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Day 1 – Session 1

Gas Turbine Basics

By

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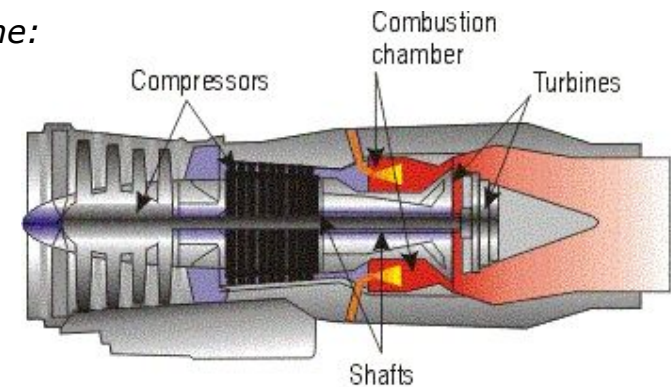
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GAS TURBINE BASICS®

An introduction to the basics of the industrial **gas turbine generator** engine:

- Heavy-duty frame and aero-derivative
- The gas turbine generator package
- The auxiliaries

For the cogeneration or combined-cycle power plant.

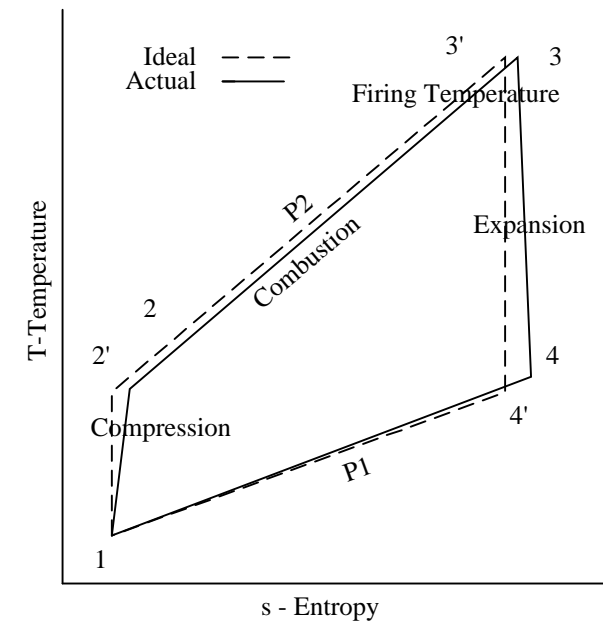
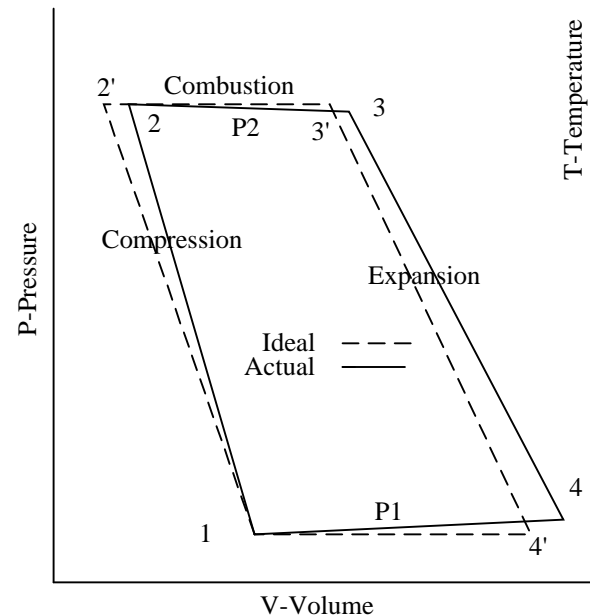
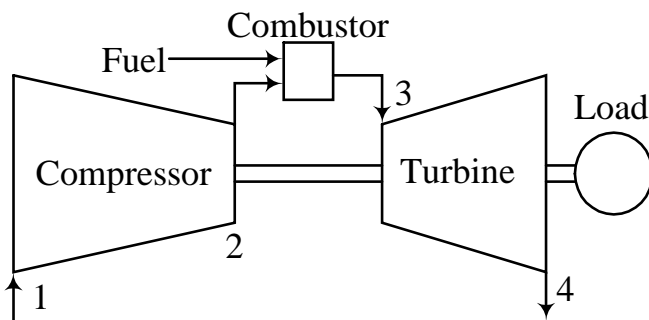


GAS TURBINE CONCEPTS

The Basic Gas Turbine Cycle

Brayton Cycle – a continuously operating process using air as the working fluid, moving through state points:

- Ambient Air (state 1)
- Continuous compression (states 1 to 2): the compressor requires power
- Continuous fuel combustion (states 2 to 3): which adds heat / small % of mass flow at relatively constant pressure
- Expansion back to atmospheric pressure (states 3 to 4): the turbine makes power



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Mechanical Operating Principles

The **Turbine Section** and its power output physically drives (i.e. rotates) the **Compressor Section** which requires power to operate.

Excess Turbine Shaft Power drives the load – generator (or mechanical-drive pump/compressor).

Firing Temperature

Firing Temperatures (T3): over time, have climbed from 1400 deg F to 2000~2200 and now 2600 F and beyond with better turbine section materials, coatings and cooling methods.

High T3 = improves power output & efficiency.

Pressure Ratio

Pressure Ratio (P2/P1); high ratio = high efficiency & specific output (hp/lb/sec).

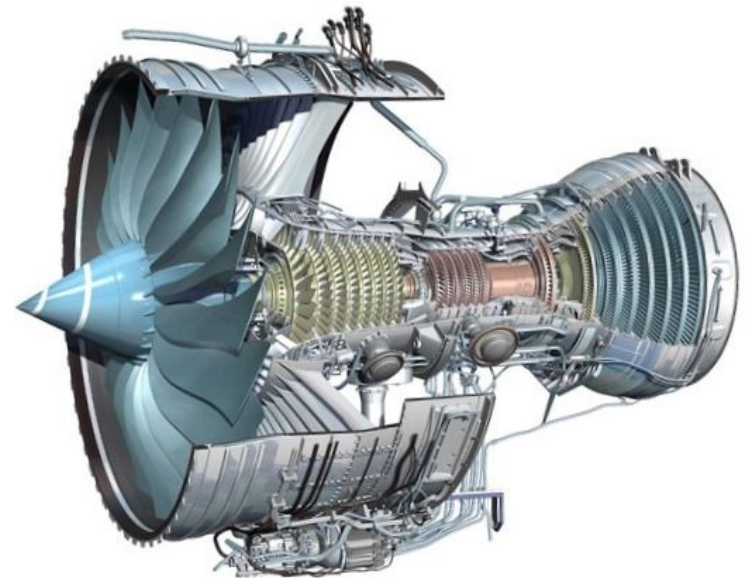
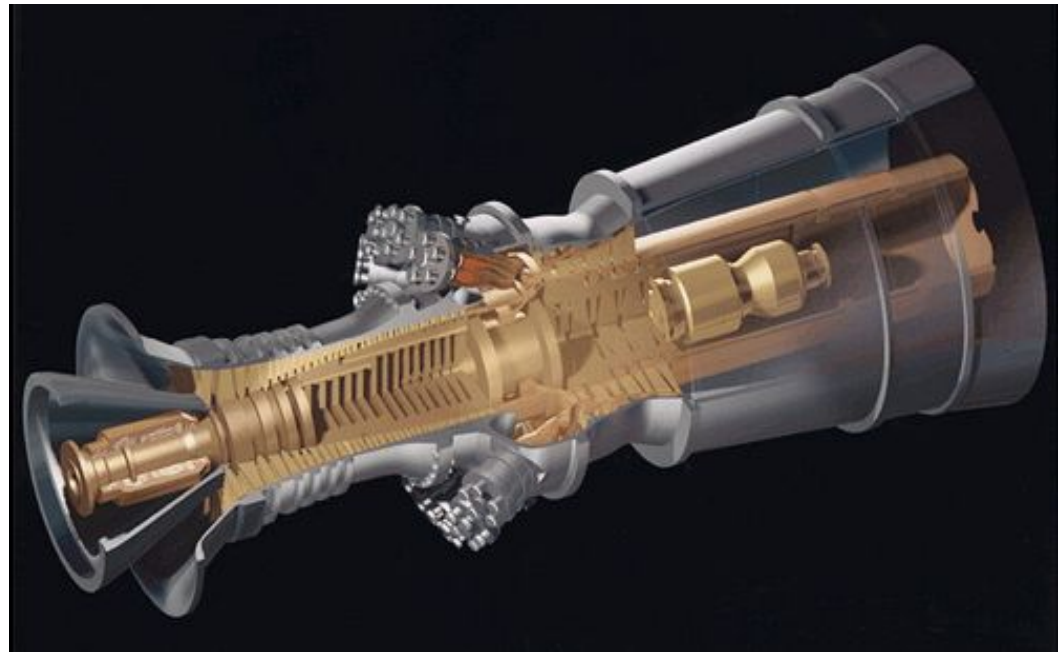
Gas turbine design pressure ratios vary:

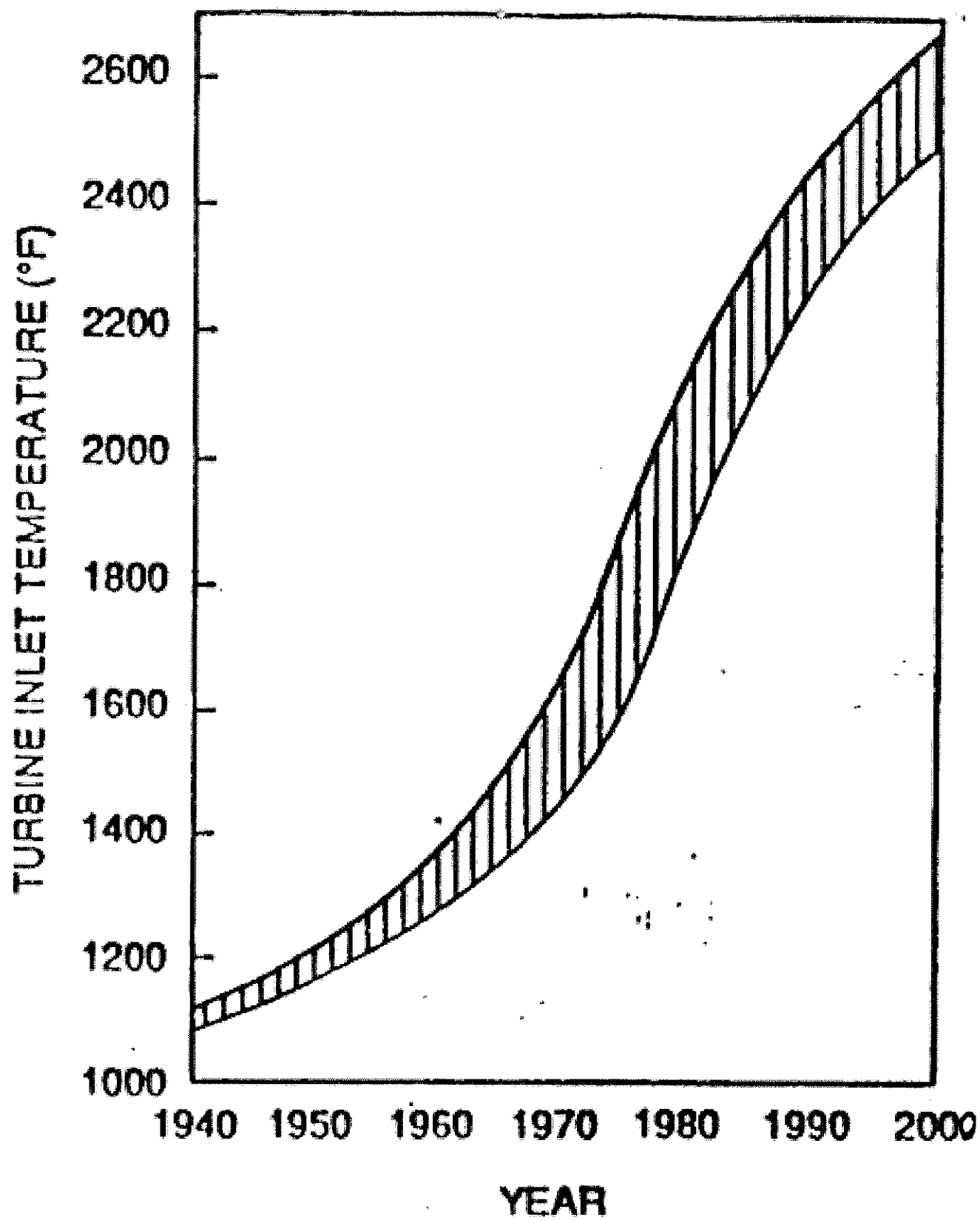
- 7.5:1 – smaller & older technology GT's,
- 35:1 ~ 40:1 – recent, most advanced GT's.

"Aircraft Jet Engines" are "Gas Turbines"

- **Jet Engines:** propulsion via change in DeltaV / momentum
- **Turboprops Engines:** propulsion via propellers
- **Low-Bypass & High-Bypass Turbofan Engines:** propulsion via large Fans and jet DeltaV

All generally use high pressure ratio & high firing temperature = minimum weight & frontal area.





Gas Turbine Inlet Temperature Trend

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Turbine Cycle Variations – of the “Basic Cycle”:

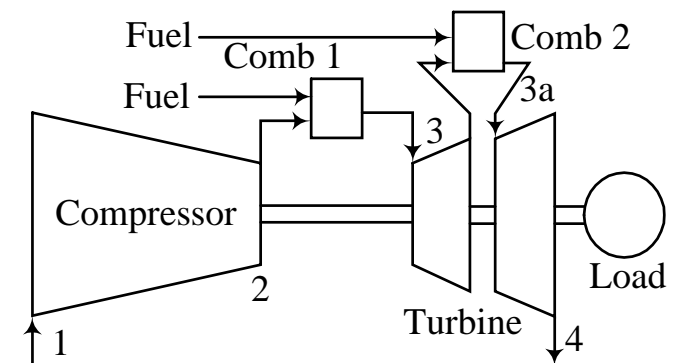
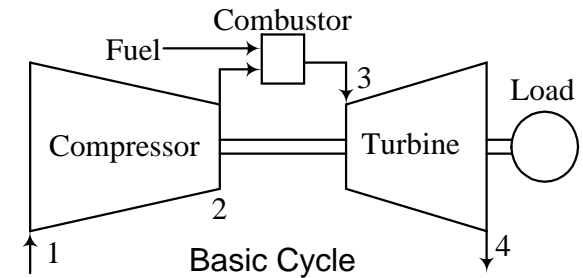
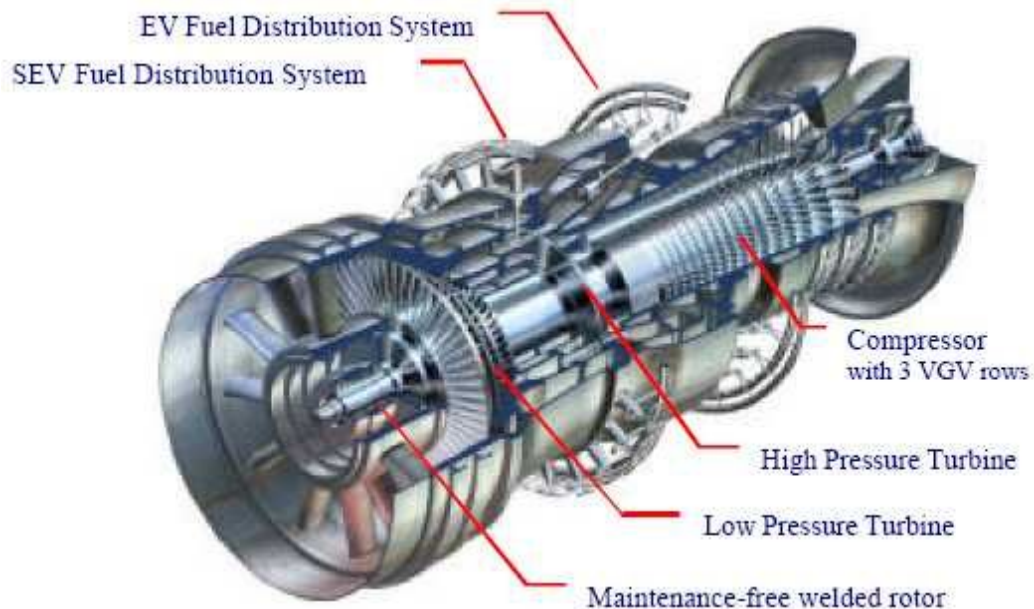
Reheat or Sequential Combustion – in high-pressure ratio GT’s.

Hot HP Turbine Section gases are reheated by combustion of additional fuel (3a).

Reheated gases enter into LP turbine section (3a to 4).

The reheat configuration:

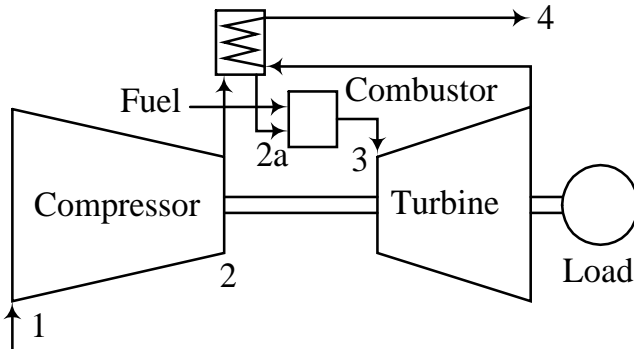
- Increases LP Turbine output (fired to a similar temperature as T3)
- Raises the turbine’s final exhaust temperature (good for HRSGs)
- Increases simple-cycle power output
- Increases combined-cycle power output (HRSG and STG)



Example: **GE-Alstom GT24/26.**

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Turbine Cycle Variations – of the basic cycle:



Recuperated or Regenerated GT's

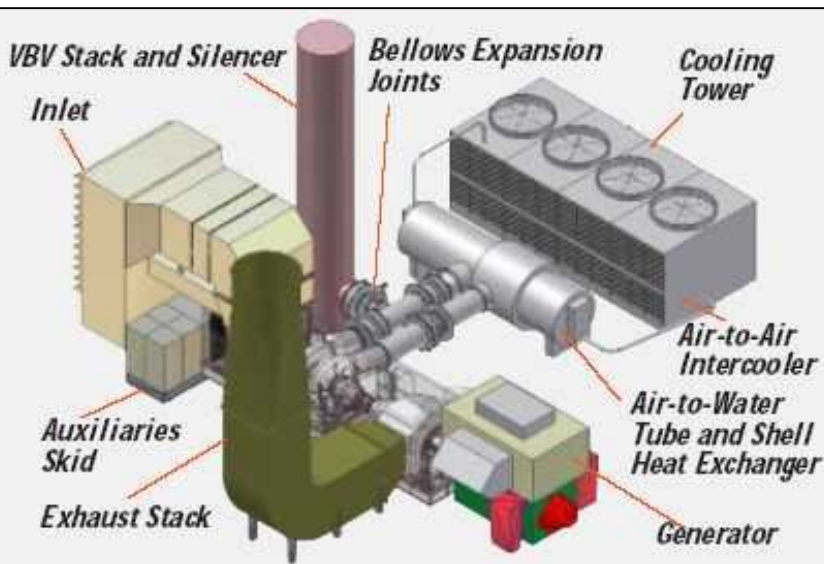
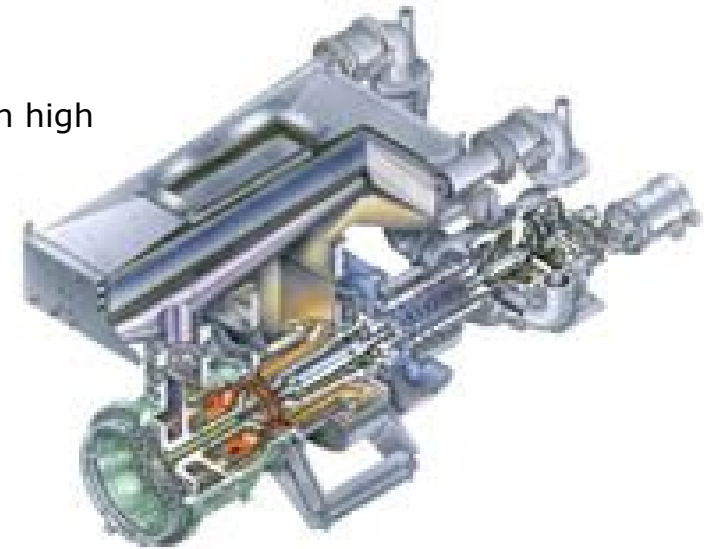
Generally for low-pressure ratio units with high firing temperatures.

An external regenerative heat exchanger transfers exhaust heat to compressor discharge air.

Regenerative Configuration:

- Saves fuel
- Increases efficiency
- Low exhaust energy

Example: **Solar Mercury 50**



Inter-Cooled GT's

For high-pressure ratio multi-shaft units.

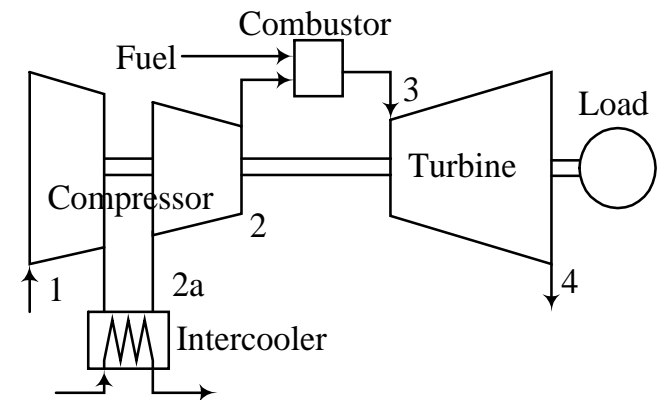
LP compressor air directed to external heat exchanger.

Cooling medium (water or air) decreases air temperature. Cooled air re-enters HP compressor.

Intercooled Configuration:

- decreases HP compressor power,
- improves efficiency & specific output

Example: **100 MW GE LMS100**, w/ air or water cooling.



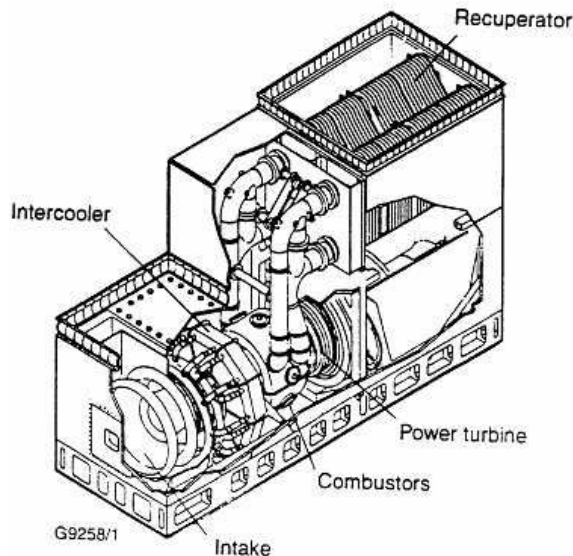
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Turbine Cycle Variations – of the basic cycle:

Spraywater Cooling – similar to intercooling, evaporative cooling and/or fogging.

Very clean water injected before the LP compressor, and between LP & HP LM6000 compressor of the multi-shaft aero-derivative **GE LM6000 Sprint**. Systems are also available on ISI versions of the **Rolls-Royce Trent**.

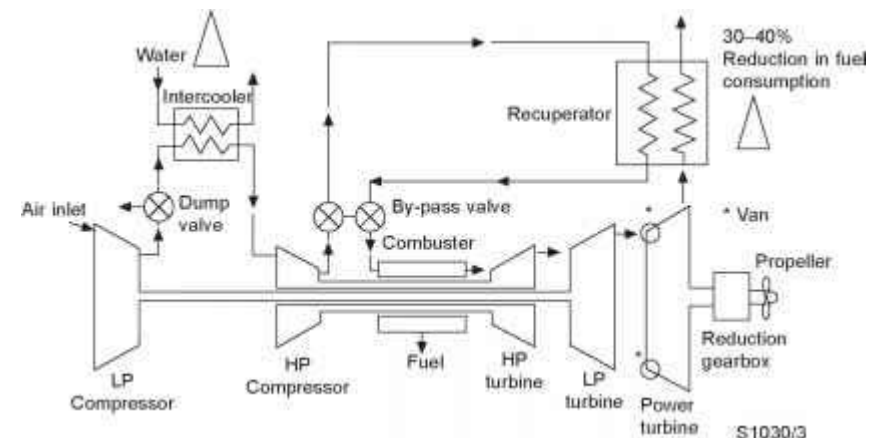
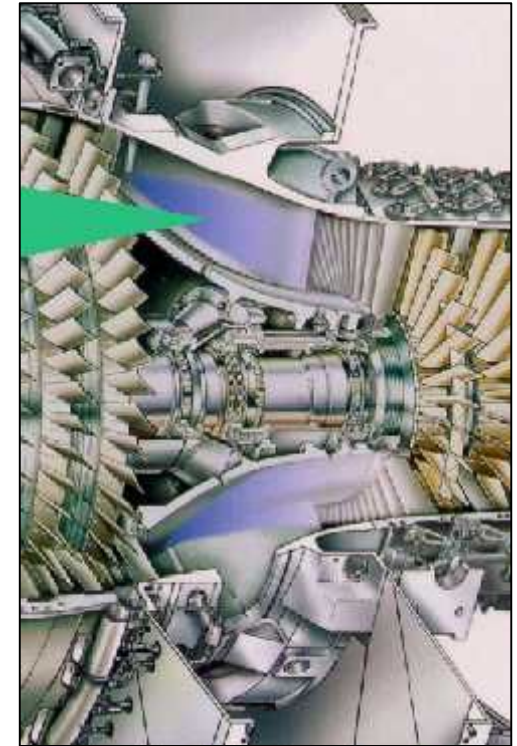
- Increases HPC mass flow
- Increased pressure ratio
- Increased power output & efficiency @ high ambients



Intercooled & Recuperated Gas Turbine

Rolls-Royce WR-21 marine drive unit.

- Special high-efficiency configuration.
- Exhaust recuperator & sea-water cooled intercooler.
- For interest only - there are no land applications.



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Basic Components of the Gas Turbine

Compressor Section:

Usually multi-stage axial configurations, or centrifugal in the smallest units.

Each stage consists of a row of stationary blades (stators) & rotating blades.

Pivoted-variable inlet guide vanes (IGV's) – industrial & aero-derivative units – manage bulk inlet air flow.

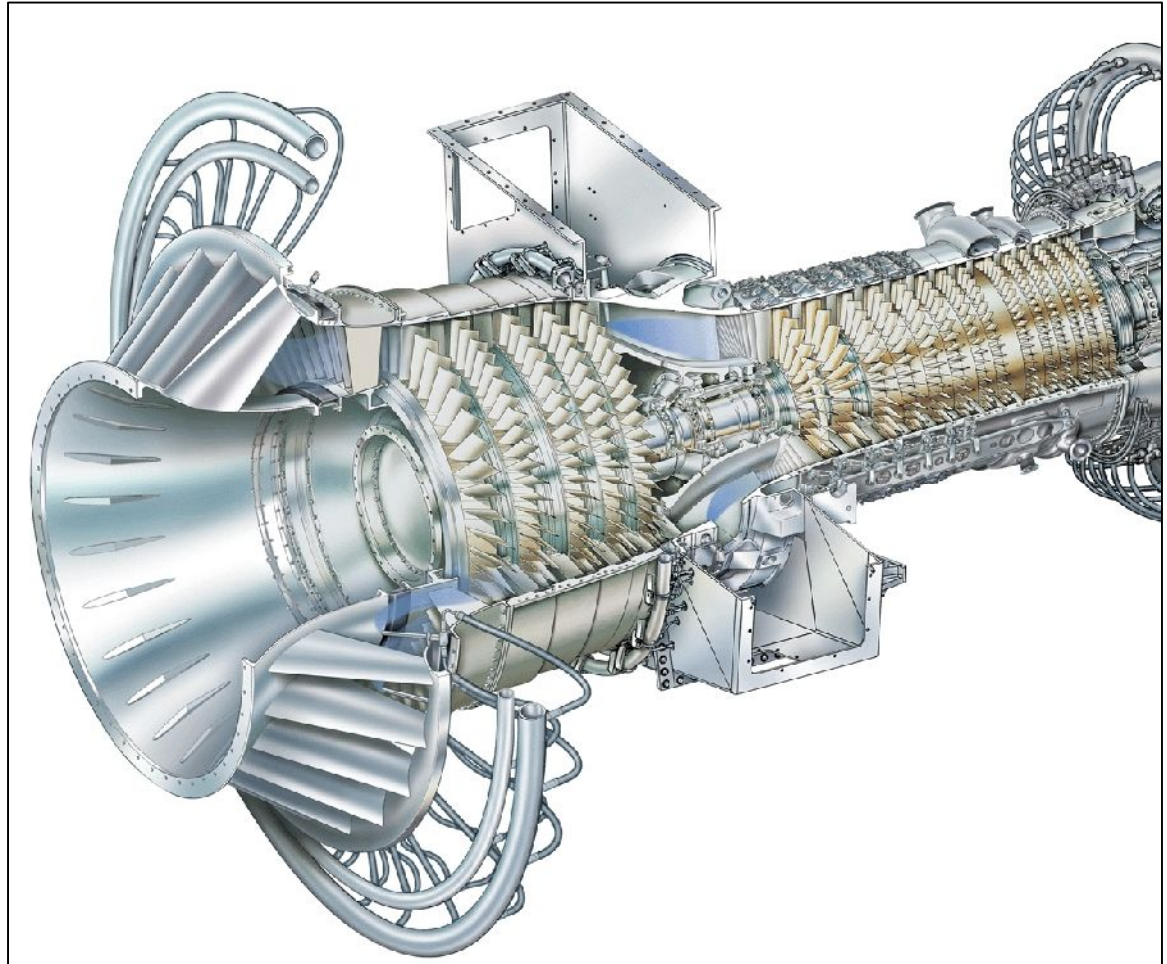
Outlet guide vanes (OGV) & diffuser – straighten & slow air stream prior to entry into the combustor section.

Compressed air bled out & used for cooling purposes in hot sections.

Compressor air bled out for startup & part-load operation or dry low-NOx control

IGV's sometimes manipulated to keep exhaust temperatures high for cogeneration or combined-cycle steam generation considerations.

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

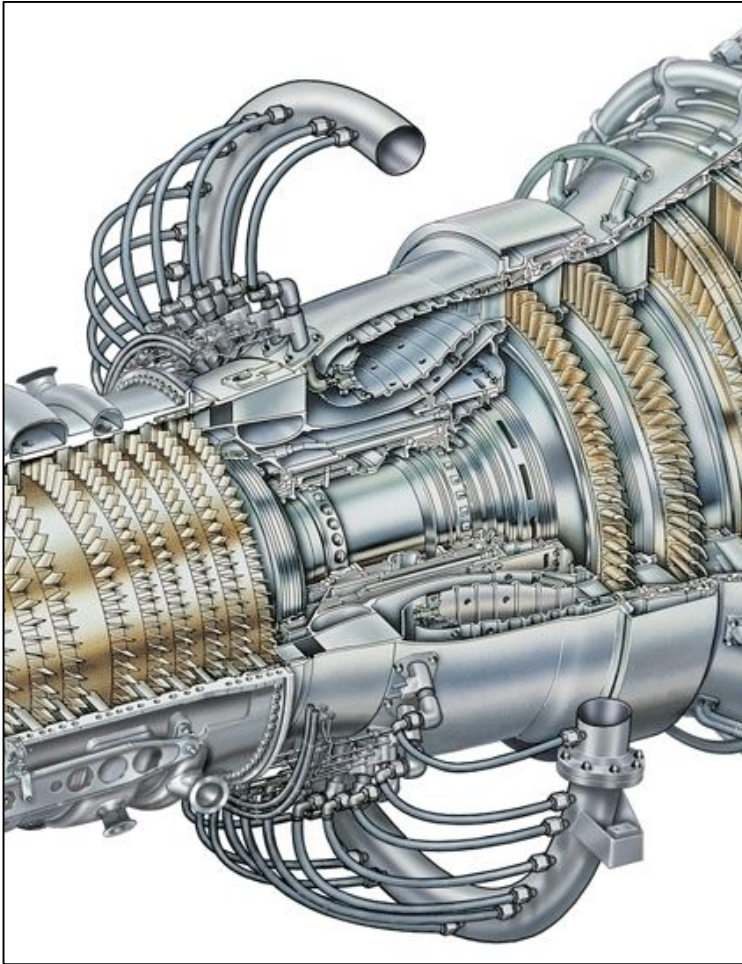


LM6000 Compressor with variable bleed valves (VBV), IGV's and VSV's
Courtesy of GE Energy

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Basic Components of the Gas Turbine

Combustor Section:



Multi-can (basket) design or an annular ring design.

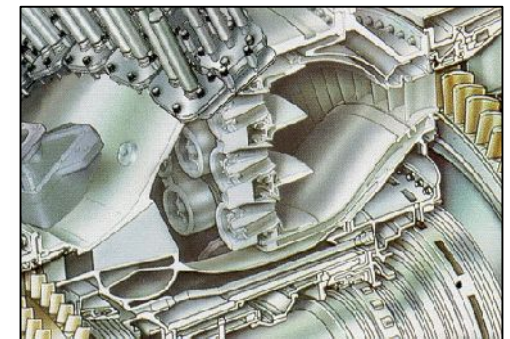
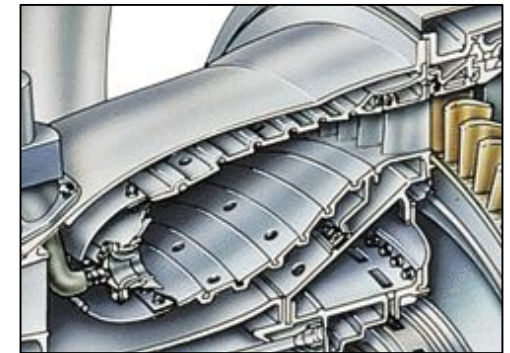
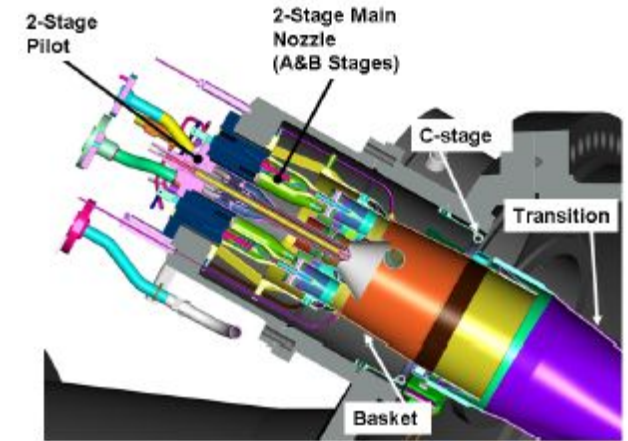
For standard diffusion-combustion systems (i.e. non dry low-NOx), gaseous or liquid fuels introduced via nozzles located at the head of each combustor can, or front of combustion annulus chamber.

Portion of compressor air introduced directly into the combustion reaction zone (flame). Remainder introduced afterwards – for flame shaping and quenching to T3.

Water or steam injection – for environmental or power enhancement.

Transition ducts / liners - carefully shape the hot gases for the turbine section.

Fuel, steam and/or water injection manifolds & hoses around the combustor section circumference.



Current generation dry low-NOx (DLN or DLE) combustion systems use lean pre-mix principle, frequently multi-nozzle (Siemens Ultra Low-NOx and GE LM shown).

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Basic Components of the Gas Turbine Turbine Section:

Usually multi-stage axial design.

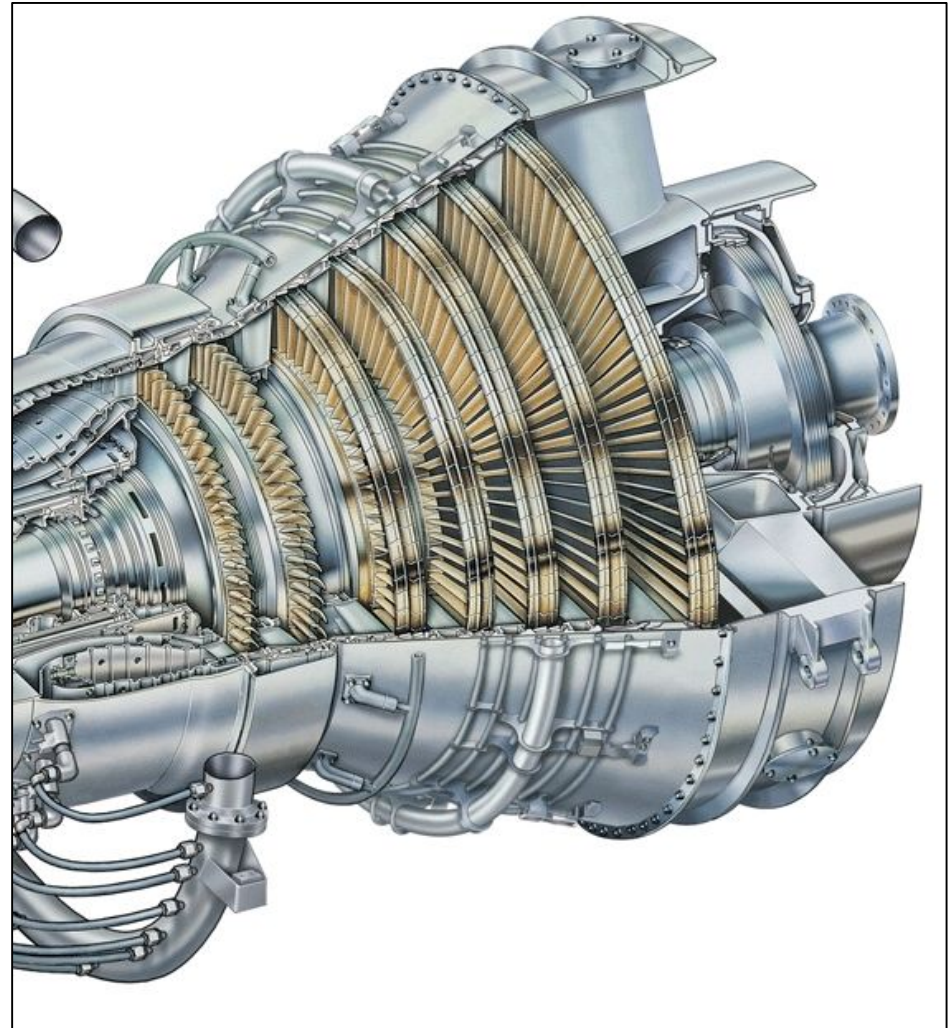
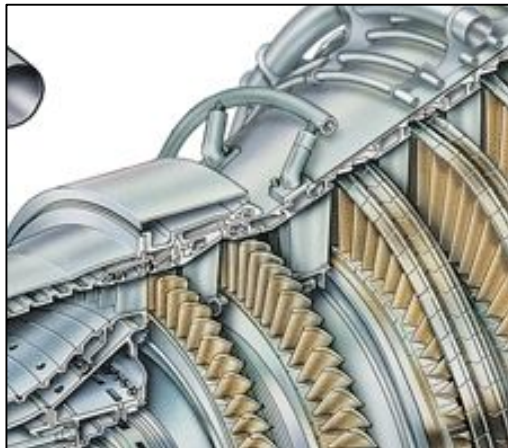
Each stage includes a stationary nozzle row which imparts correct angle to hot gases, for succeeding rotating blades.

The most critical section of turbine = 1st few stages.

Nozzle & rotating blade exposed to “red-hot” gases at design firing temperature – far in excess of acceptable creep-fatigue limits for engineered alloys employed.

Rotating blade is required to survive under high centrifugal & mechanical stresses.

Internal cooling passages cast and machined into nozzles & blade. Raw or cooled compressor bleed air (and some units employ steam) is passed through to maintain material temperatures at acceptable limits.



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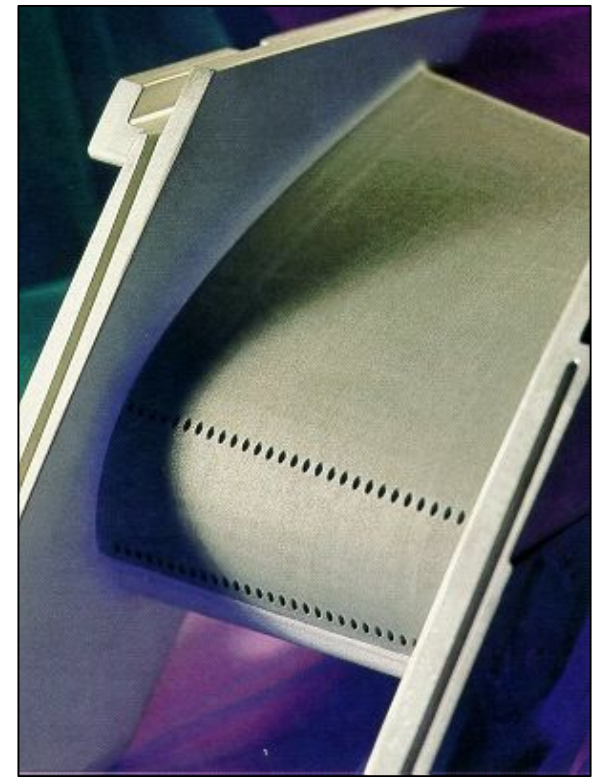
Turbine Section:

Creep-resistant directionally-solidified (DS) & single-crystal (SC) blade production technology – introduced from the aircraft GT world.



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

Thermal barrier coatings (TBC) employed to protect aerodynamic surfaces & materials from corrosion, oxidization and erosion.
Turbine Nozzle w/ TBC & cooling air exit holes



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THE GAS TURBINE ASSEMBLY (let's put the sections together)

The Basic Gas Turbine Machine

Individual **Compressor**, **Combustor** & **Turbine** sections and their **casings** are bolted together.

Supported via struts & baseplates - to make a complete **machine**.

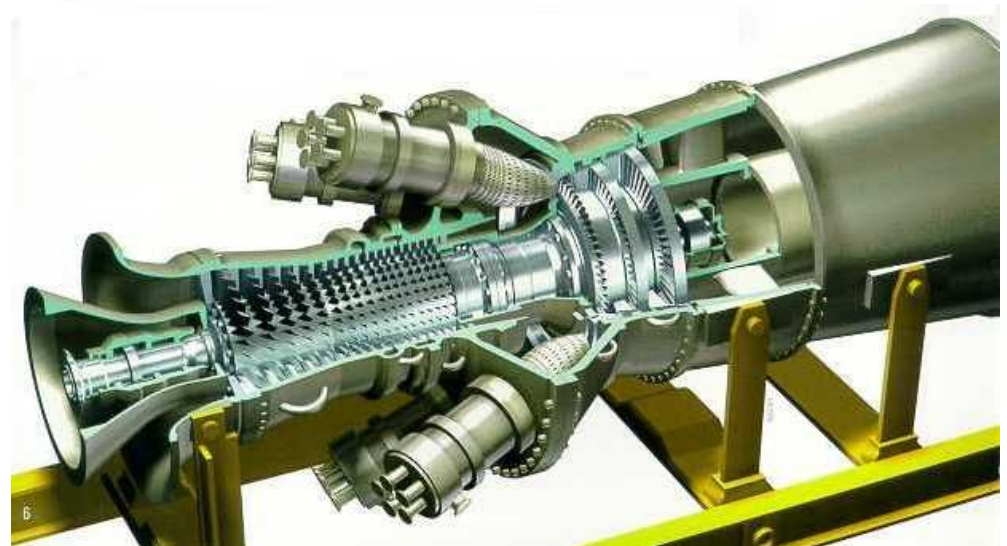
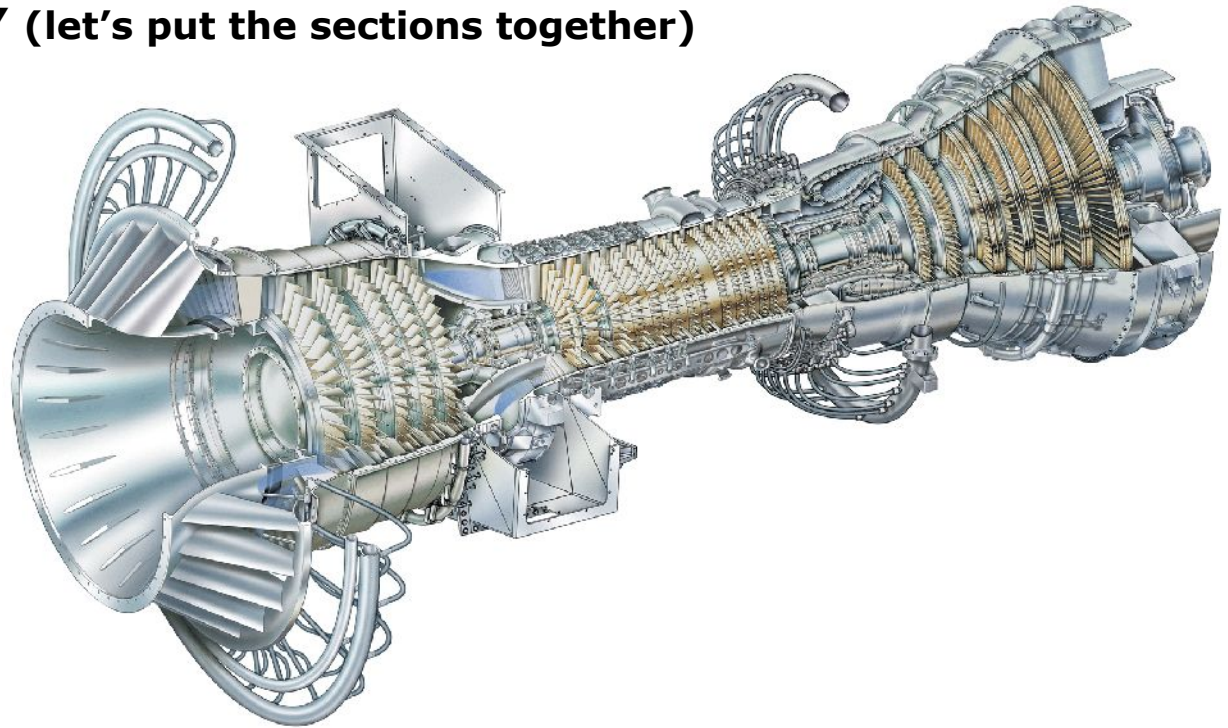
Rotating compressor & turbine sections mechanically interconnected.

Compression power is provided by turbine section's power output. Excess turbine shaft power drives pump, compressor or generator via output shaft:

- Cold-end drive
- Hot-end drive

60~70% of the turbine section's power output used by compressor.

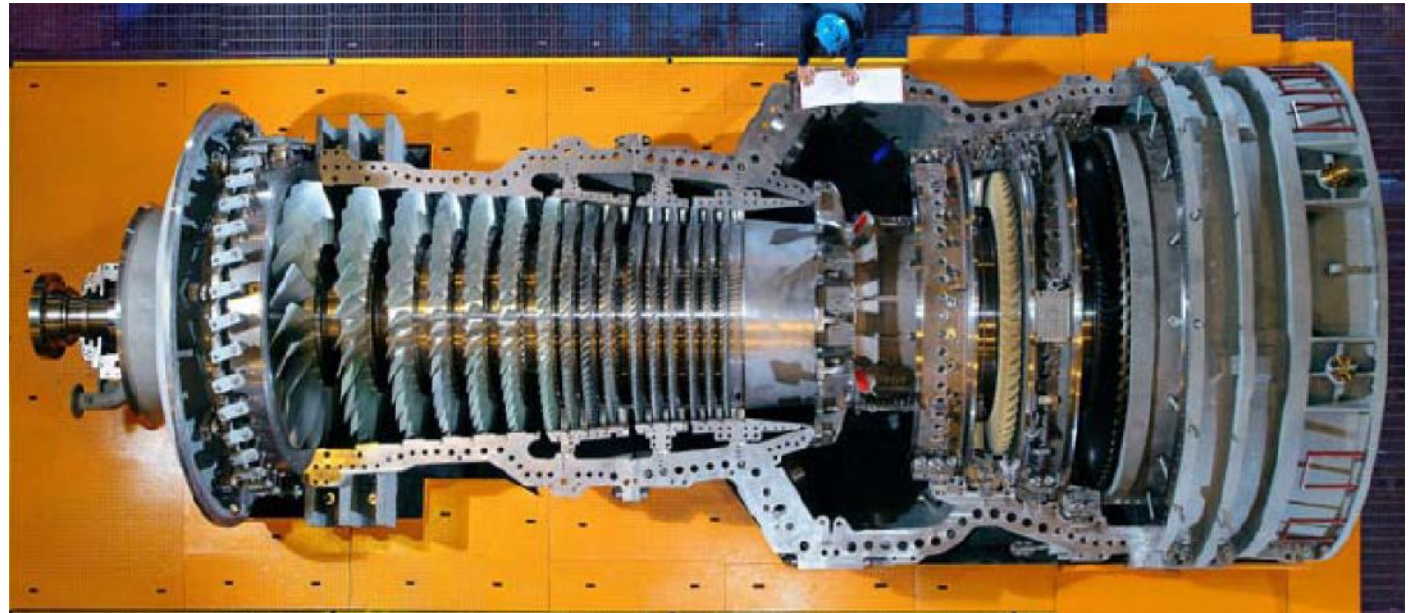
The remaining 30~40% available as true shaft output power, e.g. a typical nominal 50 MW single-shaft industrial gas turbine produces ~150 MW in the turbine section, gives ~100 MW to the compressor section, and has 50 MW left to run a generator.



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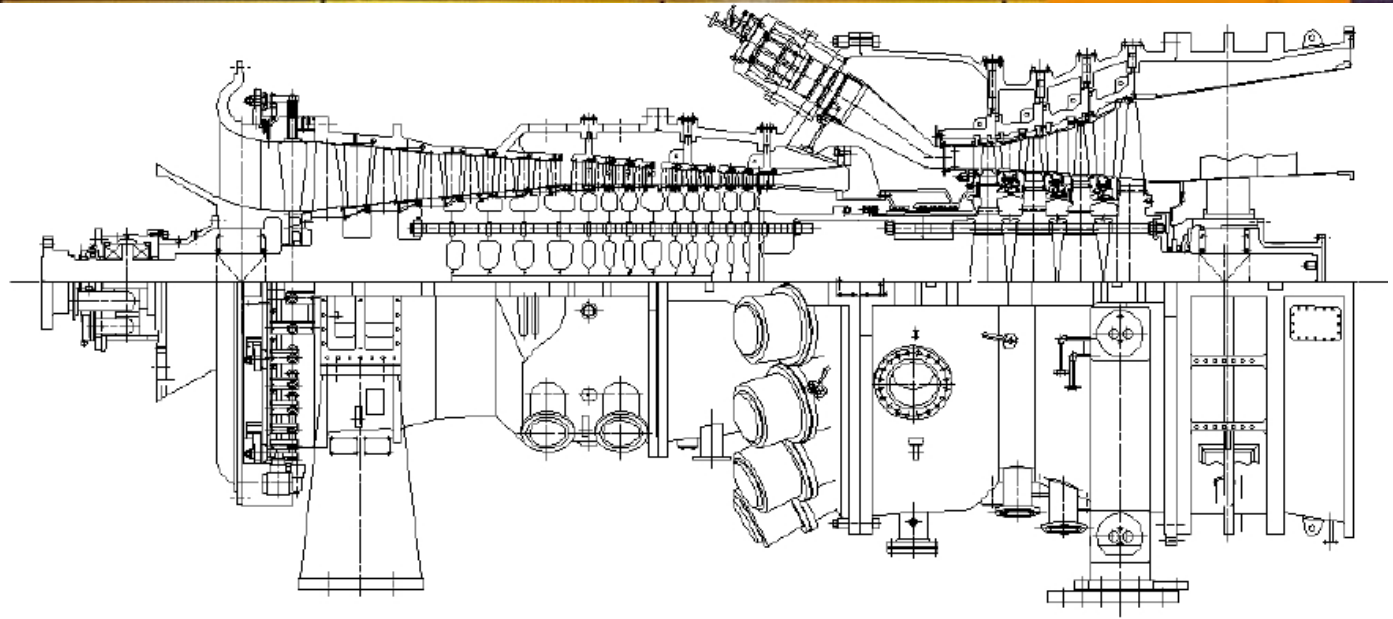
F-Class Gas Turbine Assembly

Top-Half removed –
multi-stage compressor with
IGVs, multi-can combustor
with baskets, multi-stage
turbine section and exhaust
diffuser



Longitudinal Assembly Drawing

Cold-End drive



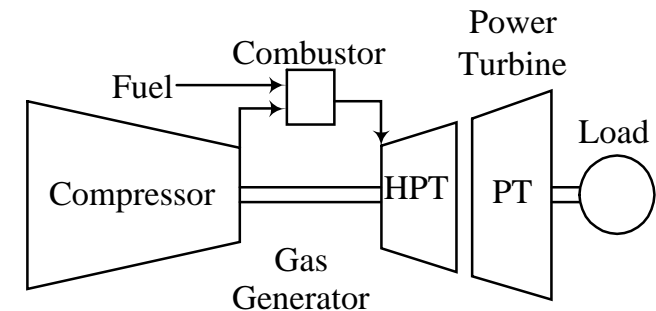
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Gas Turbine Variations – from the single-shaft design.

Single-Shaft with PT – industrial & aero-derivative units.

A single-shaft GT operates at the speed and firing temperature to keep itself self-sustained (frequently called a “jet”, or “gas-generator”, for convenience).

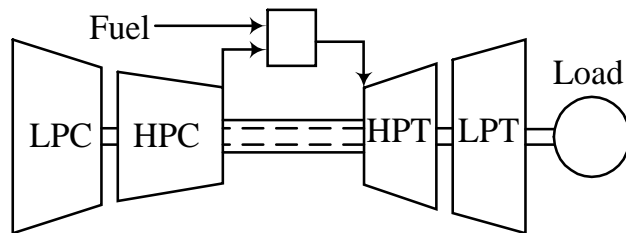
The jet’s exhaust gases pass to an aerodynamic-coupled free power turbine (PT) which drives the load – at fixed (generator) or variable (mechanical drive) speed.



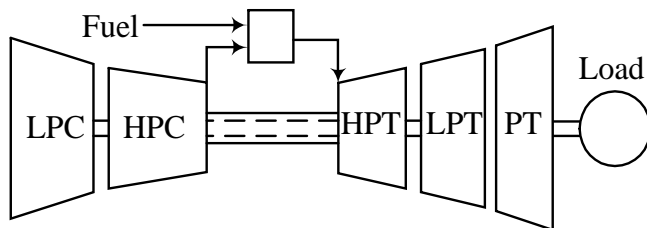
Multi-shaft, with & without PT

Industrial units designed for variable-speed mechanical drive or derivatives of aircraft engines.

Basic compressor & turbine sections divided into HP and LP units. HP and LP each operates at different speed – depends upon load & ambient conditions. The LP compressor (LPC) is coupled to and is driven by LP turbine (LPT). The HP compressor (HPC) is coupled to and is driven by the turbine (HPT).



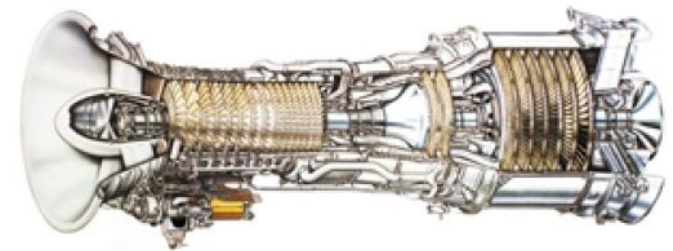
In some three-shaft machines, an intermediate compressor (IPC) & turbine (IPT) also used, in between LP & HP sections (configuration not shown).



Fixed or variable-speed loads are driven off LP shaft.

Some units can drive off cold-end or hot-end of LP shaft.

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



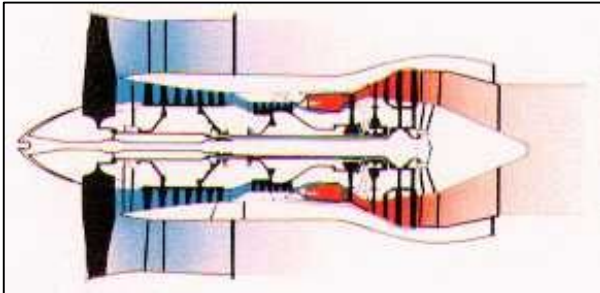
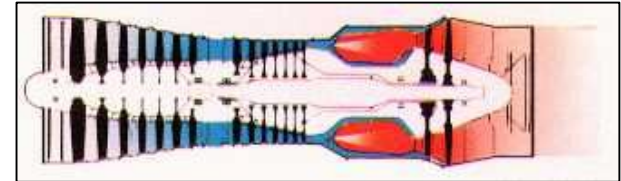
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AERO-DERIVATIVE & HEAVY-DUTY INDUSTRIAL GAS TURBINES

The “**THERMODYNAMIC COUSINS**” – sharing the same basic cycle.

Aero-Derivative GTs – based on aircraft engines; usually low weight & low frontal area (generally inconsequential for industrial service).

The original **jet engines** have their nozzles removed & power turbines (PT's) installed for industrial service.



Later **turbo-prop** & **turbo-fan** engines – industrialized by redesign of the prop or fan takeoff drives' or LP section; or by a PT.

Most aero-derivatives (compared to same-size industrial cousins):

- very efficient because of their high T3 and P2/P1 designs.
- less HRSG steam generation due to lower exhaust gas flows.

Major Maintenance – generally conducted by complete removal of gas turbine from package – special lifting frames required.



Modules disassembled into smaller components - LPC, HPC, combustion module, HPT and LPT, etc.

Minor maintenance activities – conducted at site.

Major maintenance & overhaul - unit returned to certified shop.

Lease engines available – replaces original engine while under repair.

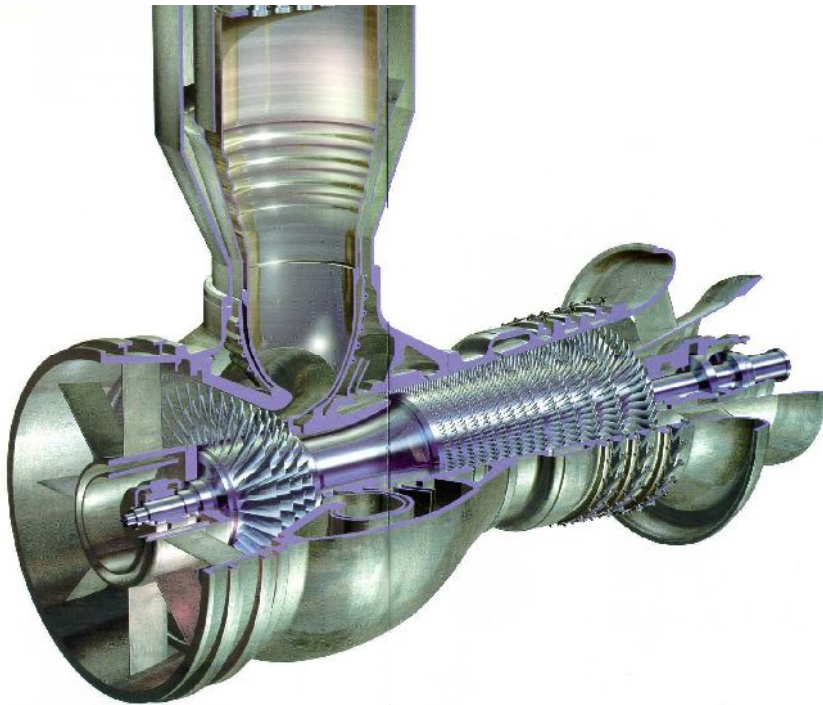


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Heavy-Duty Industrial GTs – heavier and more rugged.

Optimized to operate over narrow speed range & generally for base-load duty.

Typically, the scheduled maintenance intervals are longer than aero units.



Heavy multi-cylinder castings and fabrications.

Large bolted horizontal and vertical split joints.

Heavy built-up rotors & journal bearings.

Large solid couplings

Large baseplates and frames.



Major Maintenance – usually accomplished at site:

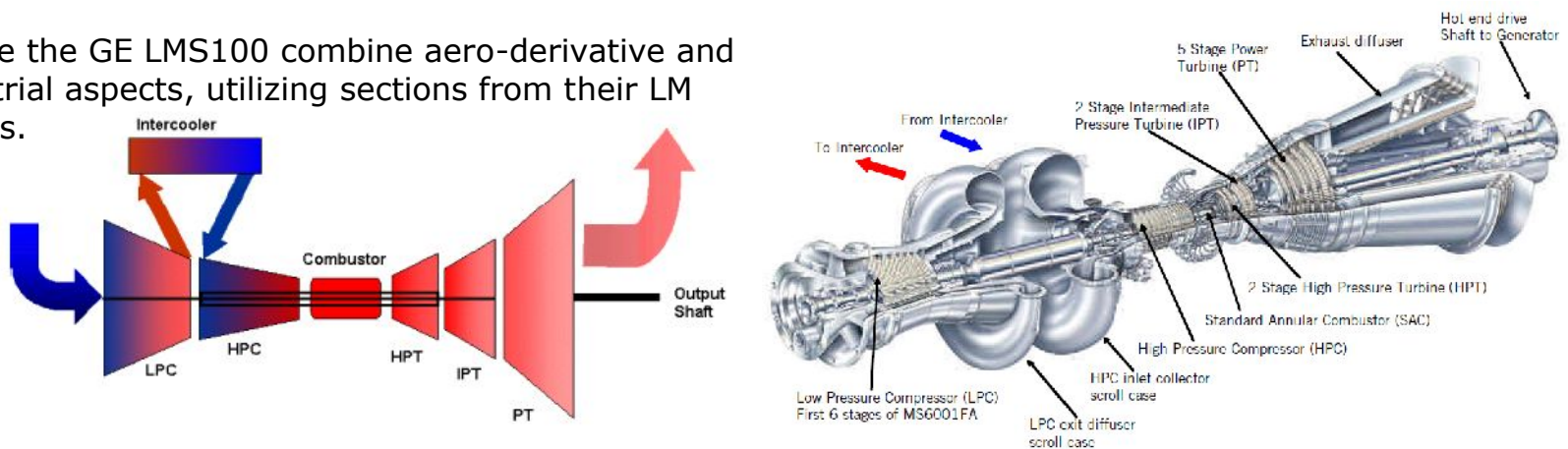
- removal of top half cylinder;
- removal of diaphragms and blade rings;
- lifting and removal of the turbine rotor;
- subsequent blade removal.

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COMPARISON – Aero-Derivative & Heavy-Duty Industrial Gas Turbines

	Aero-Derivative	Heavy-Duty Industrial
Performance	Up to 50~60 MW. Up to 41~45% efficiency (LHV). Generally, less waste heat opportunity from the exhaust gases.	Up to 240 MW+. Up to 35~45% 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

Some GT units like the GE LMS100 combine aero-derivative and heavy-duty industrial aspects, utilizing sections from their LM and industrial lines.



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THE GAS TURBINE PACKAGE

“Packaging” completes the machine - needs to be straightforward to install & commission; and easy to maintain.

Driven Equipment

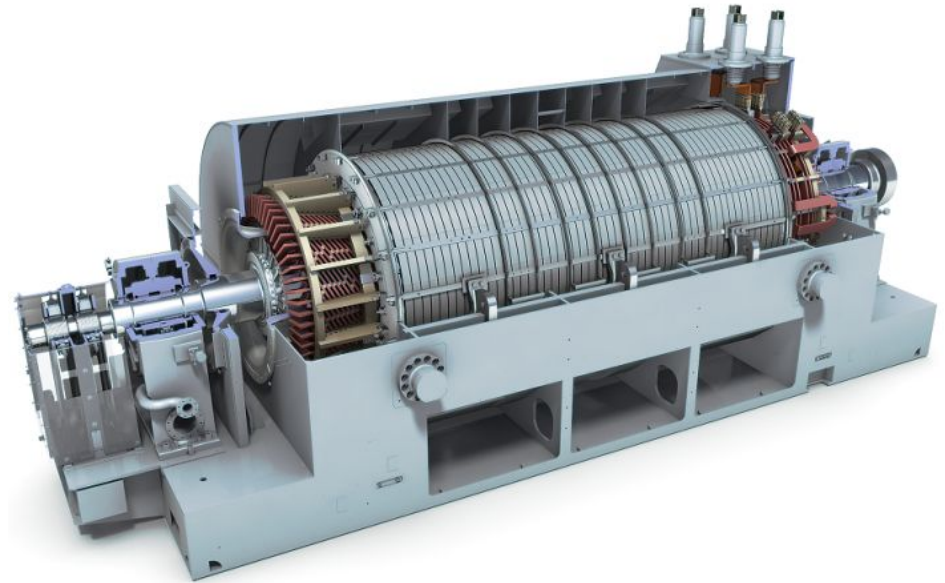
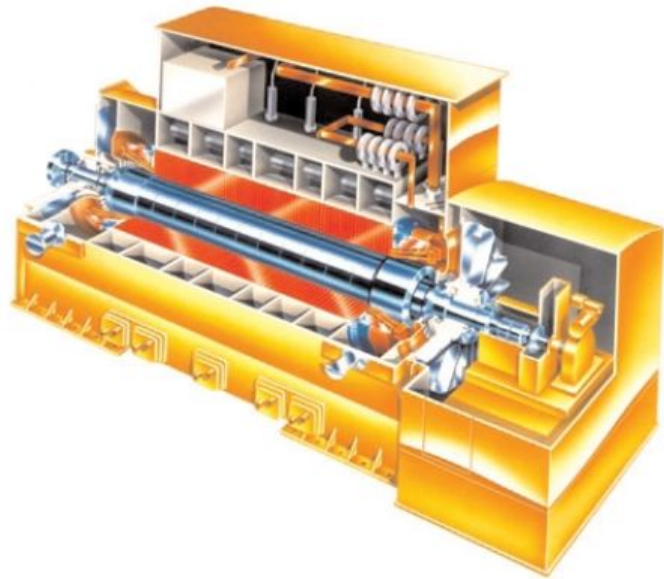
Typically:

- synchronous generators – rated per ANSI C50.14.
- process or pipeline compressors
- occasional use as large pumping sets for oil.

For cogeneration / combined-cycle – typically a **Generator**.

2-pole (3600 rpm) or 4-pole (1800 rpm) for 60 Hz.

Air-cooled, water-cooled (TEWAC) or hydrogen-cooled (the largest units).

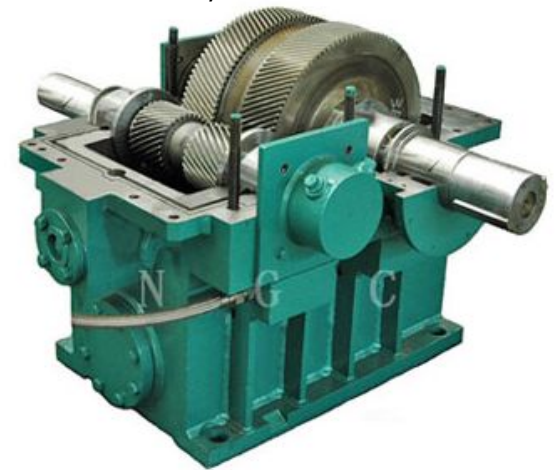


Generator output voltages:

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

Excitation System for voltage & power factor/var control – brushless or static.

Gearbox: when GT output speed doesn't match generator speed - double-helical or epicyclic gearboxes



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Air Inlet Systems – Filtration, Silencing, Air Heating and/or Cooling

Critical to GT health, for noise mitigation and/or performance.

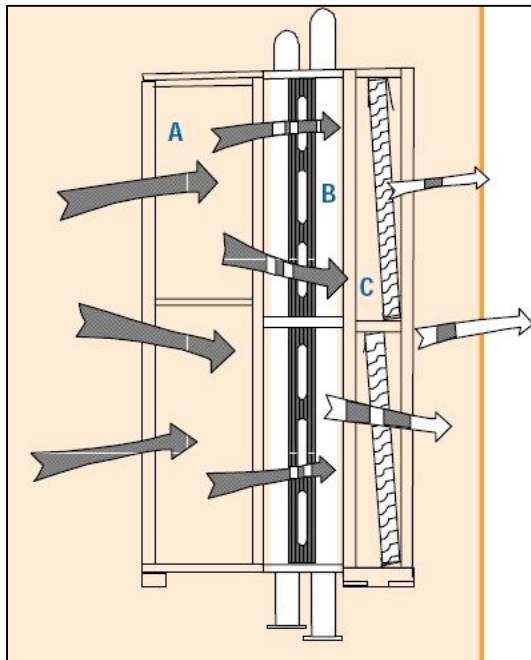
Filtration: high-volume multi-stage high-efficiency filtration systems – capture atmospheric particles and prevent their deposition on the blade path

Inlet Air Heating: via coils or bleed air systems - for anti-icing; inlet temperature / performance optimization; DLE control.

Inlet Air Cooling; via coils – for inlet temperature / performance optimization at higher ambient temperatures.

Evaporative Cooling Systems & mist eliminators.

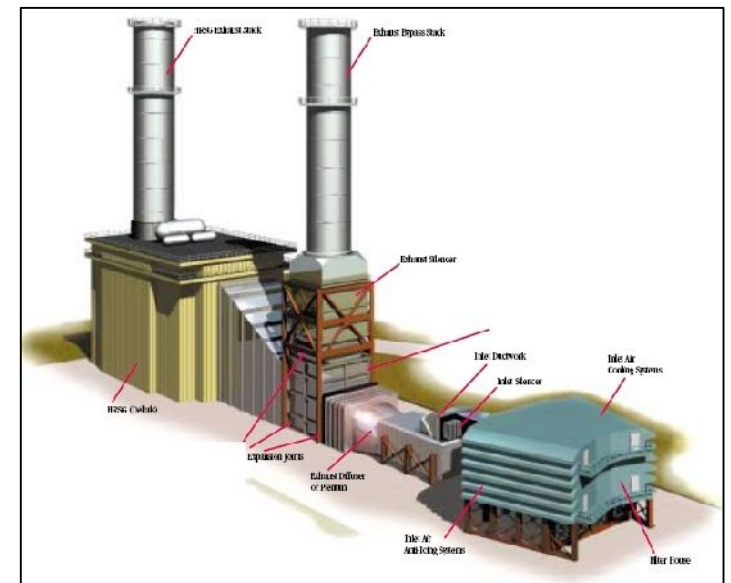
Fogging systems & mist eliminators.



Tuned inlet air silencers – absorb sound & acoustic emissions from intake.

Many companies providing all the air inlet filtration, cooling, heating, and silencing equipment to GTG packagers

Plus supplying exhaust systems – silencers, expansion joints, bypass systems, stacks & enclosures.



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Lubricating Oil Systems

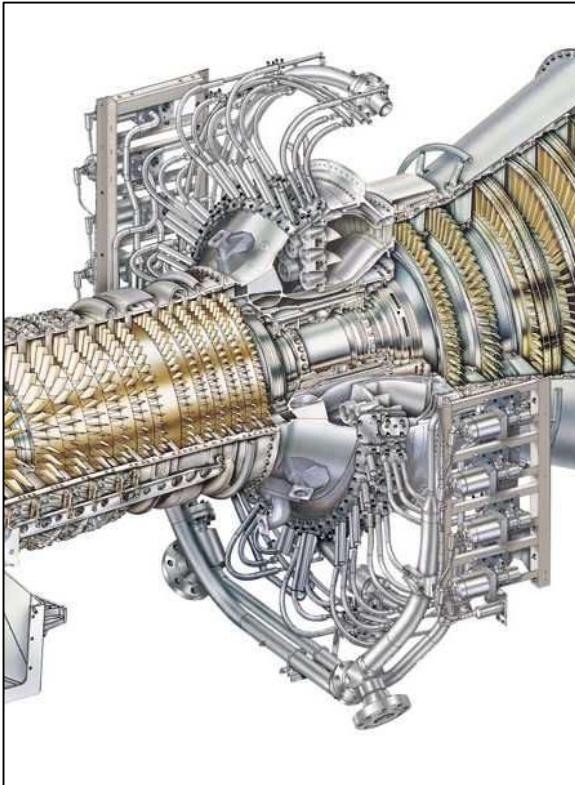
Main, auxiliary and emergency lubricating and control oil (as required) systems – provided for gas turbine and driven equipment.

Aero-derivatives – usually fire-resistant synthetic lube oils.

Power turbines, gearboxes & generators – mineral-based lube oils.

Most heavy-duty industrial GT's have common lube oil system.

Lube oil – is cooled by aerial fin-fan coolers, or oil-to-water heat exchangers.



Fuel Systems

Aero-derivative & heavy duty gas turbines – light-liquid or gaseous fuels.

Only frame units – operate on heavy fuel oils & 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 – sometimes reciprocating or centrifugal gas compression equipment required, plus pulsation dampening equipment.

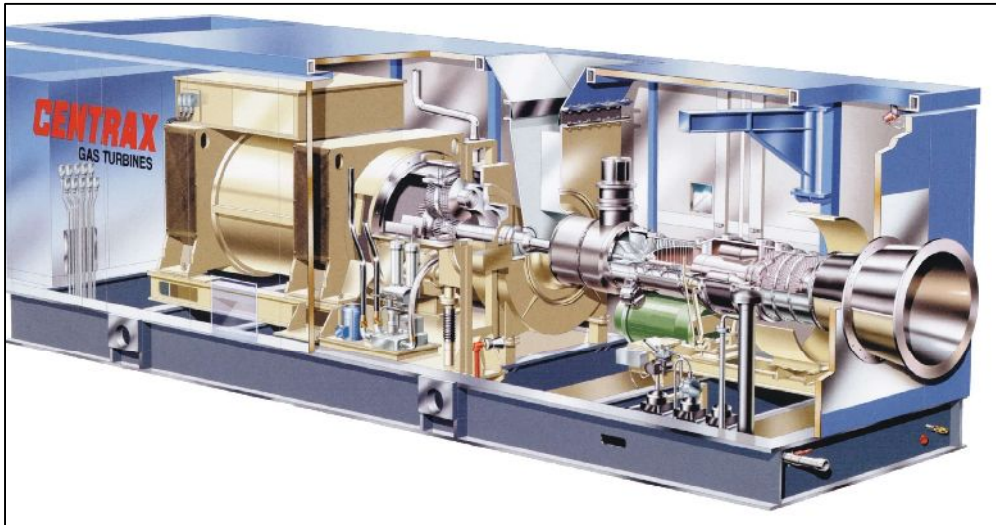
Complex dry low-NO_x (DLE) units – some units require several throttle valves, staged and sequenced to fire:

- pilot / ignition,
- primary,
- secondary and/or tertiary nozzle and basket sections (as applicable) of the DLE combustion system;

All as required for startup/shutdown, speed ramps, and load changes. Several fuel manifolds usually required.

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Acoustic and Weatherproof Enclosures



Most smaller industrial & almost all aero-derivative GTG packages – pre-packaged - complete drivetrain enclosed in acoustic enclosure(s).

The turbine & generator compartments - separately ventilated.

Can be easier and quicker to install.

40~50 MW+ industrial / heavy-duty GT machines – generally too large to pre-package.

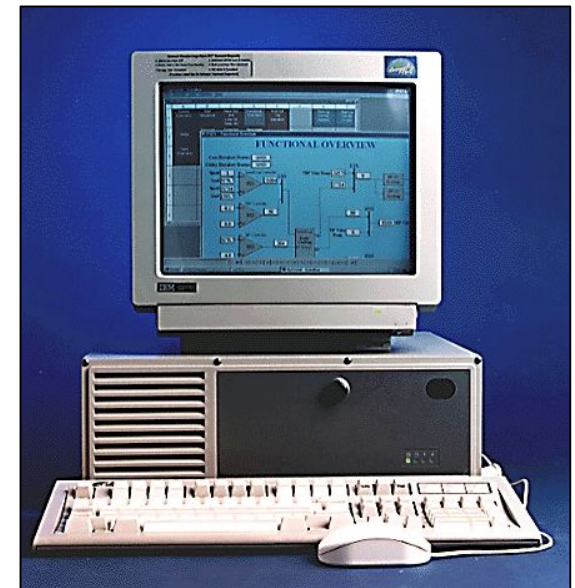
Components shipped in major blocks – assembled at site. Enclosures or buildings (if required) built around the complete drivetrain.

Controls and Monitoring

Complex combinations of digital PLC and/or processor systems – Woodward; vendor-proprietary systems; occasionally DCS-based.

Systems include, manage, sequence, monitor and control:

- GT fuel control and speed/load control
- generator's voltage, power factor or var control
- breaker synchronization
- auxiliaries
- vibration, temperature & pressure monitors
- sequence of events recorders
- certified metering systems
- communication to plant DCS.



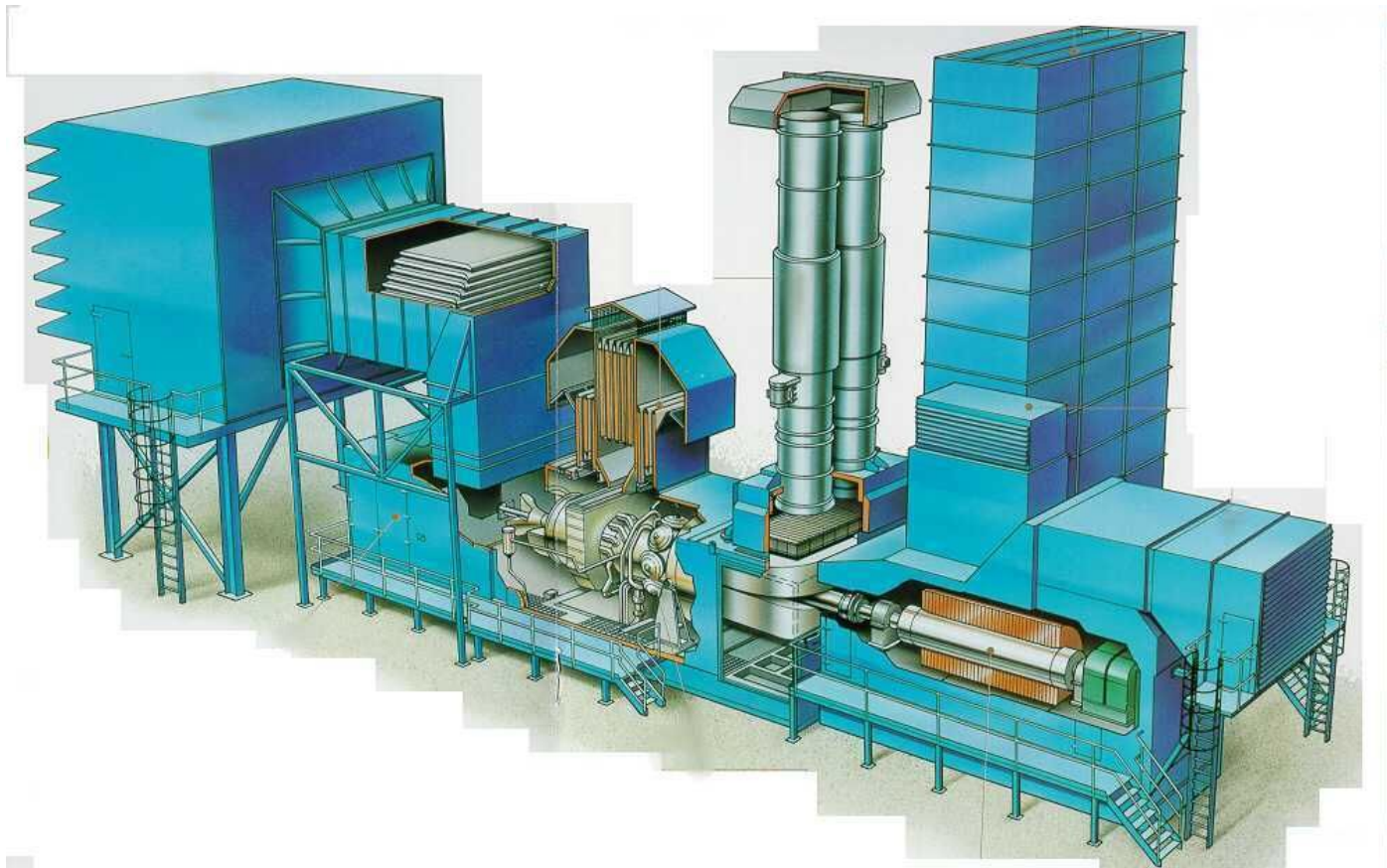
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Miscellaneous Auxiliaries

- 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 CO2 suppression systems;
- battery and charger systems;
- ventilation and heating;
- exhaust expansion joint;
- silencer & stack systems (simple-cycle).

Complete Package Examples

Rolls-Royce Trent Package

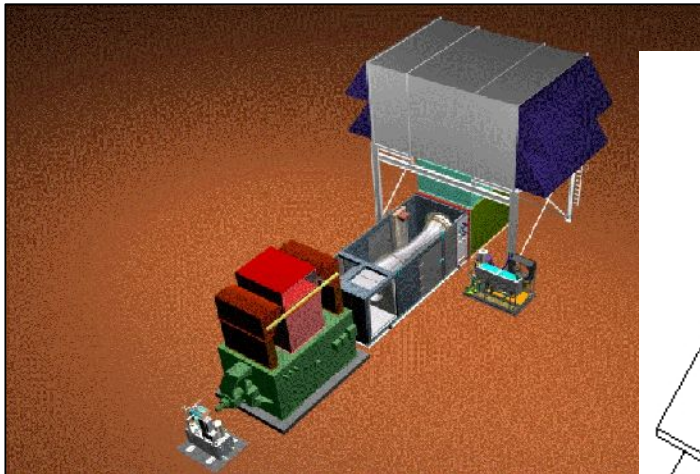


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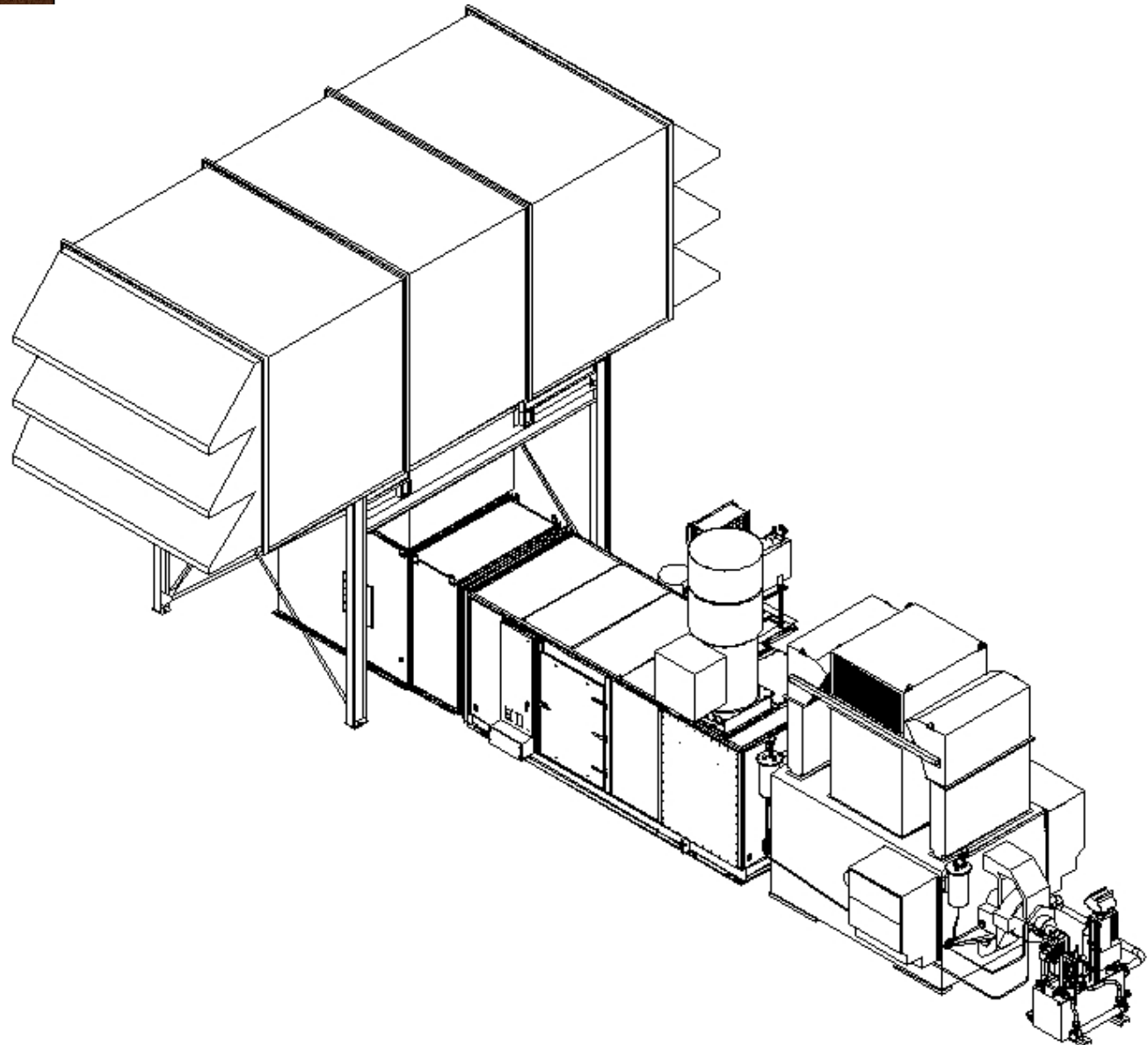
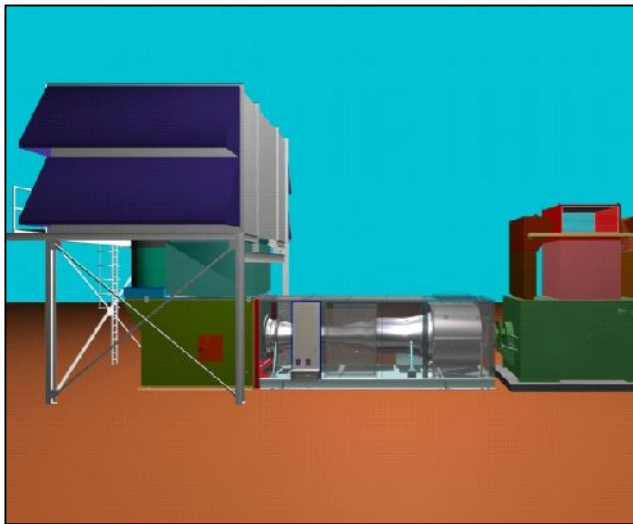
GE LM6000 NXGN Package



GAS TURBINE BASICS©



**GE LM2500 / LM2500 Plus
Package**



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Rolls-Royce RB211 Package / Plant

