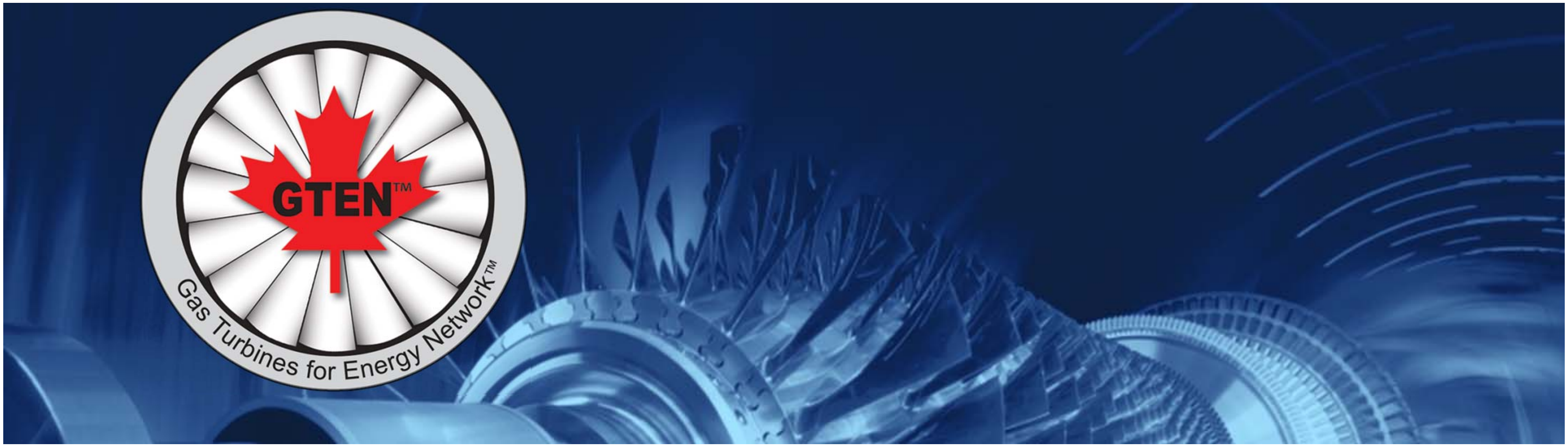


Gas Turbines: Clean, Reliable Power Enabling the Energy Transition

Tuesday, October 4th, 2022

GAS TURBINE BASICS

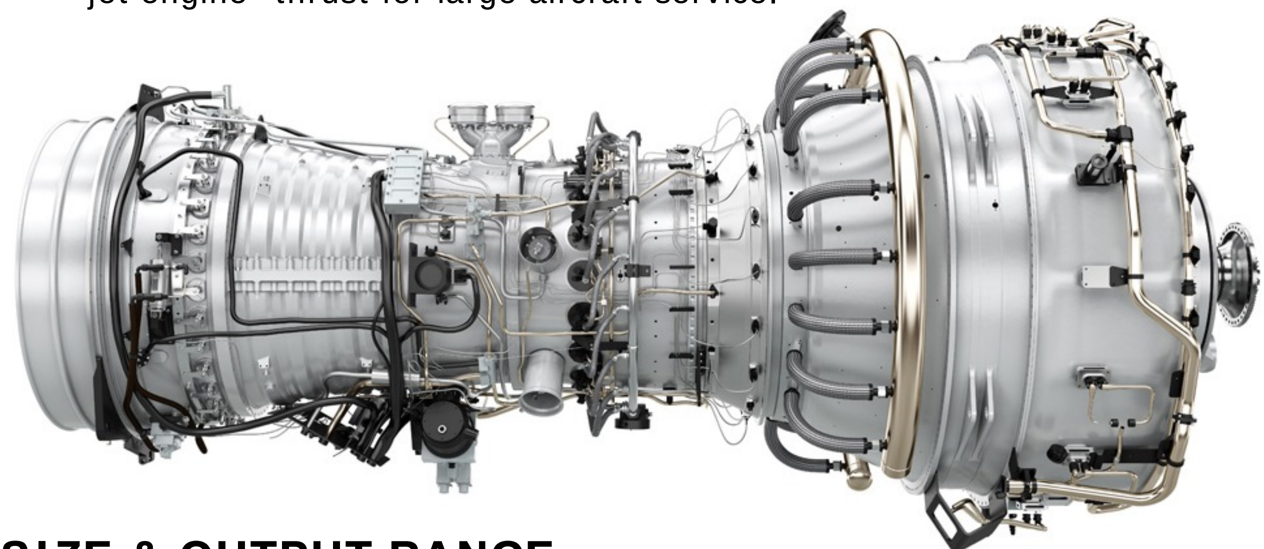
Presenter: Jim Noordermeer, Noord Power Consulting Inc.

www.gten.ca

WHAT EXACTLY IS A GAS TURBINE?

A unique “suck-squeeze-burn-blow” machine originally developed in the late ‘30’s and early ‘40’s, that continuously and efficiently burns ambient air and a fuel to produce:

- mechanical shaft output power to drive a “generator” for electricity generation, or
- mechanical shaft power for pipeline (“gas compression”), large pumping service or heavy-vehicle service, or
- mechanical shaft power for smaller aircraft (“turboprop”) or marine (“propellor drive”) service, or
- “jet engine” thrust for large aircraft service.



WHY ARE THEY CALLED GAS TURBINES?

A steam turbine uses steam and a hydro turbine uses water as working fluids. Instead, a gas turbine uses “air” (i.e. a gas) as its working fluid.

SIZE & OUTPUT RANGE:

- 65~100~200 kW (microturbines)
- 70~75 MW (nominal aero-derivative limit)
- beyond 300 MW (heavy-duty industrial)

All can be used for cogeneration / CHP (combined heat-and-power) & combined-cycle. Some can be used for CAES (compressed air energy storage).

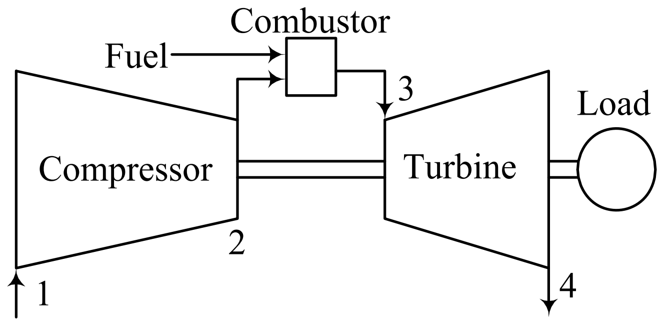
WHAT FUEL IS REQUIRED?

Gas turbines can uniquely burn a variety of gaseous & liquid fuels including natural gas, syngas, pure hydrogen and/or NG blends, biogas, biodiesels, diesel and distillate fuels, kerosene and crude or heavy residual fuel oil.

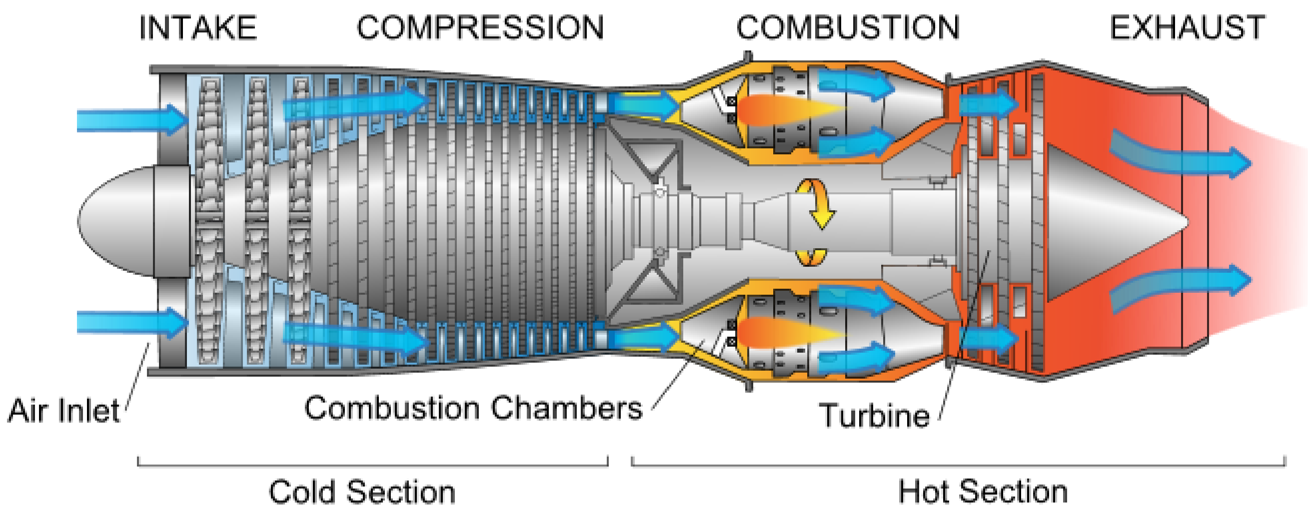
GAS TURBINE CONCEPTS

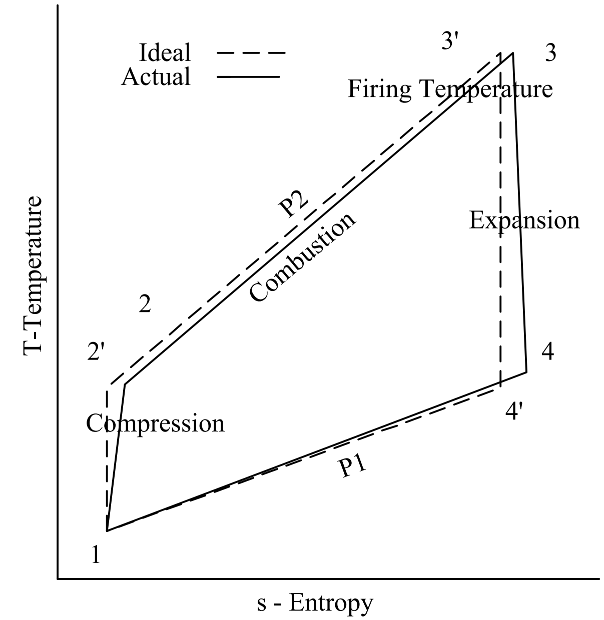
The Basic Thermodynamic Gas Turbine Cycle

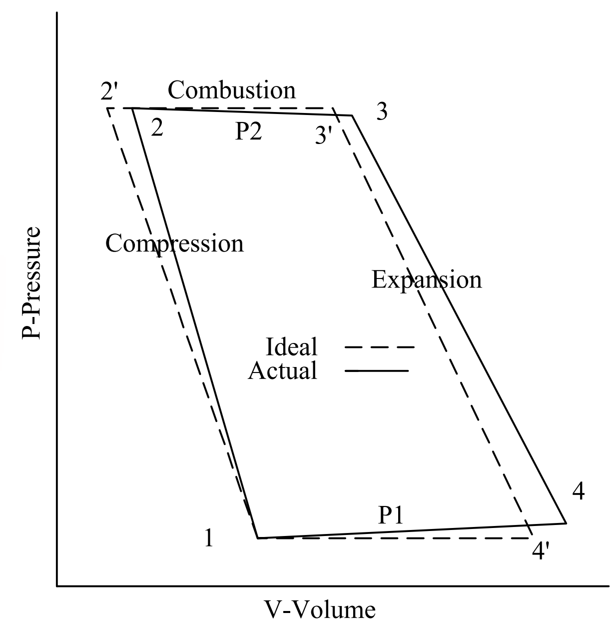
Brayton Cycle – a continuously operating process using air as the working fluid, moving through four **State Points**:



- **SUCK:** Air Intake (**State 1**): *ambient air enters the unit*
- **SQUEEZE:** Continuous air compression (**States 1 to 2**): *the compressor requires power to operate*
- **BURN:** Continuous fuel combustion (**States 2 to 3**): *which adds heat and small % of mass flow at relatively constant pressure*
- **BLOW:** Hot air expansion back to atmospheric pressure (**States 3 to 4**): *with the turbine making shaft power and driving the compressor and a load (or jet thrust via a nozzle per the below illustration)*

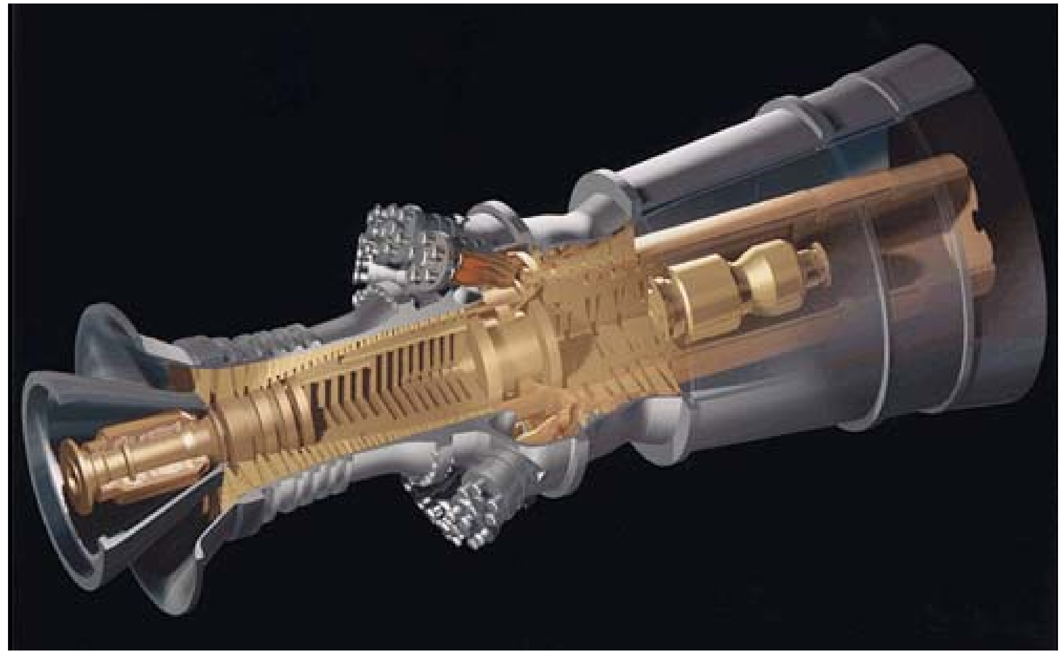






GAS TURBINE BASICS©

Mechanical Operating Principles



The **Turbine Section** (hot-section) and it's power output physically drives (rotates) the **Compressor Section** (cold-section) which needs power to operate.

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

Firing Temperature

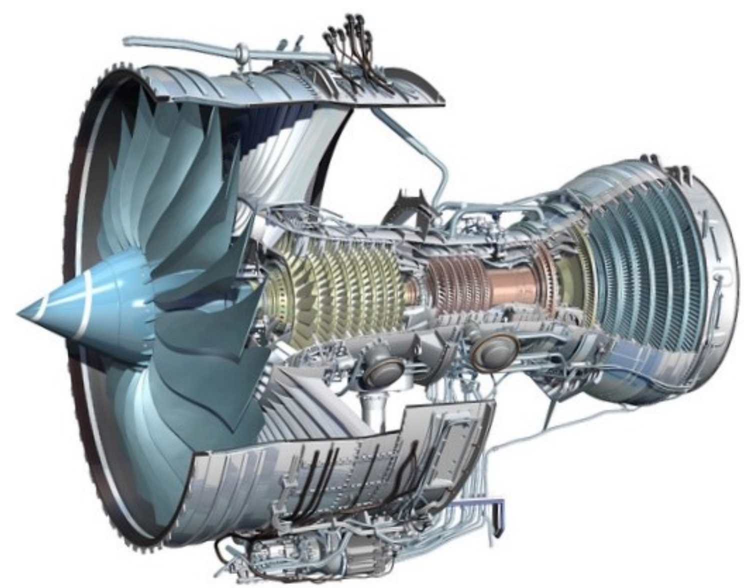
Firing Temperatures (T3): over time, have climbed from 1400 deg F to 2000~2200, and now 2700~2900 deg F and beyond with better turbine section materials, coatings and cooling methods

High T3 = improves power output & efficiency.

Pressure Ratio

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

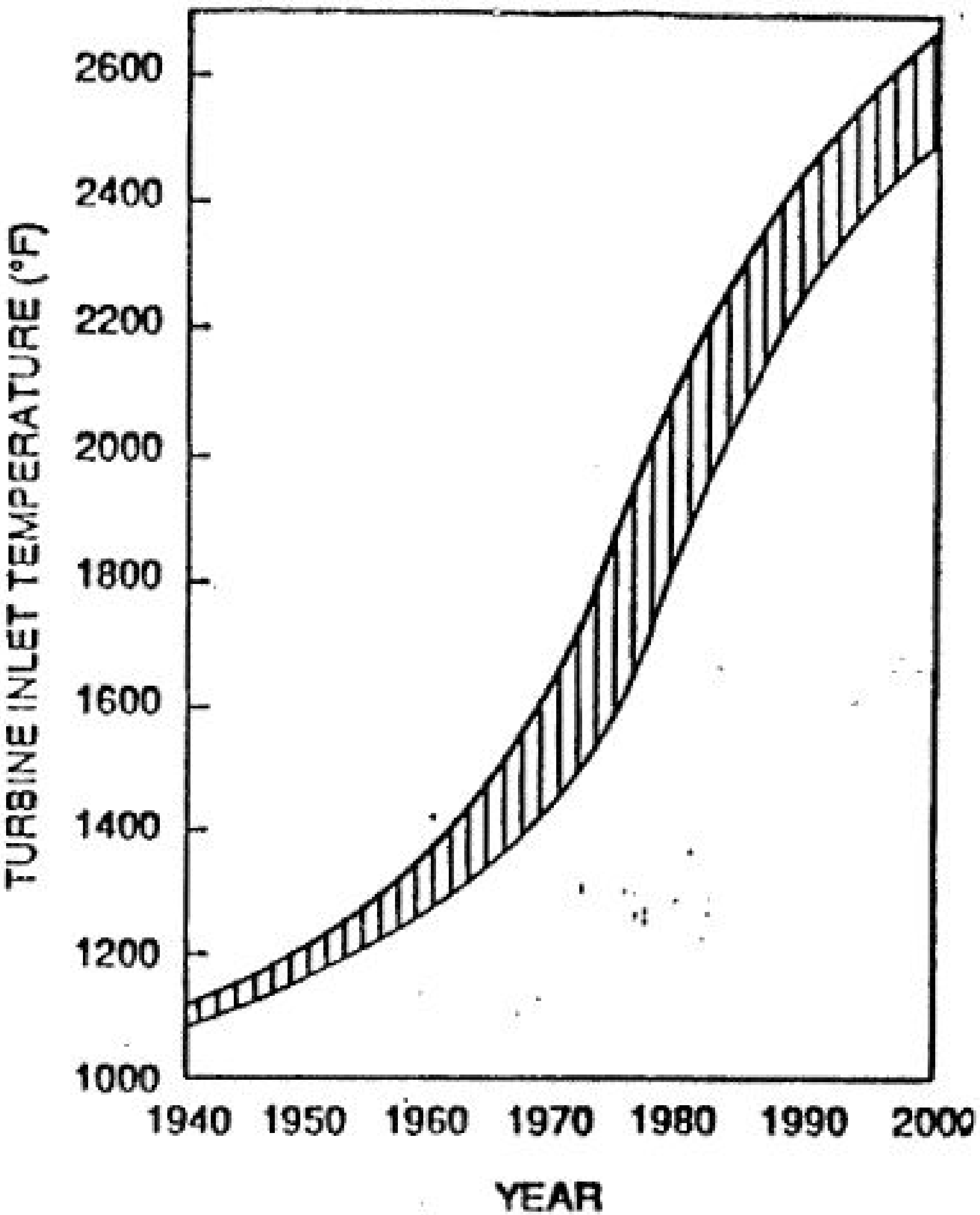
Gas turbine design pressure ratios vary:
- 7.5:1 – smaller & older technology GT's,
- 35:1 ~ 40:1+ – recent, most advanced GT's.



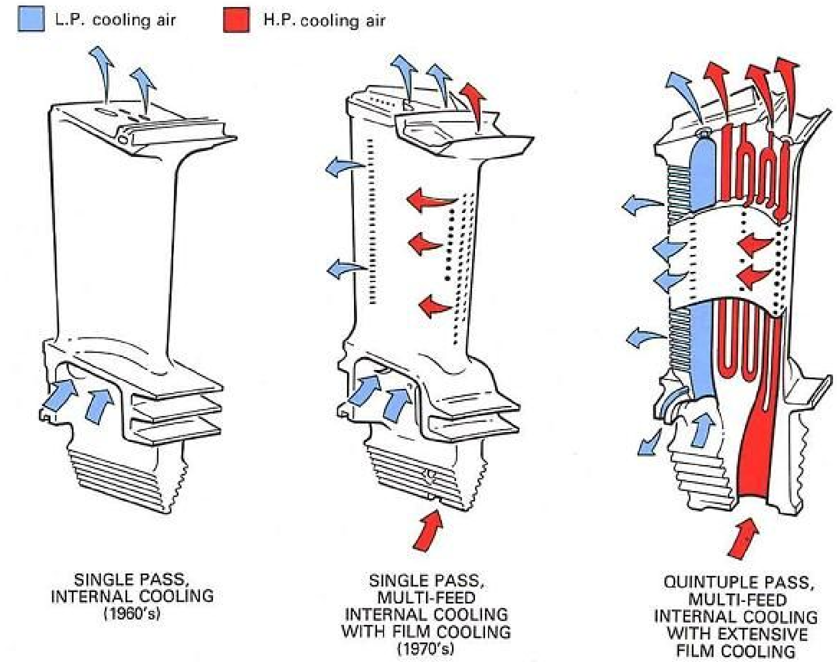
Aircraft "**Jet Engines**" are also "Gas Turbines"

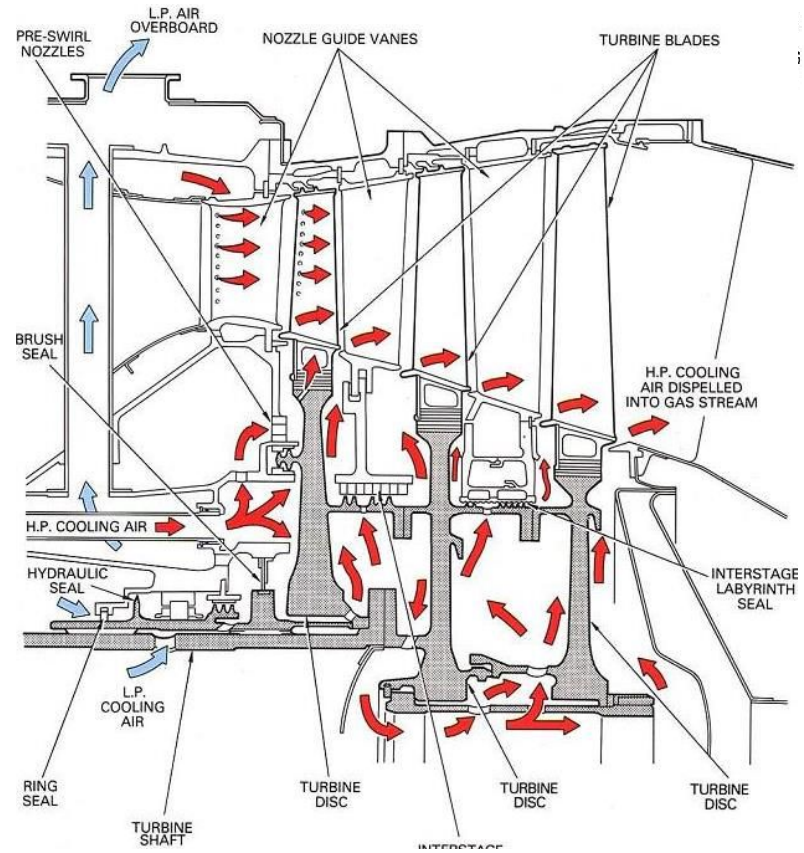
- **Jet Engines**: propulsion via change in DeltaV / momentum
- **Turboprops Engines**: propulsion via propellors
- **Low-Bypass & High-Bypass Turbofan Engines**: propulsion via large Fans and jet DeltaV

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



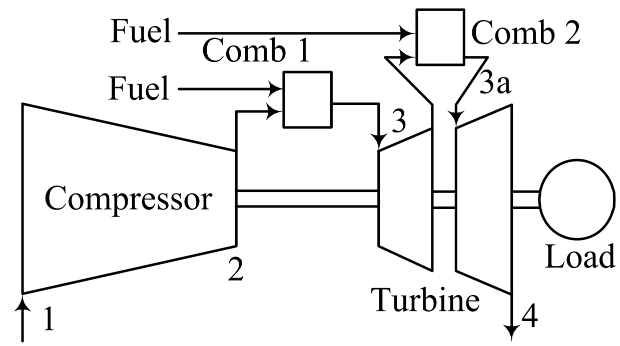
Gas Turbine Inlet Temperature Trend

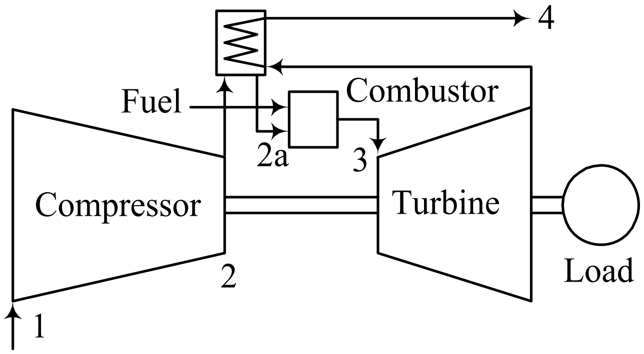




Turbine Cycle Variations – of the "Basic Cycle":

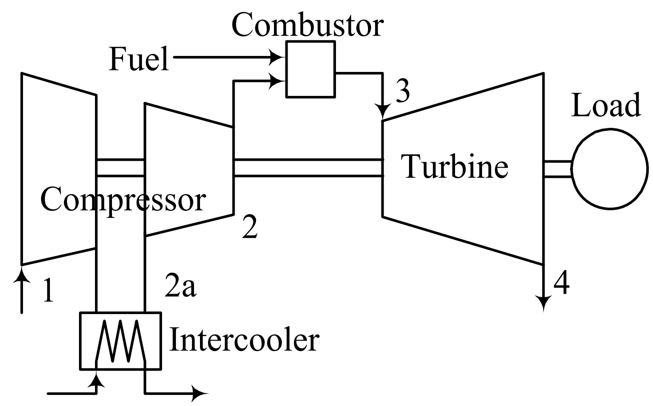
Reheat or Sequential Combustion: Hot HP Turbine Section gases are reheated by combustion of additional fuel (3a). Reheated gases then enter into the LP turbine section (3a to 4).





Recuperated or Regenerated Gas Turbines

An external regenerative heat-exchanger transfers heat from the turbine exhaust to the compressor discharge air (before fuel is introduced).



Inter-Cooled Gas Turbines

LP compressor air is directed to an external heat exchanger. A cooling medium (water or air) decreases air temperature and increases flow density. The cooled air re-enters the HP compressor.

Further Variations

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

Inter-Cooled & Recuperated Turbines - special high-efficiency configuration.

CAES Compressors & Turbines – modified for Compressed Air Energy Storage service.

Basic Components of the Gas Turbine

Compressor Section:

Usually a multi-stage axial configuration, or centrifugal in smaller 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.

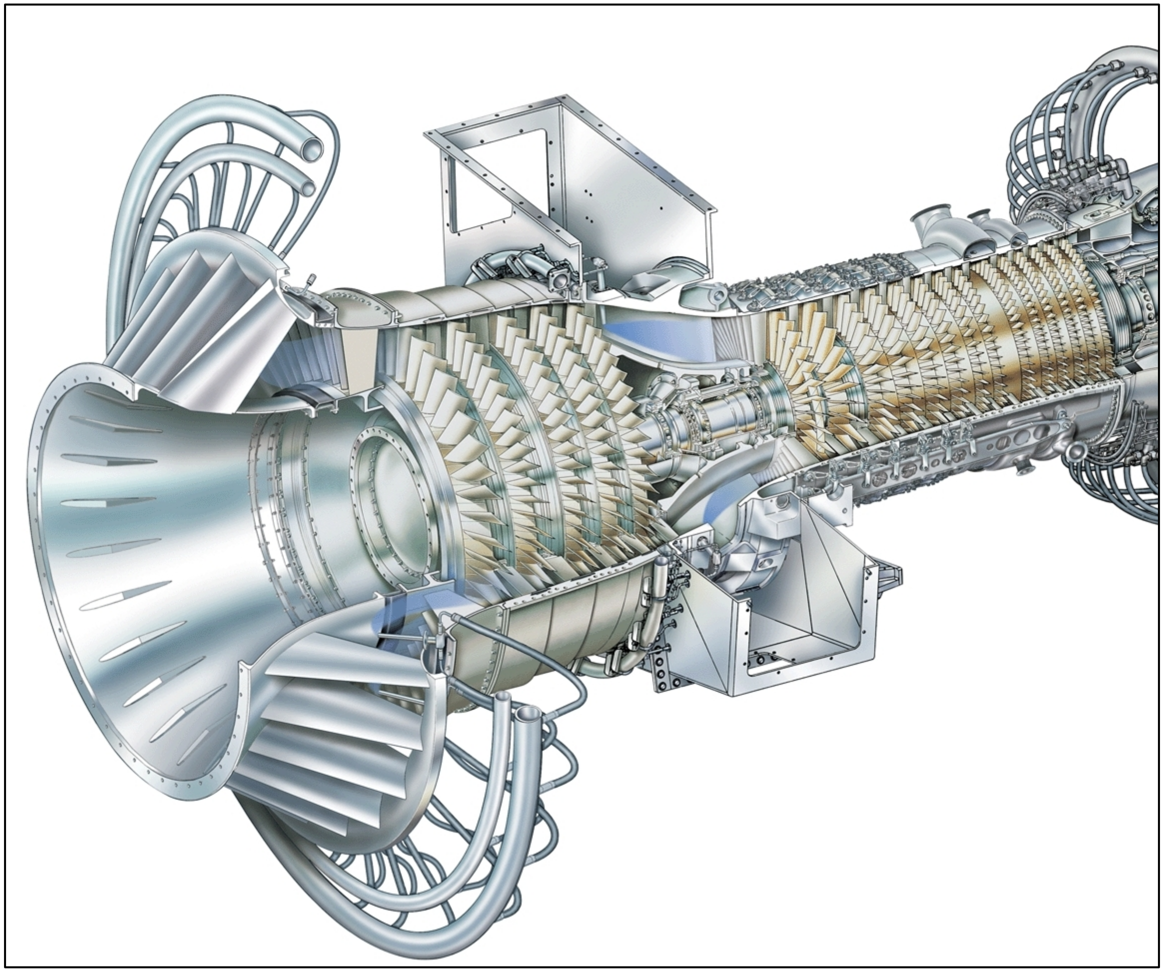
Outlet Guide Vanes (OGV) & diffuser – straighten & slow air stream prior to entry into the combustor section.

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

Compressor air is bled out for startup (to prevent surge) and part-load operation and/or dry low-NOx control

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

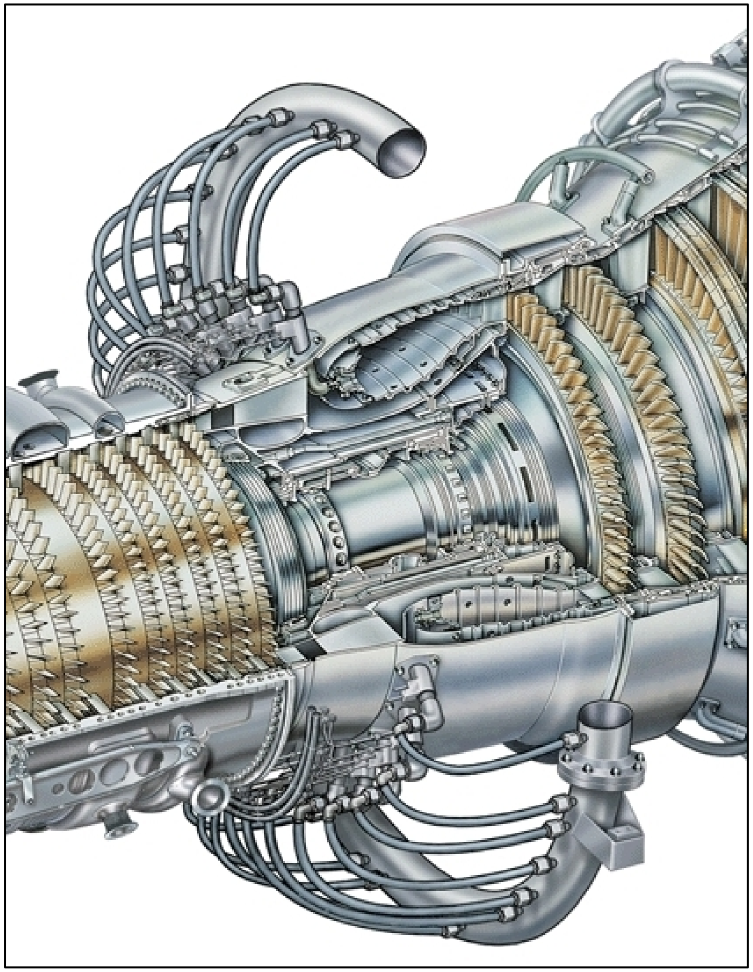
Many aero-derivative units employ Variable Stator Vanes (VSV) to control air flow and rotor speed in the higher-pressure section.



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

Basic Components of the Gas Turbine

Combustor Section:



Generally multi-can (basket) design or annular-ring design

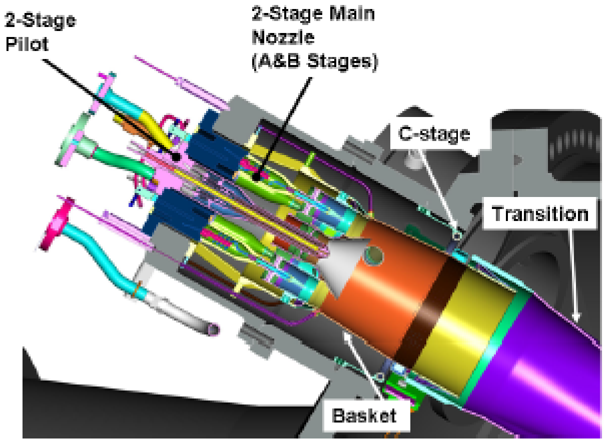
For standard diffusion-combustion systems (i.e. non dry emissions), gaseous or liquid fuels is introduced via nozzles located at the head of each combustor can, or front of combustion annulus chamber.

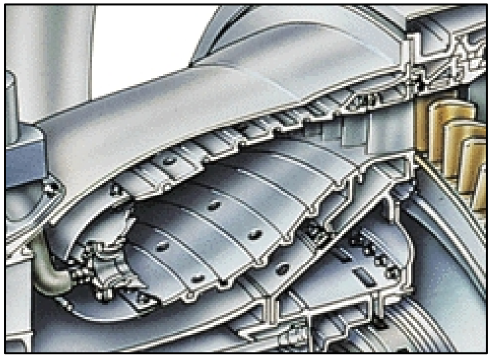
Portion of compressor air introduced directly into the combustion reaction zone (flame); remainder introduced afterwards – for flame shaping and quenching to T3.

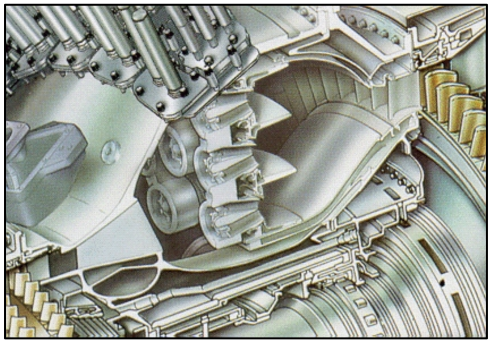
Water or steam injection: for environmental or power enhancement

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).

Basic Components of the Gas Turbine

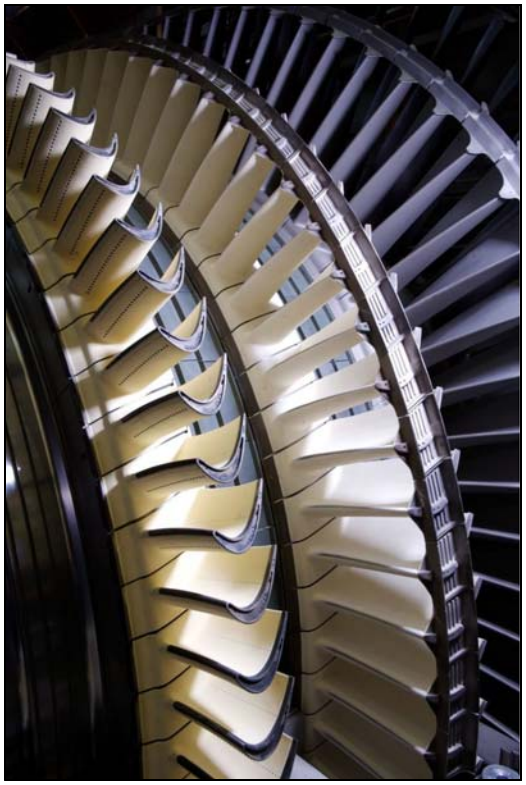
<u>Turbine</u> Section:

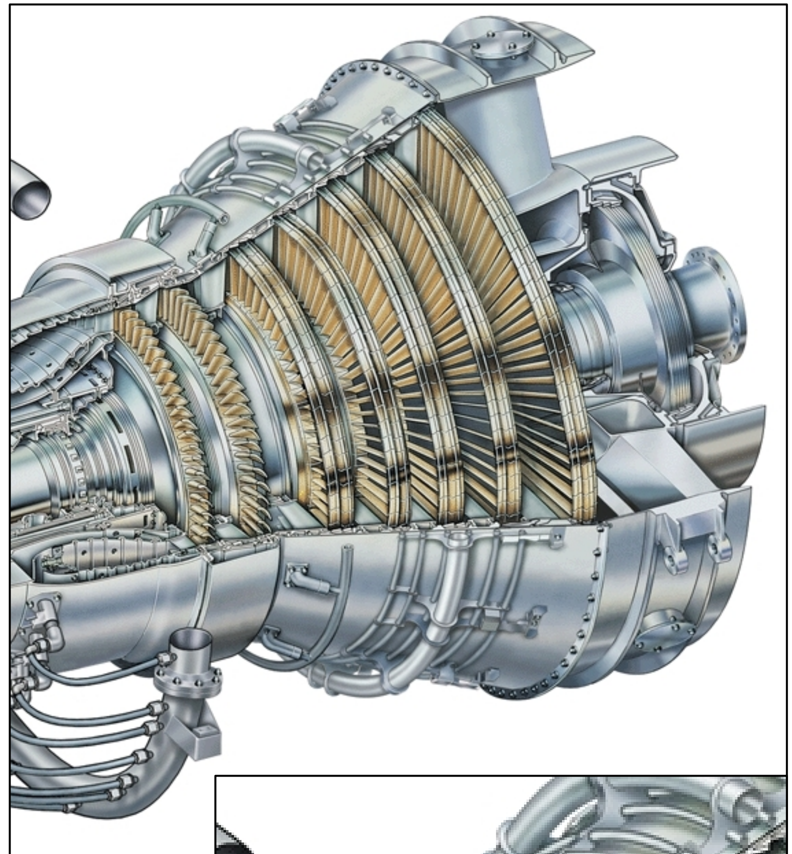
Usually a multi-stage axial design.

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.

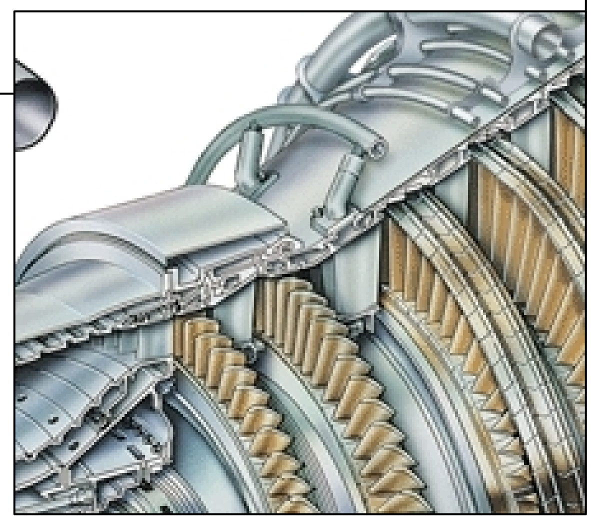




Plus, the rotating blade is required to survive under high centrifugal & mechanical stresses.

Internal cooling passages are 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.



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

The Basic Gas Turbine Machine

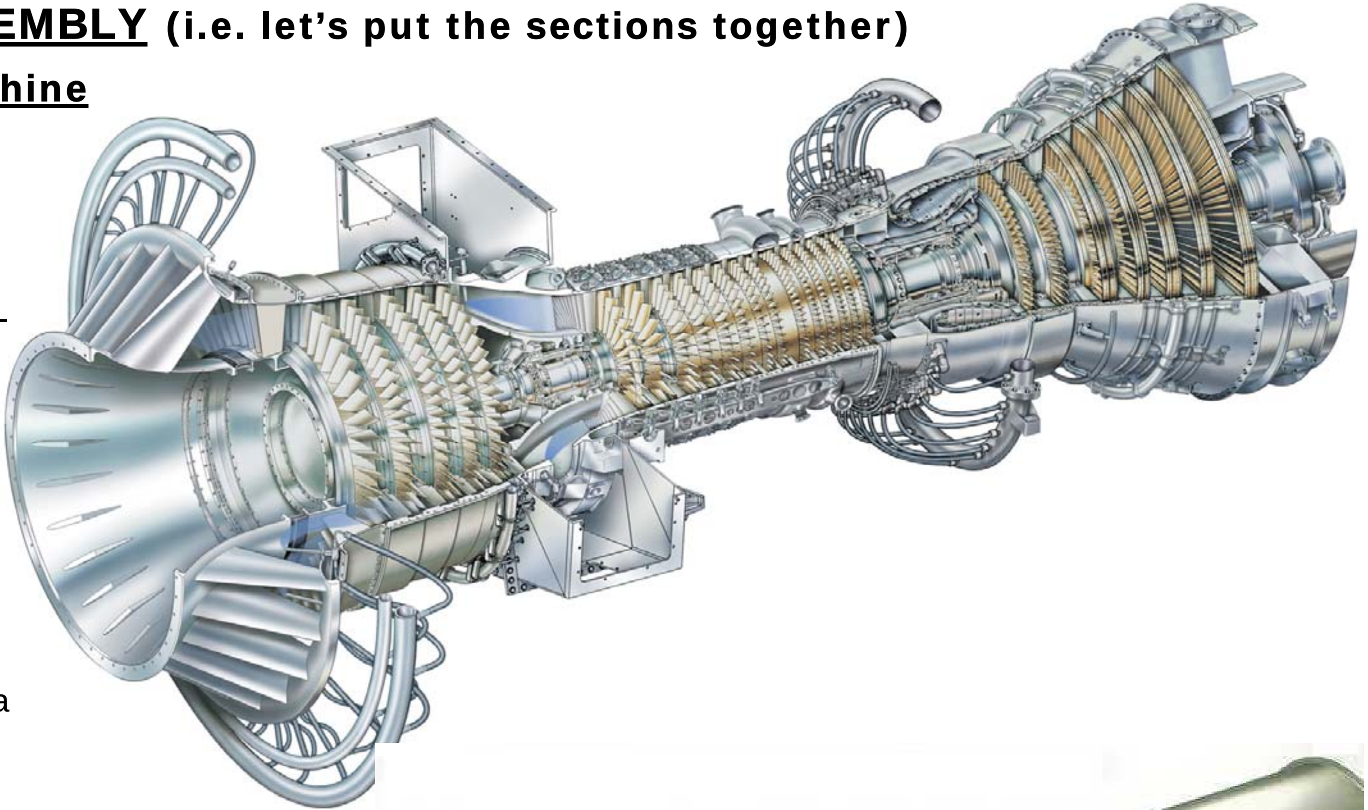
Individual **Compressor**, **Combustor** & **Turbine** sections and their **casings** and **shafts** are bolted together.

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

Rotating compressor & turbine sections are mechanically interconnected at their shafts through the combustor section.

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

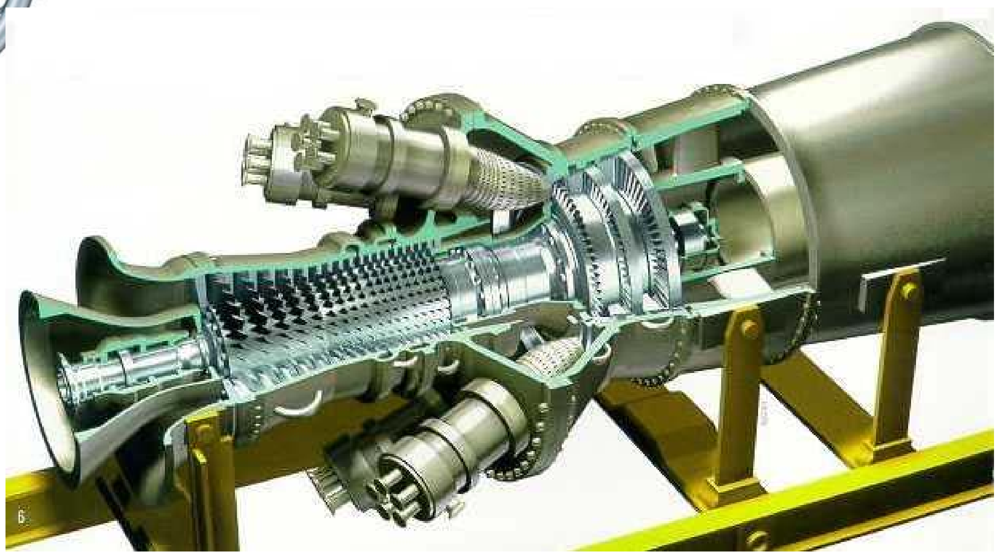
- Cold-end drive
- Hot-end drive



The 2/3 to 1/3 "Rule of Thumb"

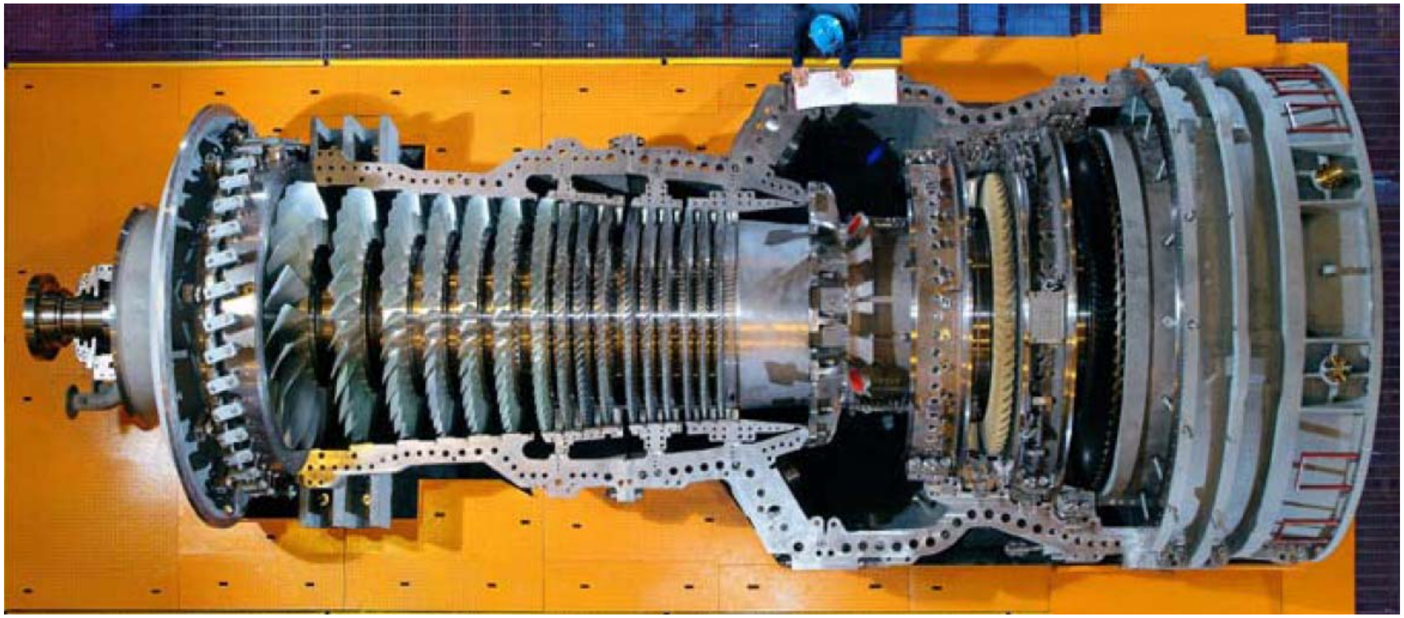
60~70% of the Turbine Section's power output is used by the Compressor Section to drive it.

The remaining 30~40% is 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.

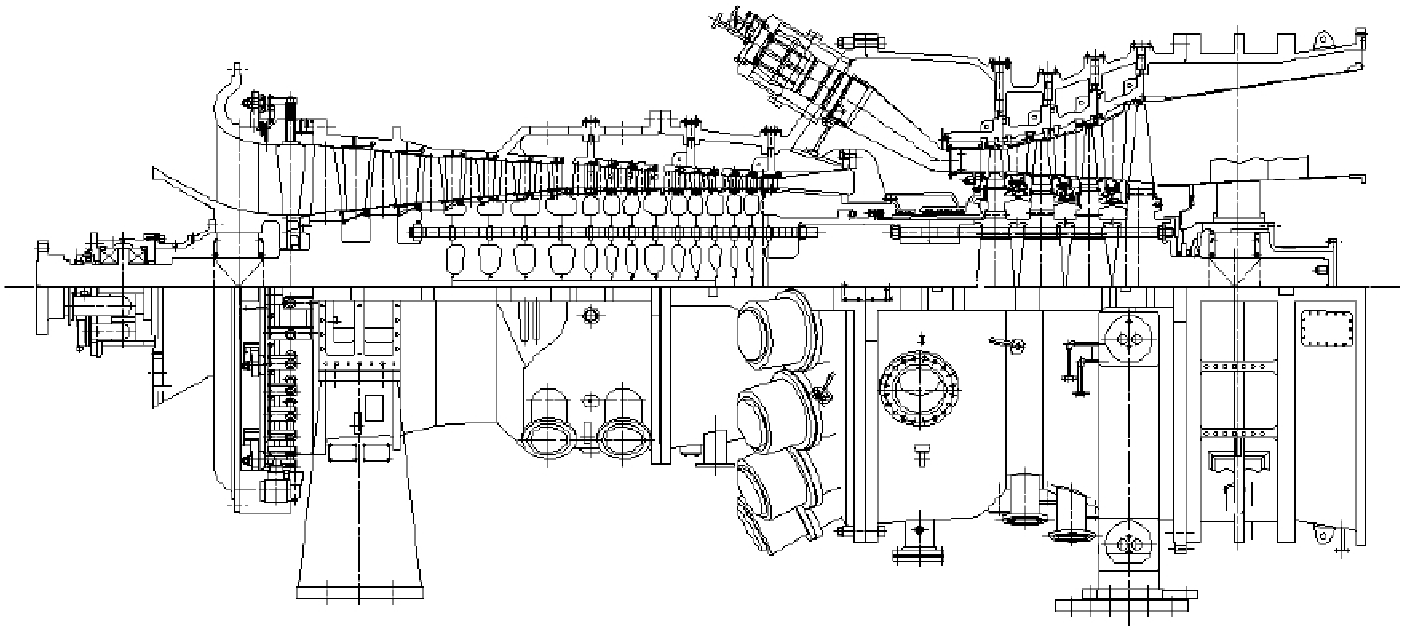


F-Class Gas Turbine Assembly
(175~225 MW)

Top-Half removed –
Cold-end drive, multi-stage compressor with IGVs, multi-can combustor with baskets & transition pieces, multi-stage turbine section and exhaust diffuser



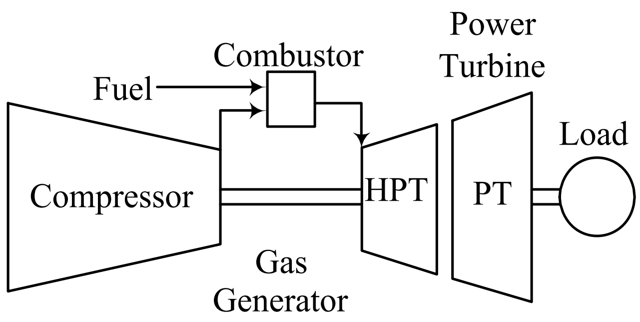
F-Class Longitudinal Assembly Drawing
A cutaway drawing of the same above unit

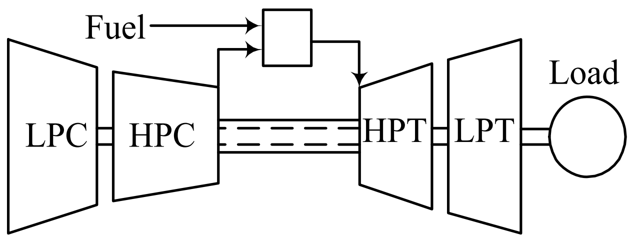


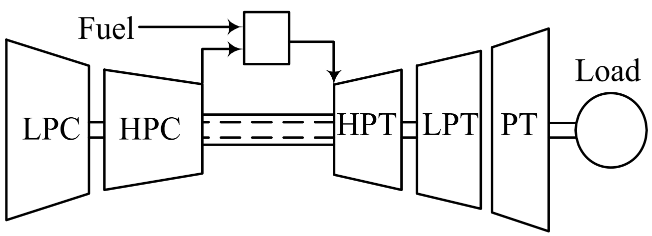
Gas Turbine Variations – from the single-shaft design

Single-Shaft with PT – industrial & aero-derivative units with aerodynamically-coupled Power Turbines (PT).

Usually derived from a jet engine ("gas generator"). Allows PT speed to vary for mechanical drive service, but also used in generator service.







Multi-Shaft, With & Without PT

Usually derivatives of advanced aircraft engines.

Basic compressor & turbine sections divided into HP and LP units. HP and LP each operates at a different speed – depends upon load & 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) & turbine (IPT) also used, in between LP & HP sections (configuration not shown).

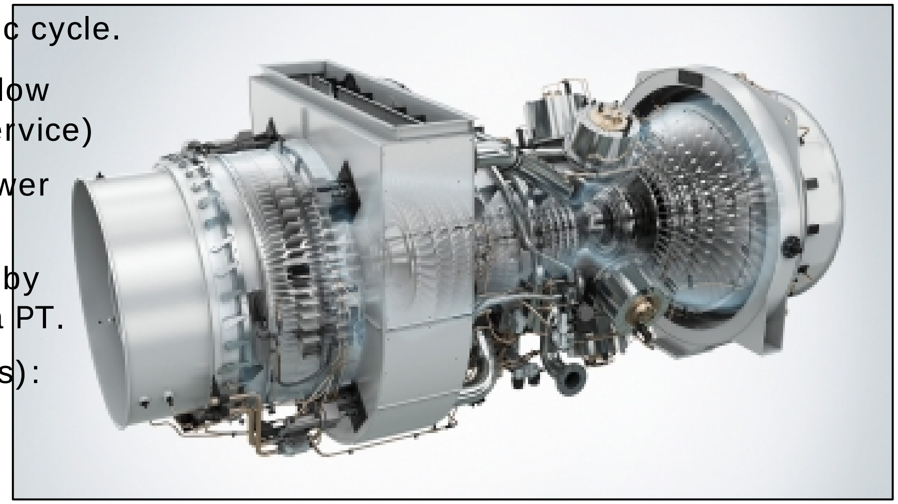
Fixed or variable-speed loads are driven off LP shaft.

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

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

AERO-DERIVATIVE & HEAVY-DUTY INDUSTRIAL GAS TURBINES

"THERMODYNAMIC COUSINS" – sharing the same basic cycle.



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

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

Later-design **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.

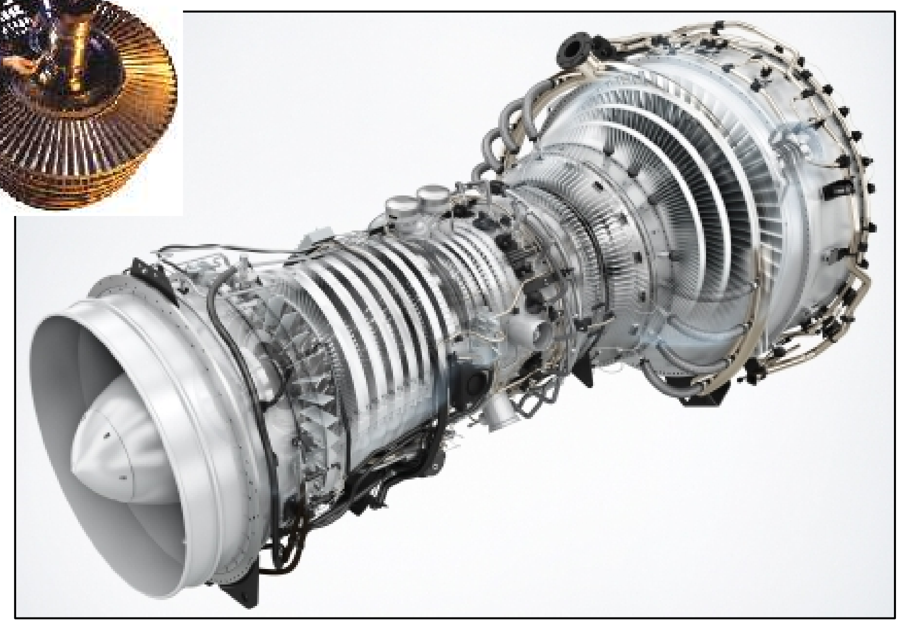
Major Maintenance – generally conducted by complete removal of gas turbine from package – special lifting frames required.

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.



Heavy-Duty Industrial GTs – heavier and more-rugged than its cousin

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

Typically, the scheduled maintenance intervals are longer than aero units

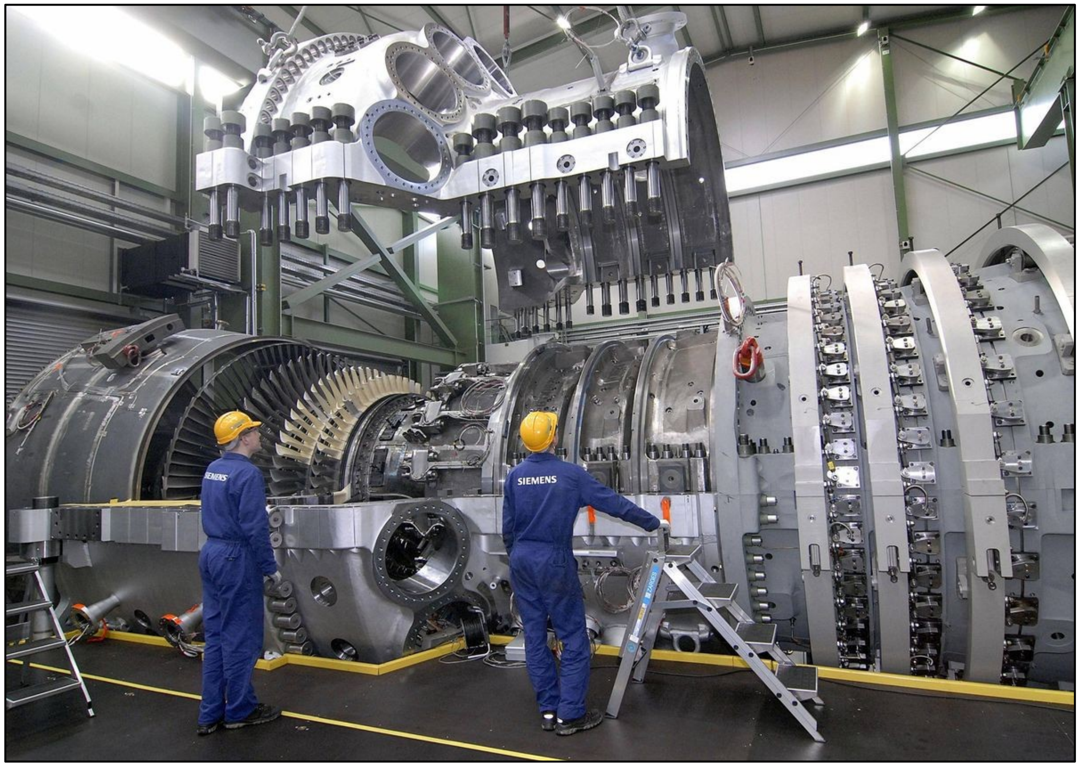
Heavy multi-cylinder castings and fabrications.

Large bolted horizontal and vertical split joints.

Heavy built-up rotors & journal bearings.

Large solid couplings

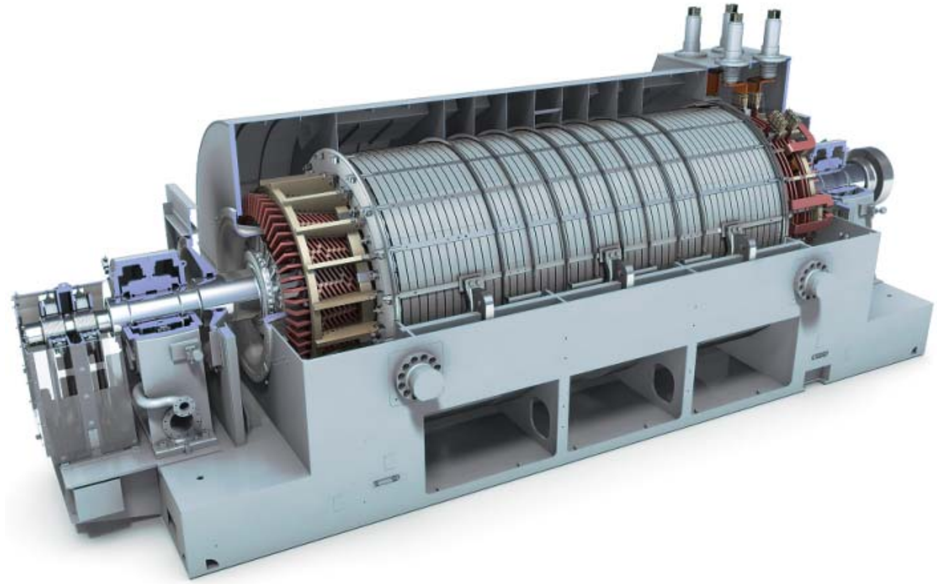
Large baseplates and frames.



Major Maintenance – usually done at site**:**

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

THE GAS TURBINE PACKAGE



"Packaging" completes the machine – it needs to be straightforward to install & commission; and must be easy to maintain and overhaul.

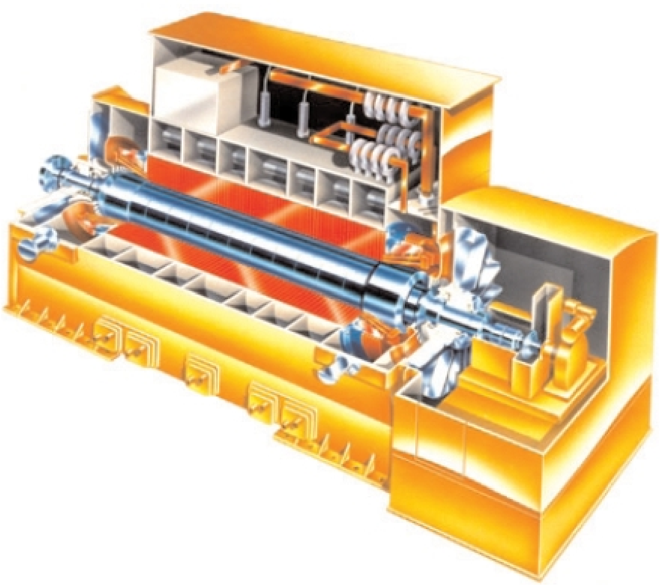
Driven Equipment

Typically:

- synchronous generators – rated per ANSI C50.14.
- process or pipeline compressors (variable speed)
- occasionally used 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).

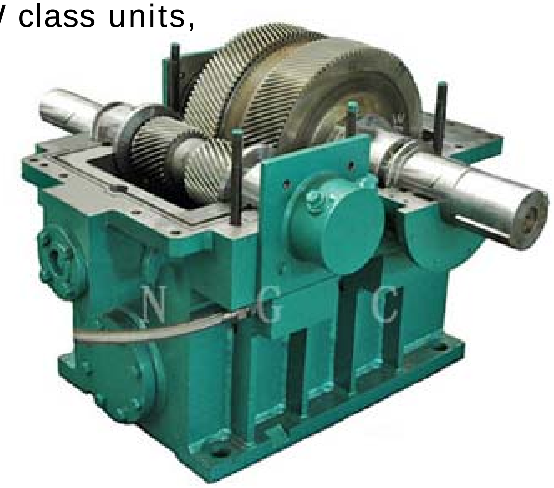


Generator output voltages:

- 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 required for voltage & power factor/var control – brushless or static.

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



Gas Turbine Air Inlet Systems
Filtration, Silencing, Air Heating and/or Cooling

Critical to Gas Turbine 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 bladepath

Tuned **inlet air silencers** – absorb sound & acoustic emissions emanating from the intake bladepath and combustion system

Potential Options

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

Rain / Snow Hoods

Lubricating Oil Systems

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

Fuel Systems

Aero-derivative & heavy duty gas turbines can use light-liquid or gaseous fuels. Only the frame units can operate on heavy fuel oils & crude oils.

Fuel control systems for gaseous and liquid fuels include:

- filters, strainers, 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-NOx (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.

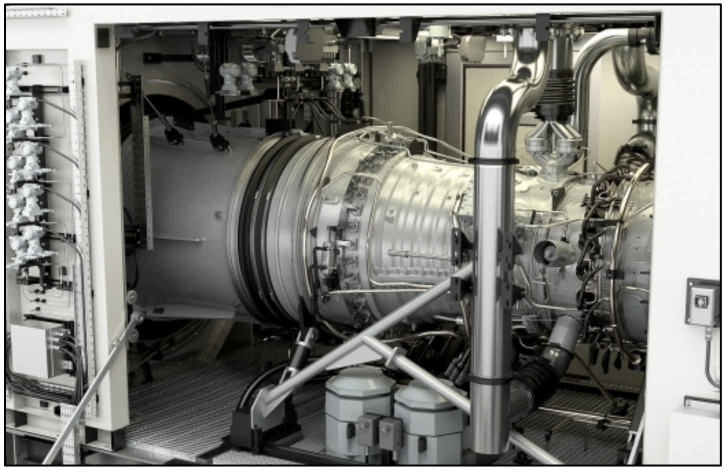
Controls & Monitoring Systems

Complex combinations of high-speed digital PLC and/or processor systems: Woodward; vendor-proprietary systems; occasionally DCS-based

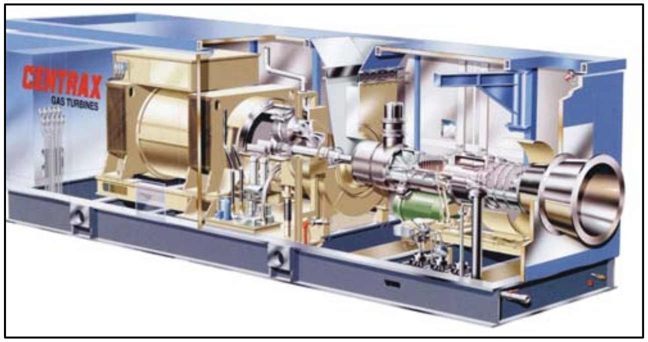
Systems include, manage, sequence, monitor and control:

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

Acoustic and Weatherproof Enclosures



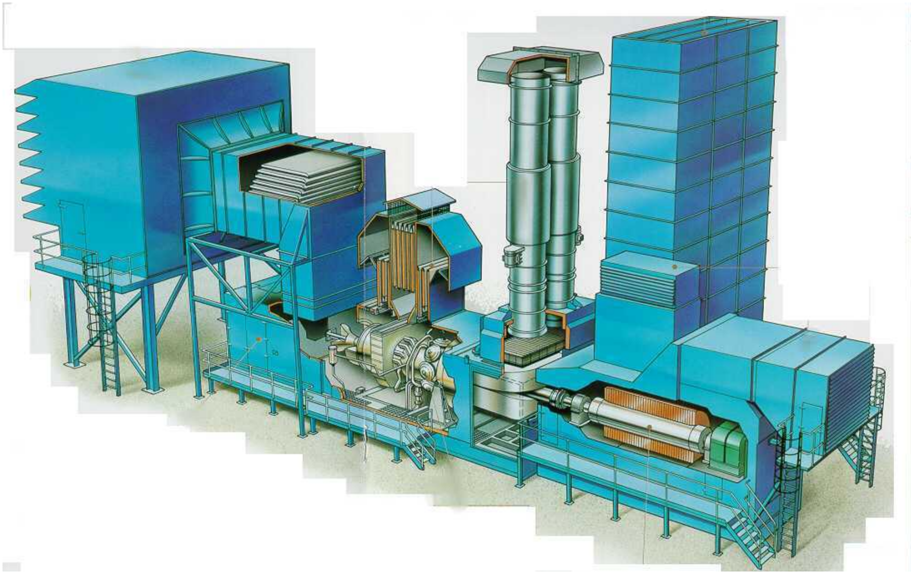
Most smaller industrial & almost all aero-derivative GTG packages are pre-packaged - complete drivetrain enclosed in acoustic enclosure(s); quicker & easier to install. The turbine & generator compartments are usually separately ventilated.



40~60 MW+ industrial / heavy-duty GT machines are generally too large to pre-package.

Components shipped in major blocks & assembled at site.

Enclosures or buildings (if required) are built around the complete drivetrain.

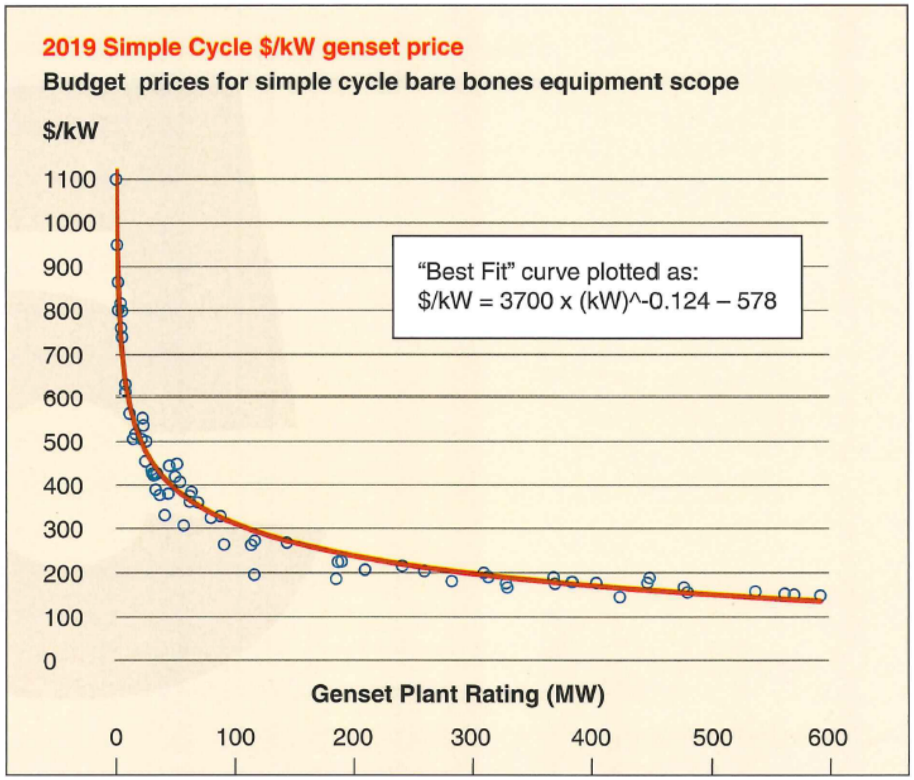


Miscellaneous Auxiliaries

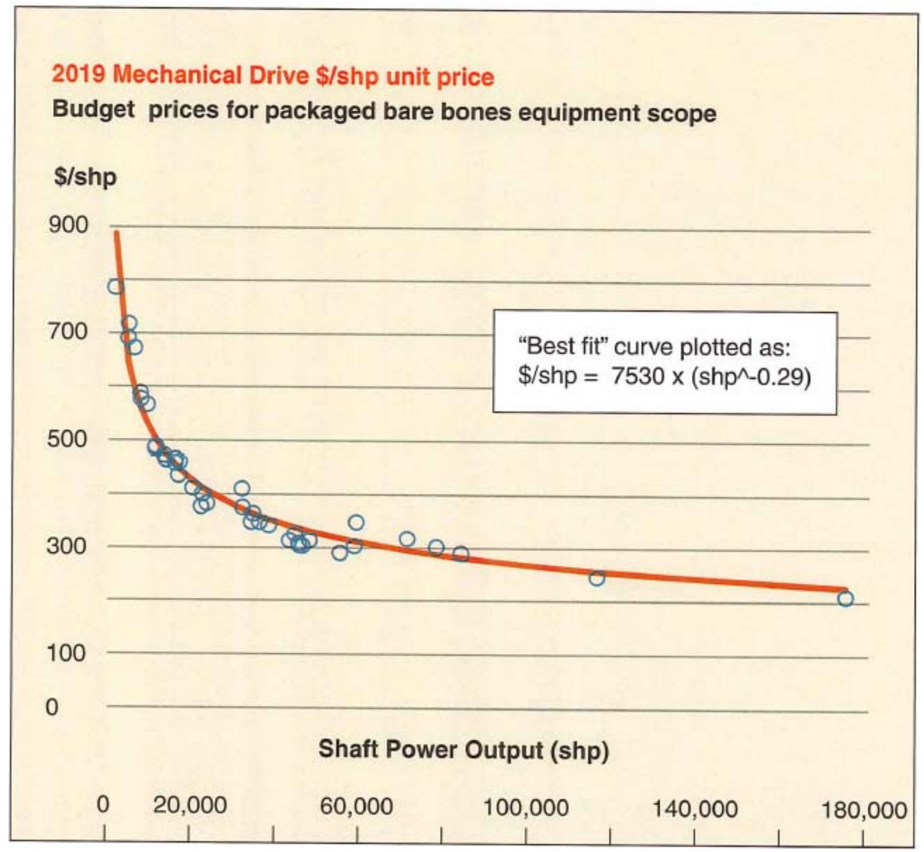
- starting, purge and turning gear systems
- inlet manifolds
- exhaust diffusers or plenums
- water wash systems
- water and steam injection (if required
- gas detection systems
- fire detection and CO2 suppression systems
- battery and charger systems
- ventilation and heating
- exhaust expansion joint
- silencer & stack systems (simple-cycle)
- HRSGs for steam production (cogen /combined-cycle)

GAS TURBINE PRICING - from the *2019 Gas Turbine Handbook*© ($USD)

Simple-Cycle GTG Prices – not total "project cost"

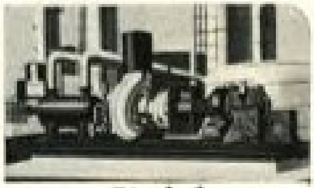


Mechanical Drive Gas Turbine Prices – gas turbine only and does not include driven equipment nor the total "project cost".



Four amazing advantages of Solar Gas Turbine Engines

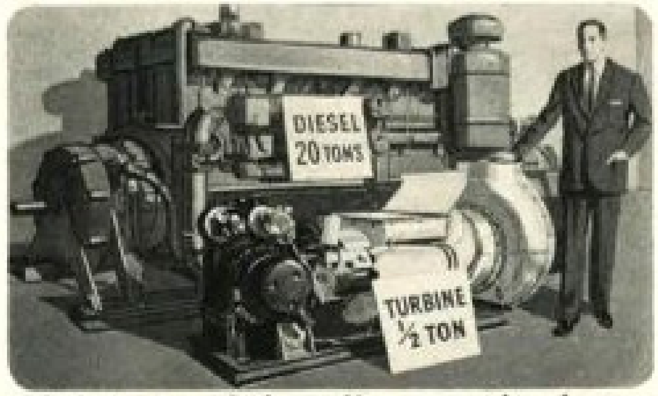
Gasoline—any kind.



Diesel oil

Kerosene.

Natural gas.



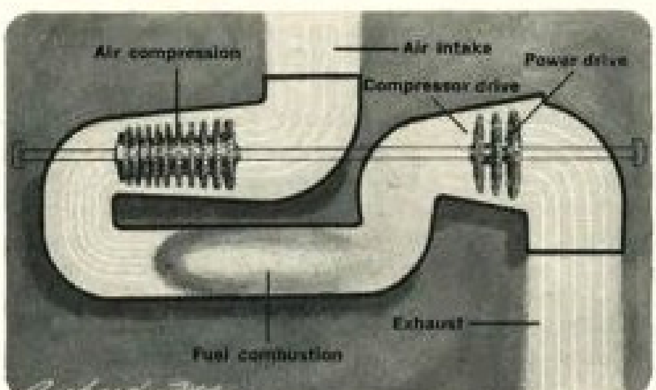
The Jupiter is completely portable—saves weight and space.

❶ Uses whatever fuel you've got!

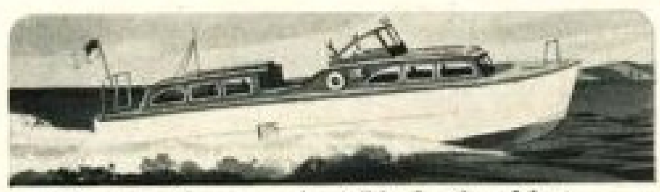
Solar gas turbines can operate on almost any available fuel—fuel that costs the least for *your* particular operation. Located in remote areas, for instance, self-sufficient Solar turbines can take fuel directly from a gas pipeline! This often results in lower total operating costs.

❷ Light—500 hp in 1/5 the space!

Solar's 500 hp Jupiter® engine is only one-fifth the size of a diesel of similar horsepower—and weighs *forty times less!* The entire unit is easily transported to remote locations. And it is especially suited to applications where space limitations create a troublesome installation problem.



Few moving parts, no reciprocation—longer life.



Instant acceleration—takes full load without laboring.

Instant emergency power.

Starts in any climate.

❸ Simple design—low maintenance!

Gas turbines are the simplest of all heat engines. In operation, large volumes of air are drawn in by the compressor, mixed with fuel in the combustion chamber, greatly expanded, and delivered to a turbine which produces shaft power. Routine servicing can be completed in a few hours at most. Overhauls are infrequent. Simple design and low maintenance make gas turbines ideal for a wide range of important applications—including boat propulsion, portable power generation, air compression and chemical processing. And other applications for these versatile power plants of the future are limited only by the imagination.

❹ Starts instantly—no warm-up!

Solar gas turbines can be turned on or shut down in seconds. And they require no warm-up—even after long periods of stand-by service. No matter what your business, no matter what your power needs, these amazing advantages can benefit you. Write to Dept. D-151 for free gas turbine brochure.

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