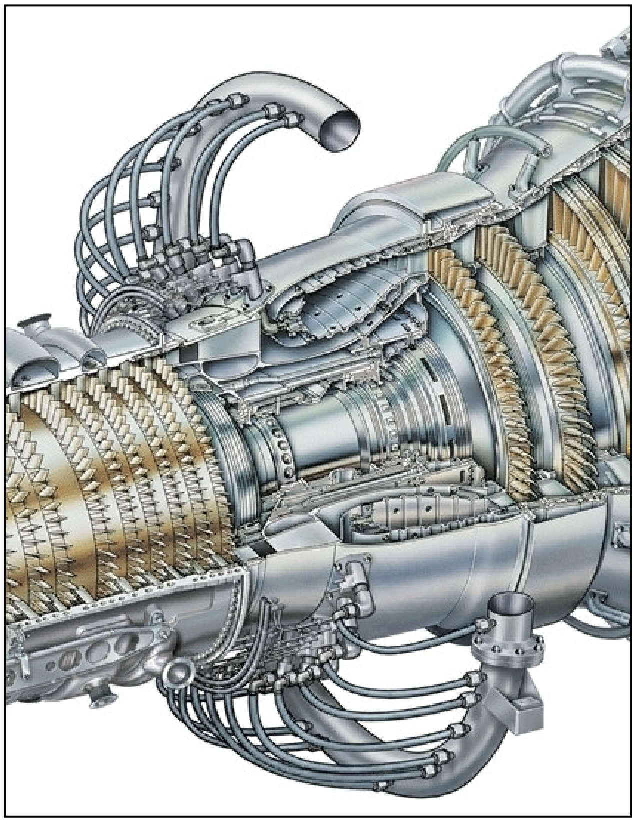
In most GT's, small portions of the compressed air are bled out along the blade path and used for cooling purposes in the hottest portions of the stationary and rotating turbine sections. In some gas turbines, small portions of the compressed air are taken out and used for pressure balance elsewhere in the GT to minimize axial loading.

Compressor air bleed systems are employed to discharge excess air during starting (when the blading design works less efficiently at lower rpm's), and during part-load operation.

Pivoted variable guide vanes are frequently employed on both industrial and aero-derivative units, to manage the bulk inlet air flow into the GT (i.e. inlet guide vanes - IGV), and to manage the mass flow further along the blade path for control reasons. On some GT's the IGV's are manipulated during part-load operation to maintain exhaust temperatures high for cogeneration / combined-cycle steam generation considerations.

Many of the aero-derivative units also employ variable stator vanes (VSV) to control air flow and rotor speed in the higher-pressure section.

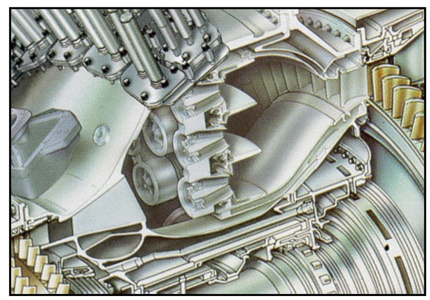
LM6000 Compressor *with variable bleed valves (VBV), IGV's and VSV's – courtesy of GE Energy*



b) **Combustor Section** – which can be a multi-can or basket design, or an annular ring design.

For standard diffusion combustion systems (i.e. non dry low-NOx), gaseous or liquid fuels are introduced via nozzles located at the head of each combustor can, or the front of the combustion annulus chamber. A portion of the air from the compressor is introduced directly into the combustion reaction zone (flame), with the remainder introduced afterwards to shape the flame, to quench the flame to an acceptable firing temperature (T3), and to cool the walls of the combustor and downstream liners.

In some cases – for environmental or power enhancement reasons – water or steam is injected into the primary combustion zone, to reduce flame temperatures and the production of thermal NOx.



Current generation dry low-NOx (DLN or DLE) combustion systems operate differently than above, using the lean premix principle, as shown above.

Between the baskets and the turbine blading, transition ducts or liners are used to carefully shape the gases for the turbine section, with velocity & temperature profiles.

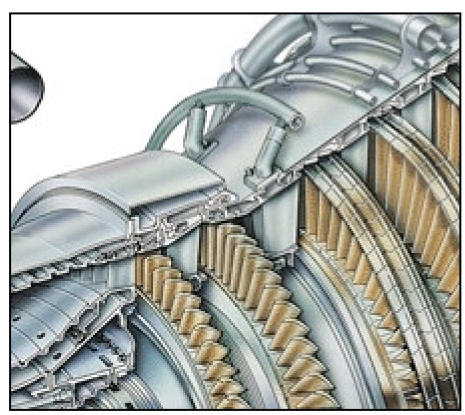
Fuel and steam and/or water injection manifolds and hoses are located around the circumference of the combustor section. Above example: ***LM6000 Combustor Section*** *– courtesy of GE Energy*

c) **Turbine Section** – usually a multi-stage axial design. In each stage, a row of stationary nozzles acts on the hot gases to impart the correct angle for the succeeding rotating blades.

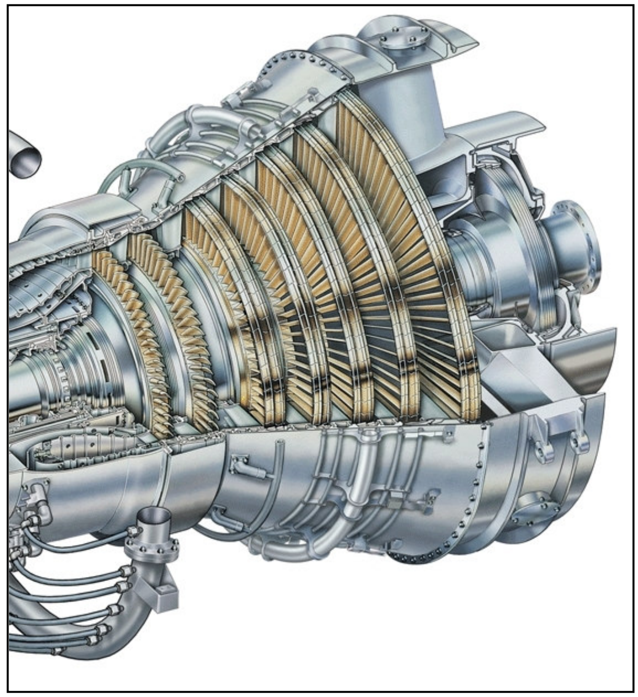
The most critical section of the turbine is the first few stages. Both the nozzle and the rotating blade are exposed to "red-hot" gases at the design firing temperature, which is far in excess of acceptable creep-fatigue limits for the engineered alloys employed.

In addition, the rotating blade has to survive while being subjected to high centrifugal and mechanical stresses.

As a result, massive research and development efforts are conducted to design materials and systems for the cooling of these stages.



Internal cooling passages are cast and machined into the nozzles and bladeS, and cooled compressor bleed air is passed through them to maintain material temperatures at acceptable limits. ***LM6000 Turbine Section -*** *courtesy of GE Energy*



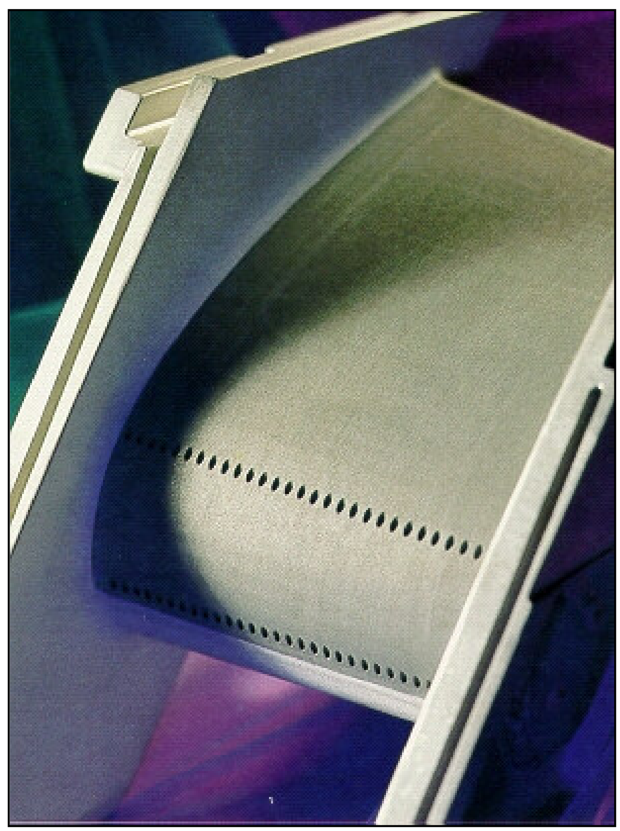
Creep-resistant directionally-solidified and single-crystal blade production technology has moved from the aircraft GT world into the industrial heavy-duty GT design world.

Directionally solidified turbine blade

Thermal barrier coatings are employed to protect the aerodynamic surfaces and materials from corrosion, oxidization and erosion.

Turbine row assembly, showing blade attachments to the rotating disk, and blade cooling air exit holes

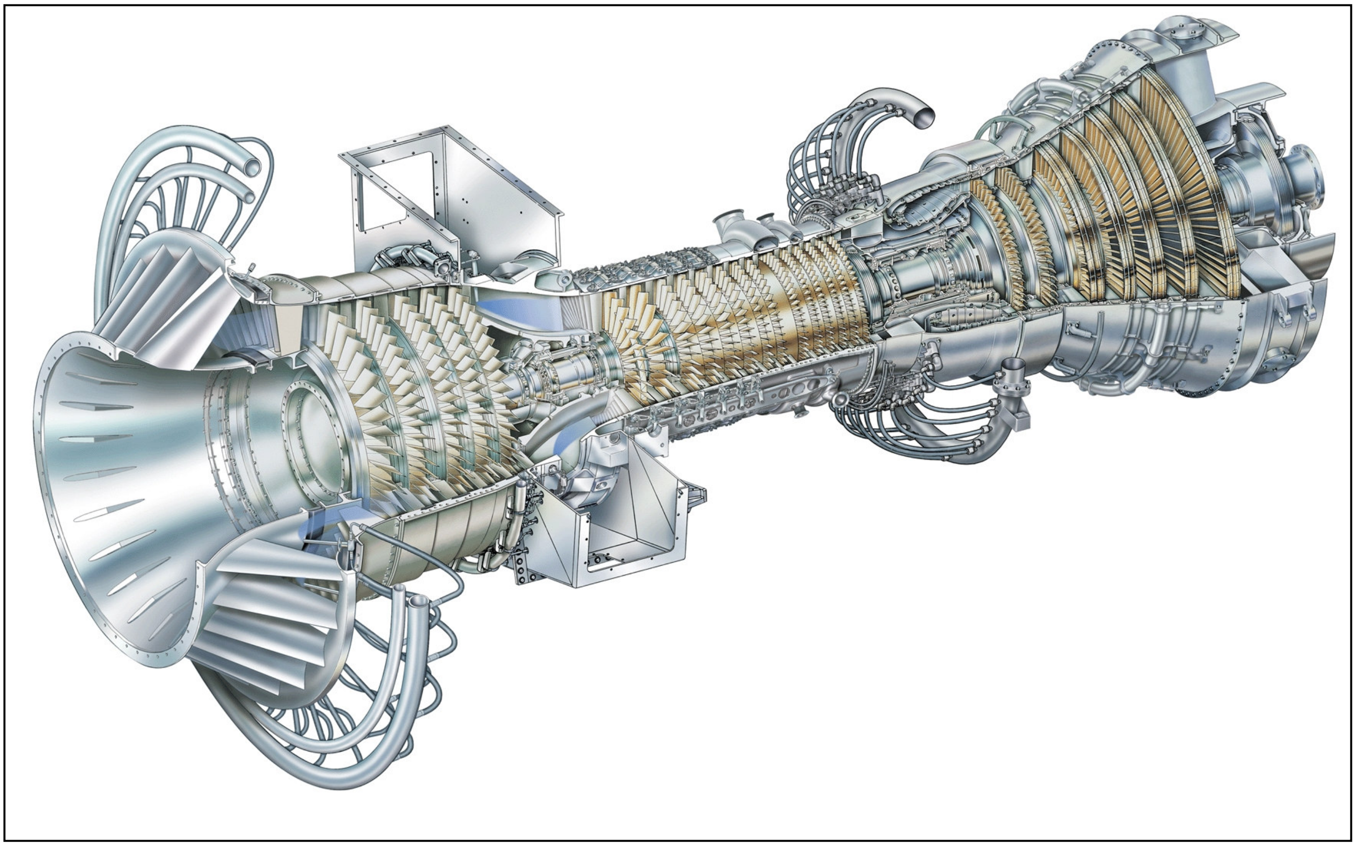
Turbine Nozzle with cooling exit holes



THE GAS TURBINE ASSEMBLY

The Basic Gas Turbine Machine

The individual **compressor**, **combustor** and **turbine** sections and their **casings** are bolted together, and supported via struts and baseplates, to make a complete **machine**. ***LM6000PC*** *– courtesy of GE Energy.*

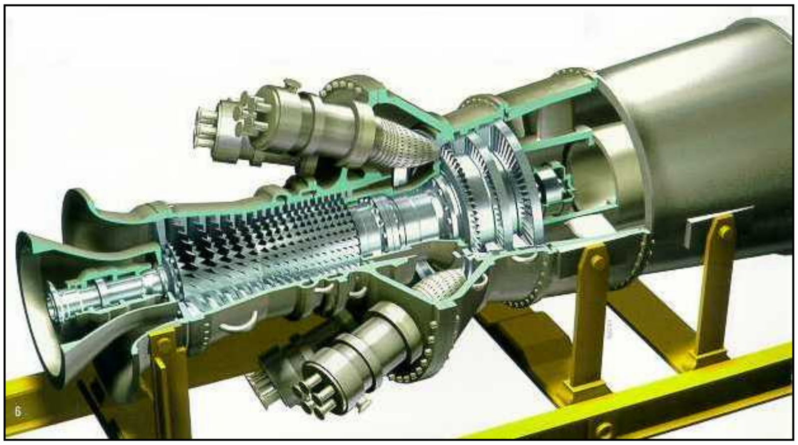


The rotating compressor & turbine sections are mechanically interconnected, and thus the required compression power is provided by the turbine section's power.

The excess turbine shaft power available is taken off an output shaft and used to drive a pump, compressor or generator. The graphic below shows a "cold-end" drive unit – "hot-end" drives are also employed on other machines.

Typically, 60% to 70% of the turbine's power output is needed to drive the compressor section, with the remaining 30% to 40% available as true shaft output power.

For example, a typical nominal 50 MW single-shaft industrial gas turbine will produce 150 MW in the turbine section, and provide about 100 MW of it to the compressor section.



GE 6FA *– courtesy of GE Energy*

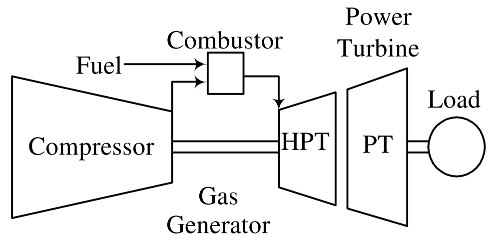
Inlet manifolds are installed to accept ducted filtered air. Exhaust gases are directed through a diffuser, to an exhaust stack or an HRSG. Fuel, steam and/or water manifolds and hoses, cooling air systems, controls and instrumentation are installed, to make a complete unit.

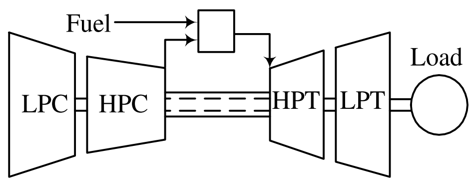
Gas Turbine Variations

Other GT configurations than the single-shafts exist, including:

a) **Single-shaft with PT** – industrial and aero-derivative units. A single-shaft GT operates at the speed and firing temperature that keeps itself self-sustained. It's exhaust gases are passed to an aerodynamic-coupled free power turbine (PT) that drives a load, at either fixed (generator) or variable speed (mechanical drive).

The prime unit is sometimes simply called a "jet", or "gas-generator", for convenience.





b) **Multi-shaft, with and without PT** – industrial units designed for variable-speed mechanical drive, and derivatives of aircraft engines.

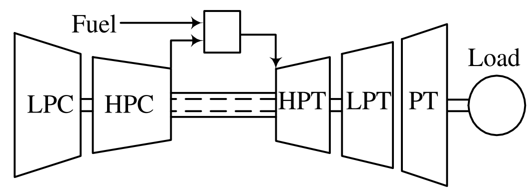
The basic compressor and turbine sections are divided into HP and LP units, and each usually operates at a different speed depending upon load and ambient conditions.

The LP compressor (LPC) is coupled to and is driven by the LP turbine (LPT). The HP compressor (HPC) is coupled to and is driven by the HP turbine (HPT).

In some three-shaft machines, an intermediate compressor (IPC) and turbine (IPT) are also used, in between the LP and HP sections (configuration not shown).

Fixed or variable-speed loads are driven off the LP shaft portion of the unit. Some units offer the capability to drive off either the cold-end or hot-end of the LP shaft.

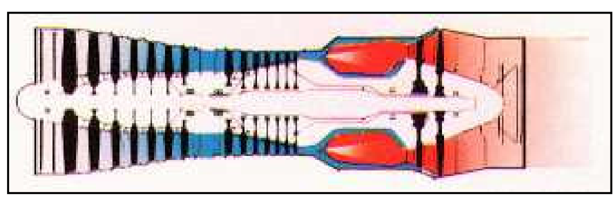
In some cases, these multi-shaft units, act as another "gas generator", and a PT is required to drive the load.

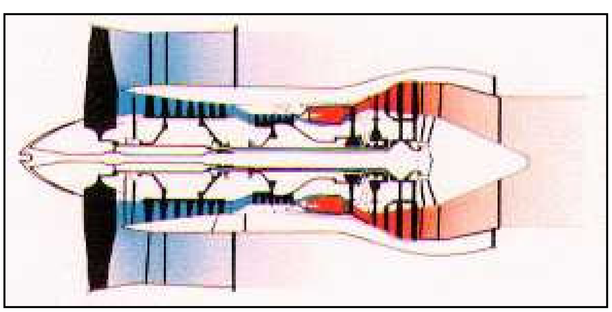


Aero-Derivative & Heavy-Duty Industrial Gas Turbines

Aero-derivative and heavy-duty frame industrial GT's are basically cousins, sharing the same basic thermodynamic cycle, but each executing the cycle differently depending upon the original design intent.

a) **Aero-Derivative GT units** are based upon aircraft engines, and are usually characterized by low weight and low frontal area, both of which are generally inconsequential in industrial service. The original **jet engines** developed for military & commercial applications produced forward thrust from the high-velocity, high-temperature exhaust gases by the use of nozzles. Most of these jet units receive a PT for industrial power application. The "jets" utilize anti-friction roller bearings, while their PT's use journal bearings.





Later derivations of the jet engine, especially for commercial application, add more turbine stages which are used to drive propellers (turbo-prop) or large fans for increased thrust (e.g. low & high-bypass ratio **turbo-fans**). The majority of these use anti-friction bearings, and are industrialized by redesign of the prop or fan takeoff drives.

Because of their high firing temperatures and pressure-ratios, most aero-derivatives are very efficient, compared to their same size industrial cousins. However, their inlet & exhaust flows [*Jet & Turbofan engines: rolls-royce.com*] are significantly less than same-size industrials, because of their high specific output (hp/lb/sec).

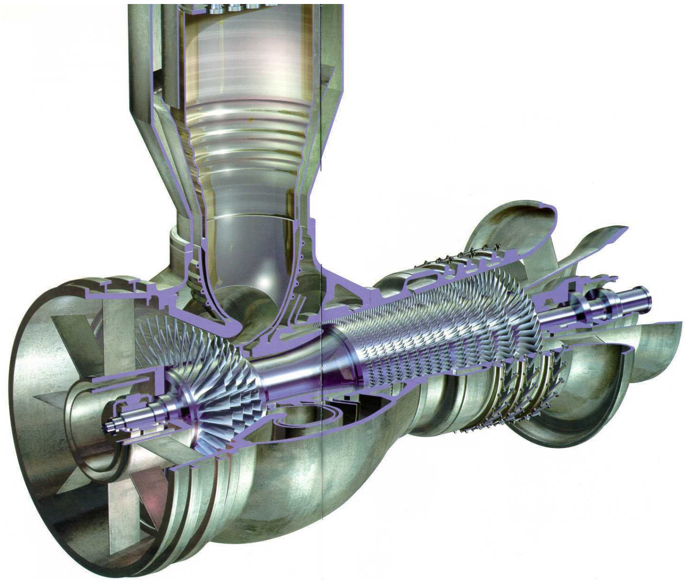
Major Maintenance of the aero-derivative gas turbine units is accomplished by the complete removal of the gas turbine from its package by special lifting frames.

This is followed by the disassembly of its modules into smaller components such as the LPC, HPC, combustion module, HPT and LPT, etc.

Most minor maintenance activities can be conducted at the plant site, but major disassembly and overhauls require that the unit be returned to certified shops.

Lease engines are generally available to replace the original engine that is under repair, during the overhaul period.

b) **Heavy-Duty Industrial GT units** for power generation are heavy & rugged units optimized to operate within a fairly narrow speed range and at base load duty. Typically, scheduled maintenance intervals are longer than aero units.



The industrial units are characterized by the use of heavy multi-cylinder castings and fabrications, large bolted horizontal and vertical split joints, and heavy built-up rotors, journal bearings and large solid couplings, large baseplates and frames.

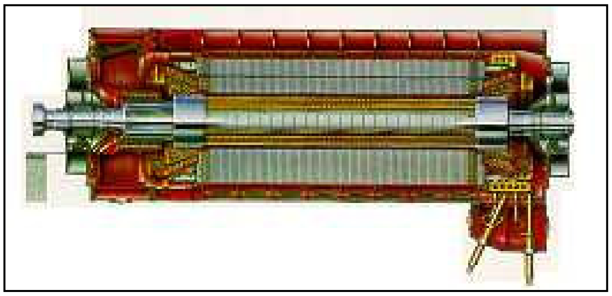
Major maintenance of the larger industrial GT units is usually accomplished by the removal of the top half cylinder, the removal of diaphragms and blade rings, the lifting and removal of the rotor, and subsequent blade removal, all of which can usually be accomplished at the plant site.

	Aero-Derivative	Heavy-Duty Industrial
Performance	Up to 50 MW. Up to 41~42% efficiency (LHV). Generally, less waste heat opportunity from the exhaust gases.	Up to 240 MW+. Up to 35~40% efficiency (LHV). Good waste heat opportunity. Large units with high exhaust temperatures allow reheat combined-cycle
Fuel Aspects	Natural gas to light distillates and jet fuels. Most require relatively high gas pressures.	Natural gas through to distillates and cheaper heavy or residual fuels. Generally require lower gas pressures. Expensive treatment of heavy / residual fuels is required.
Start-Up	Quick startup – 5~20 minutes. Relatively low horsepower starters usually electro-hydraulic	20 to 60 minutes depending on size. High horsepower diesel or motor starters, also some are started by the motoring of the generator itself
Loading	Quick loading, sometimes 10~25%/min	Slower loading, 1~10%/min depending on size
Shutdown	Many larger units require a short time of motoring to cool internals after a trip, but can then be shutdown	Many units require 1~2 days on turning gear after shutdown, but most can be motored to assist quicker cool down

THE GAS TURBINE PACKAGE

To prepare the gas turbine machine for service at a site, it needs to be packaged with driven equipment, controls and auxiliaries, in a form which is straightforward to install & commission, and that is easy to maintain.

Driven Equipment



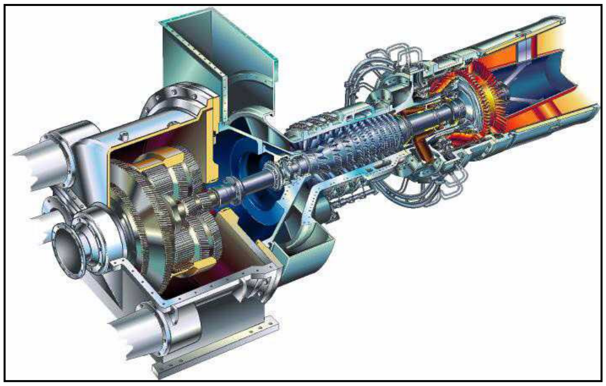
Industrial gas turbines typically drive generators and process or pipeline compressors, with occasional use as large pumping sets for oil. For cogeneration and combined-cycle, the typical driven equipment is a generator.

Synchronous **generators** for gas turbines are rated in accordance with ANSI C50.14, and are usually either 2-pole (3600 rpm for 60 Hz service) or 4-pole (1800 rpm for 60 Hz).

Generators can be air cooled, water-cooled (TEWAC) or hydrogen-cooled (the largest units).

Generator output voltages range from 600V for the very smallest GT's, to 2.4 and 4.16 kV for the 3~8 MW class units, to 13.8 kV for the 10 MW+ units, and 27.6 kV for the 100 MW+ units.

Excitation systems are used to control the generator's voltage and power factor/var, and can be either brushless (which usually derives it's excitation power from a shaft-mounted permanent magnet generator) or a thyristor-fired static system (which derives it's excitation power from an external transformer).



Brushless excitation systems are relatively maintenance-free, however their speed of response under some transient fault conditions are not as fast as static systems, and may not be satisfactory to the electrical authorities. Most large gas turbine generator (GTG) sets employ static excitation, with their attendant high-maintenance brush and slip ring systems.

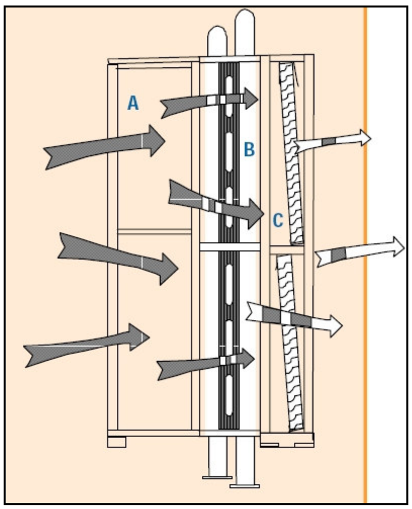
When the GT machine's output speed does not match the required generator speed, **gearboxes** are required. In the larger frame sizes, double-helical gear units are generally employed. Epicyclic gears are sometimes employed in the smaller, high-speed GT classes.

Air Inlet Systems

Proper air inlet systems for gas turbines are critical to the health of the GT and for noise mitigation.

High-volume multi-stage high-efficiency filtration systems are employed to capture atmospheric particles, to prevent their deposition on the compressor bladepath. *donaldson.com*

For some GT applications, heating of the inlet air is employed at low ambients, to prevent icing in the compressor or air inlet manifold, and/or to fool a pressure ratio limited aero-derivative GT into operating at a more optimum ambient temperature.

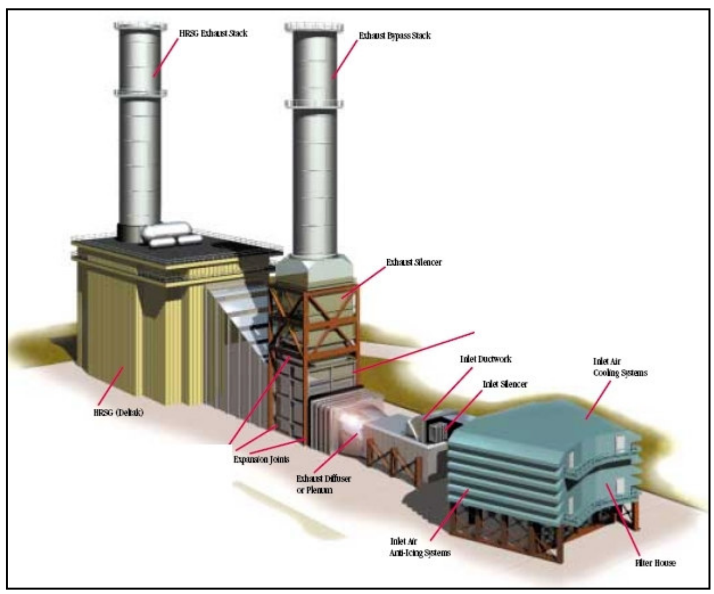


In some cases, inlet air cooling is employed at high ambients, to increase GT power output. A source of cool water-glycol (from chillers) is usually employed to provide the cooling mechanism. Large bore drainage systems are required to remove the water collected and draining from the cooling coils surfaces. Mist eliminators are required to collect any water droplets slung from the coil surfaces by the air stream.

Evaporative coolers, using clean water, can provide a performance advantage at high ambient, low relative humidity conditions. Again, mist eliminators are required to collect unevaporated water droplets.

Tuned inlet air silencers are also employed to absorb the sound & acoustic emissions from the gas turbine compressor and intake system.

There are many companies that provide all the air inlet filtration, cooling, heating, and silencing equipment to the major GTG equipment vendors. There services also extend to the provision of exhaust systems – silencers, expansion joints, bypass systems, stacks – and enclosures for the gas turbines themselves and for the HRSGs. *braden.com*



Lubricating Oil Systems

Main, auxiliary and emergency lubricating and control oil (as required) systems are provided for the gas turbine and the driven equipment.

Most aero-derivatives require fire-resistant synthetic lube oils for the GT, while their power turbines, gearboxes and generators employ mineral based lube oils. Most heavy-duty industrial GT's have a common lube oil system for the complete drivetrain.

Lube oil can be cooled either by aerial fin-fan coolers, or oil-to-water heat exchangers.

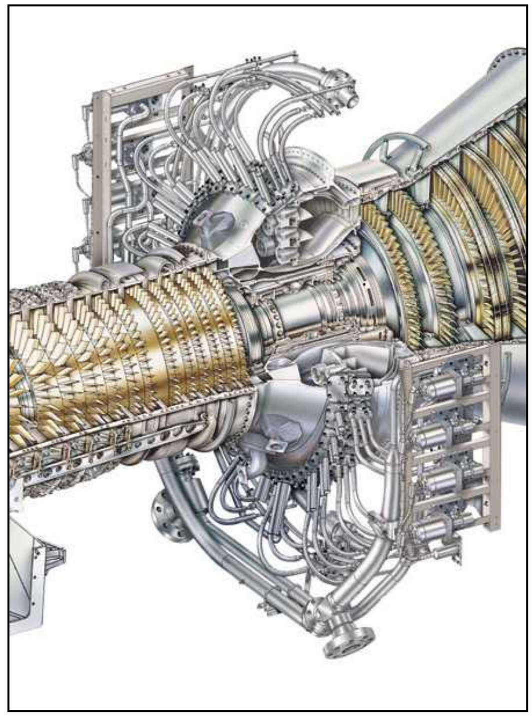
Fuel Systems

Aero-derivative and heavy duty gas turbine units can operate on most light-liquid or gaseous fuels. However, only the frame units can operate on heavy fuel oils and crude oils.

Fuel control systems for gaseous and liquid fuels include filters, strainers and separators; block & bleed valves; flow control/throttle and sequencing valves, manifolds and hoses.

For natural gas duty, gas compression equipment including reciprocating or centrifugal units, filters, and pulsation dampening equipment may be required, depending upon the available gas supply pressure.

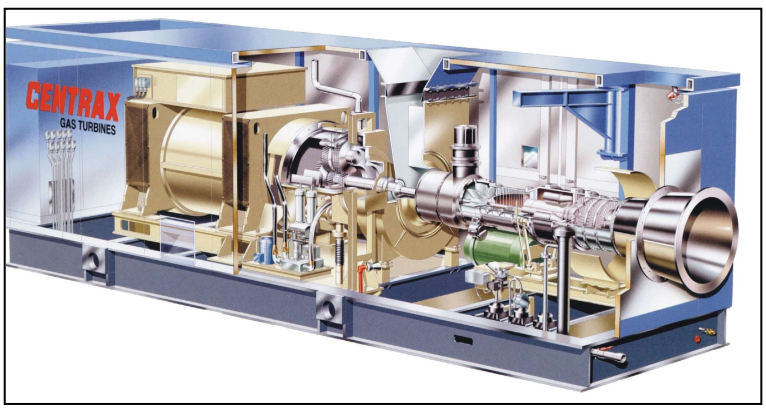
For the complex dry low-NOx (or DLE) units, some units require several throttle valves, staged and sequenced to fire pilot, primary, secondary and/or tertiary nozzle and basket sections (as applicable) of the DLE combustion system for startup/shutdown, speed ramps, and load changes. Several fuel manifolds are usually required.



LM6000PD DLE Combustor Section *– courtesy of GE Energy*

Acoustic and Weatherproof Enclosures

Enclosure *– courtesy of Centrax Gas Turbines*



For most of the smaller industrial and almost all of the aero-derivative GTG packages, the complete drivetrain is enclosed in an acoustic enclosure(s). The turbine and generator are compartmentalized and separately ventilated, for hazardous area classification reasons. As a result, these units tend to be prepackaged at the manufacturer's facility, and can be easier and quicker to install.

The 40~50 MW+ industrial GT machines are too large to pre-package in an enclosure, and the components are shipped in major blocks for assembly at site. Enclosures or buildings (if required) are built around the complete drivetrain as site construction progresses.

Controls and Monitoring

Current GTG control systems are complex combinations of digital PLC and/or processor systems, either selected from vendors such as Woodward, or based on vendor-proprietary systems, or occasionally DCS-based. The systems manage the GT fuel control and speed/load control, and the generator's voltage, power factor or var control, and breaker synchronization. The control systems manage the sequencing of all the auxiliaries, and usually include vibration, temperature and pressure monitors.

Generator protective relaying can be provided by the GTG vendor, or can be designed separately for more complex connection requirements.

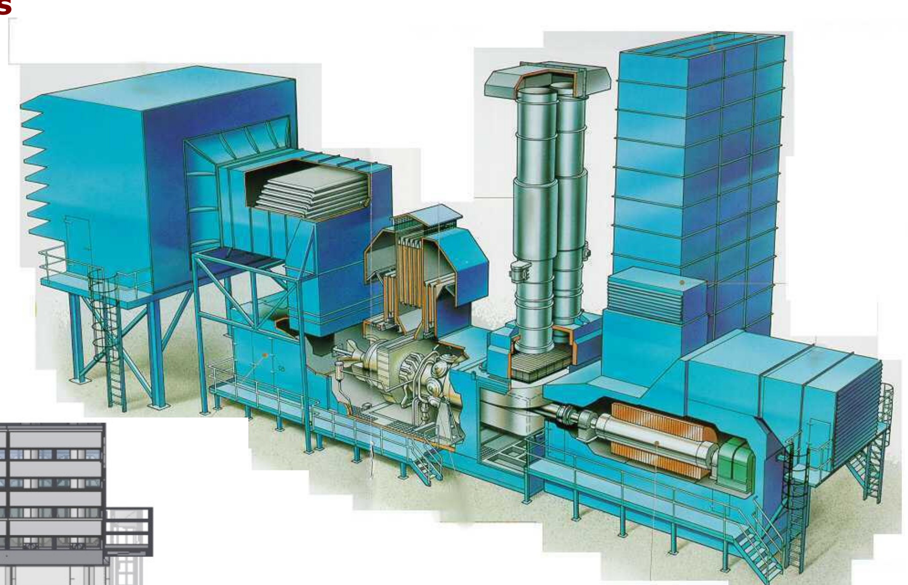
Sequence of events recorders are employed to determine causes of trips and shutdowns. Metering systems are installed to monitor and catalog billings. Most current GTG control systems will read/write to a plant DCS.

Miscellaneous Auxiliaries

Starting and turning gear systems; inlet manifolds; exhaust diffusers or plenums; water wash systems; water and steam injection (if required); gas detection systems; fire detection and CO_2 suppression systems; battery and charger systems; ventilation and heating; exhaust expansion joint, silencer and stack systems (simple-cycle).

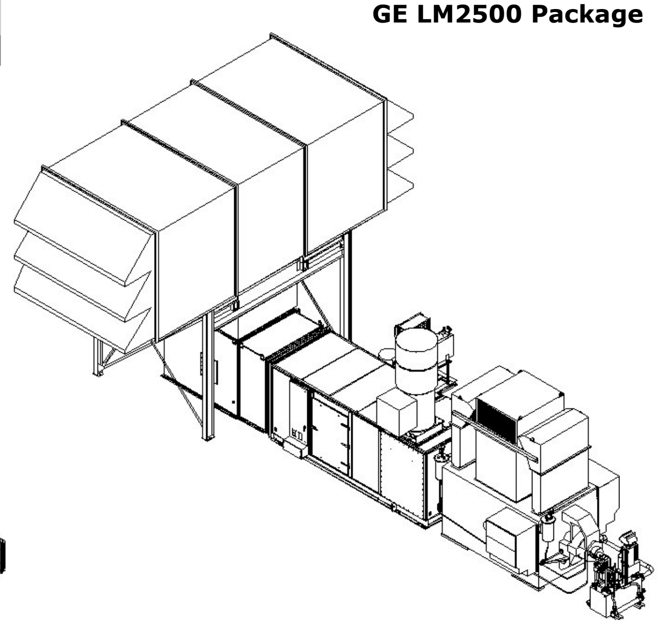
Complete Package Examples

Rolls-Royce Trent Package



GE LM6000 NXGN Package

GE LM2500 Package



Rolls-Royce RB211 Package / Plant