GTEN 2019 Symposium

October 21-23, 2019 | Banff, Alberta

Day 1 – Training Session #1

Gas Turbine Basics

Jim Noordermeer, P.Eng.
Noord Power Consulting

Pascal Robichaud, P.Eng.
CEM Engineering

*An introduction to the basics of the industrial **Gas Turbine Generator** package*

•heavy-duty and aero-derivatives

•the gas turbine generator package

•the auxiliaries

For the cogeneration, combined-cycle or peaking power plant

Presented at the Gas Turbines Energy Network (GTEN) 2019 Symposium

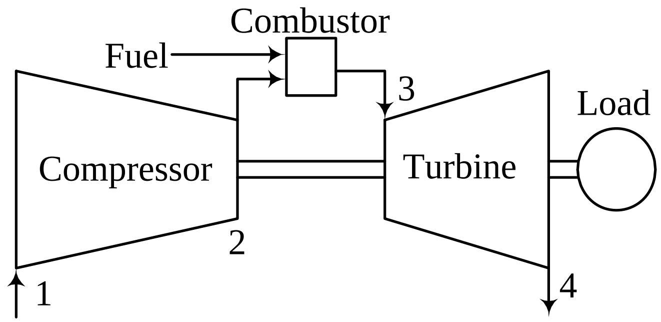
Banff, Alberta, Canada - October 2019

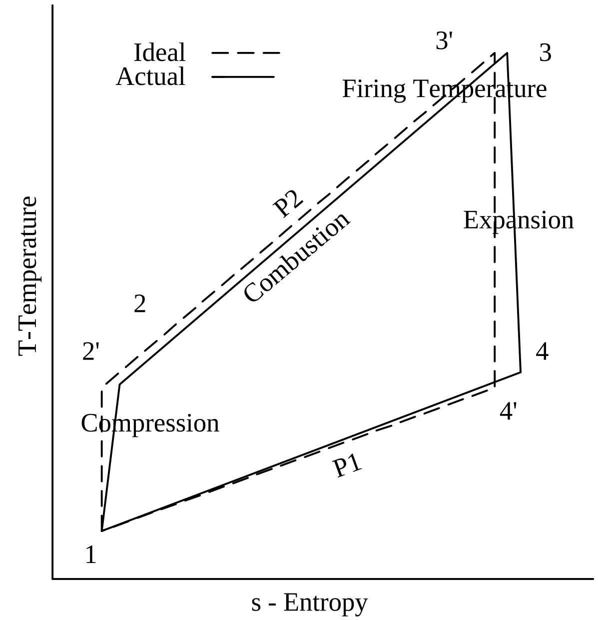
The GTEN Committee shall not be responsible for statements or opinions advanced in technical papers or in symposium or meeting discussions.

GAS TURBINE CONCEPTS

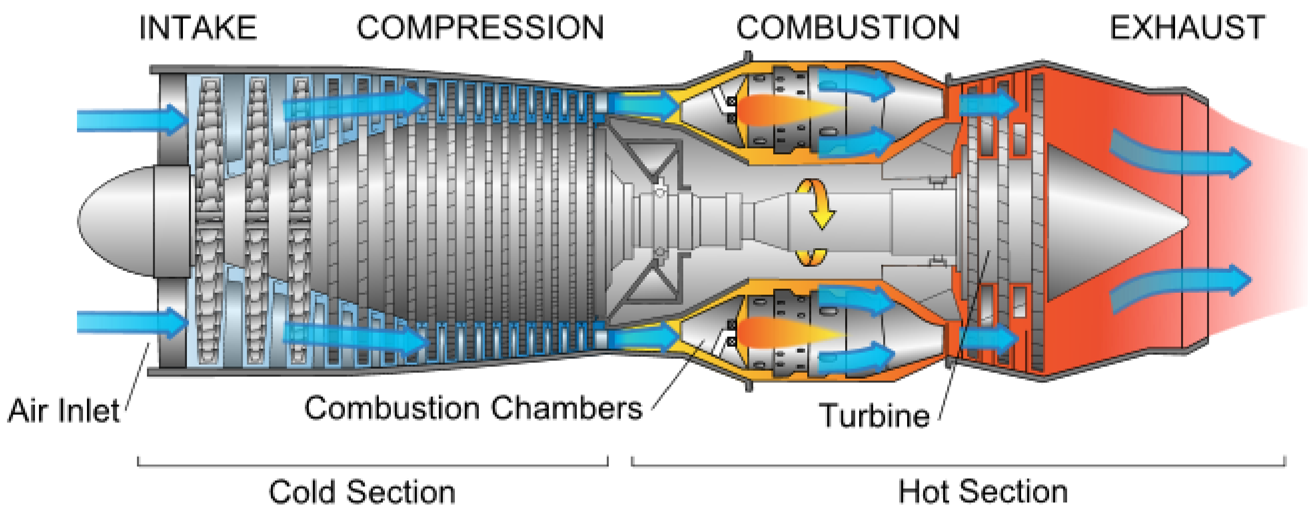
The Basic Thermodynamic Gas Turbine Cycle

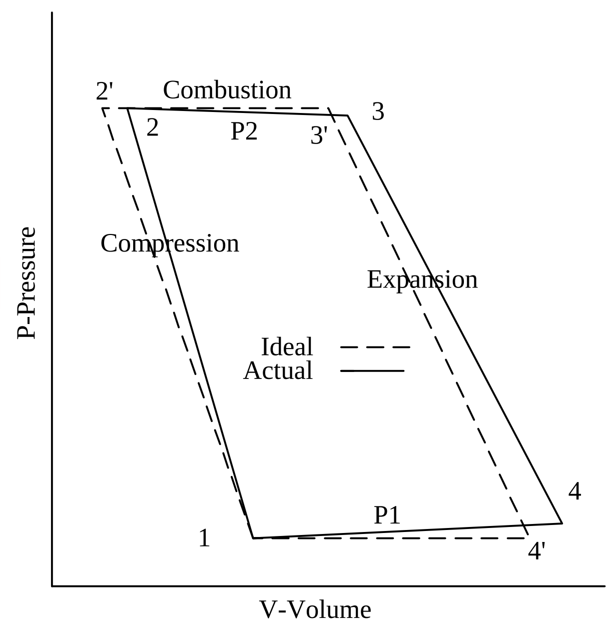
Brayton Cycle – a continuously operating process using air as the working fluid, moving through four **State Points**:



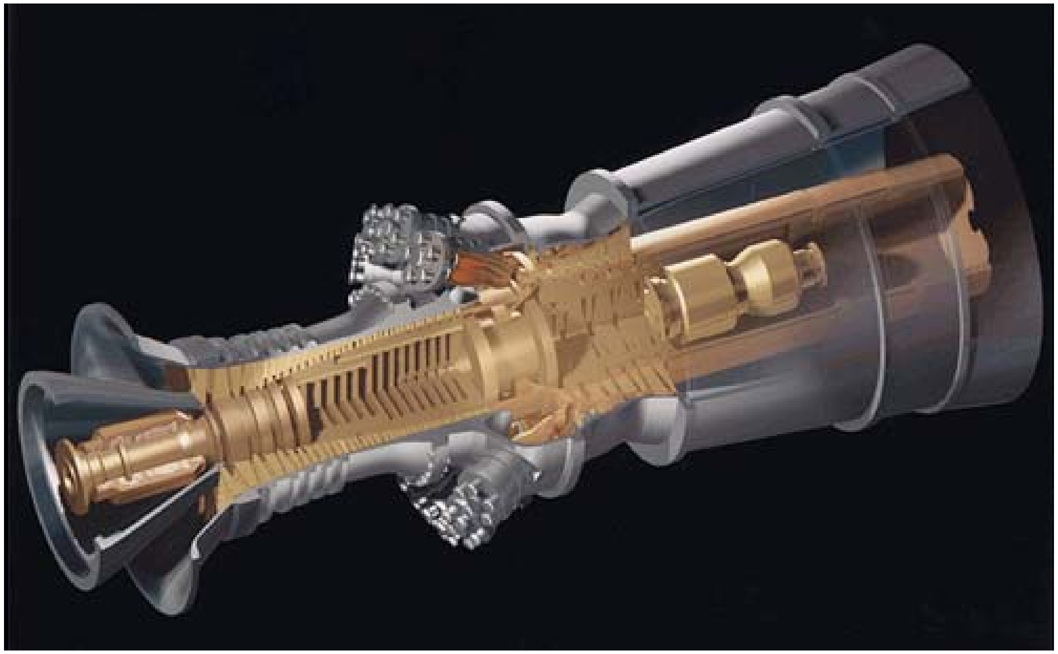


- Air Intake (**State 1**): *ambient air enters the unit*
- Continuous air compression (**States 1 to 2**): *the compressor requires power*
- Continuous fuel combustion (**States 2 to 3**): *which adds heat and small % of mass flow at relatively constant pressure*
- Hot air expansion back to atmospheric 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)*





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 2600 F and beyond with better turbine section materials, coatings and cooling methods

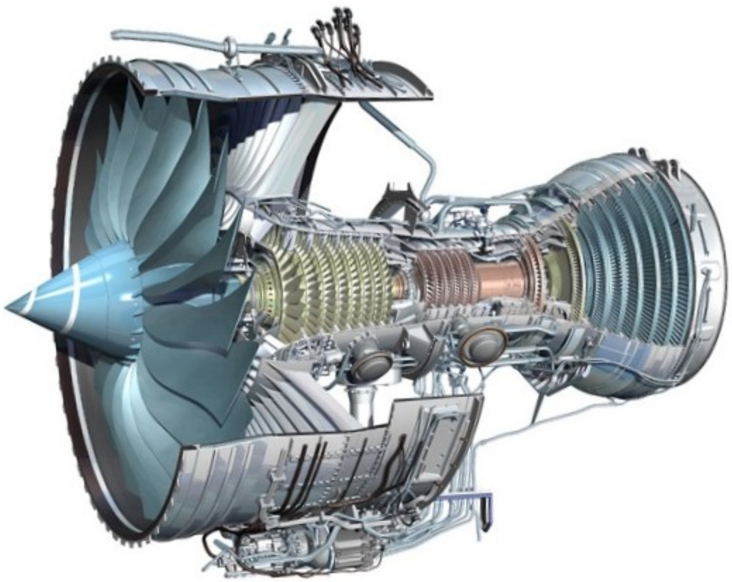
High T3 = improves power output & efficiency.

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.

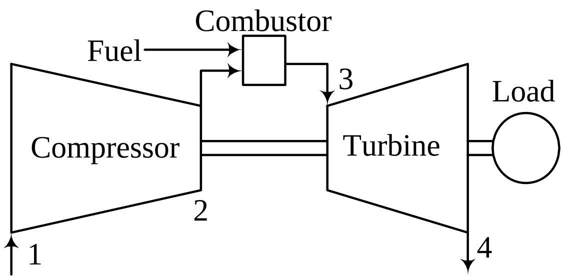
Aircraft "**Jet Engines**" are also "Gas Turbines"



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

Turbine Cycle Variations – of the "Basic Cycle":



Basic Cycle (for ref.)

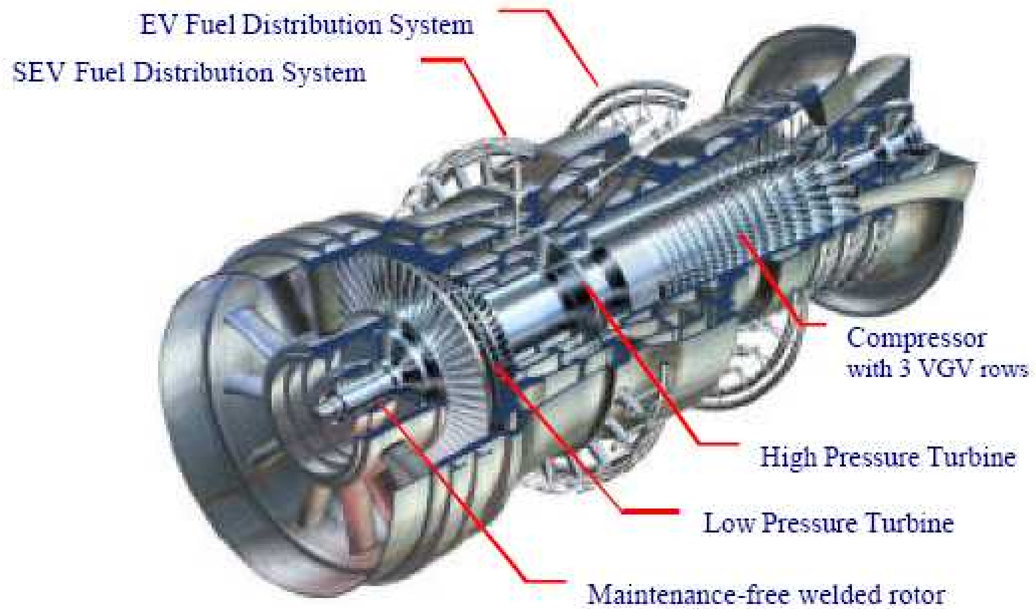
Reheat or Sequential Combustion – used in high-pressure ratio GT's.

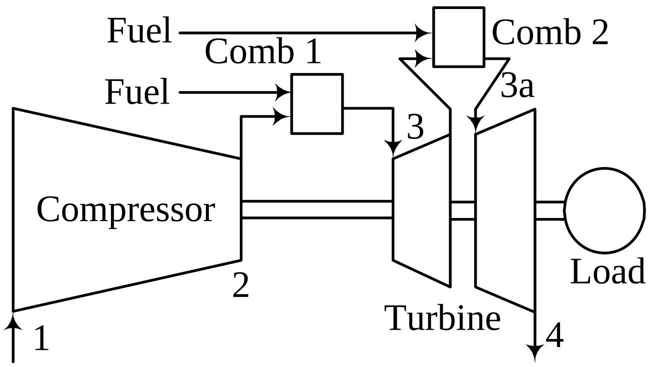
Hot HP Turbine Section gases are reheated by combustion of additional fuel (3a).

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

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***.

Turbine Cycle Variations – of the basic cycle:

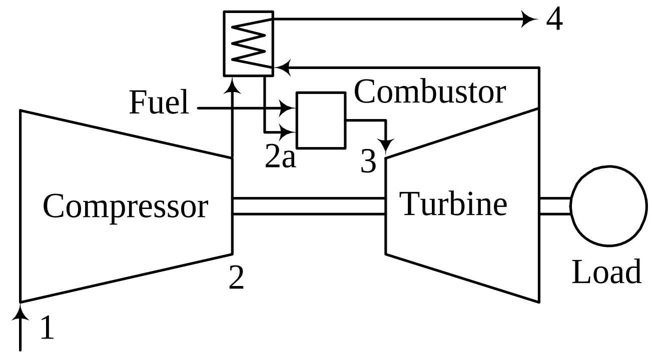
Recuperated or Regenerated Gas Turbines

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

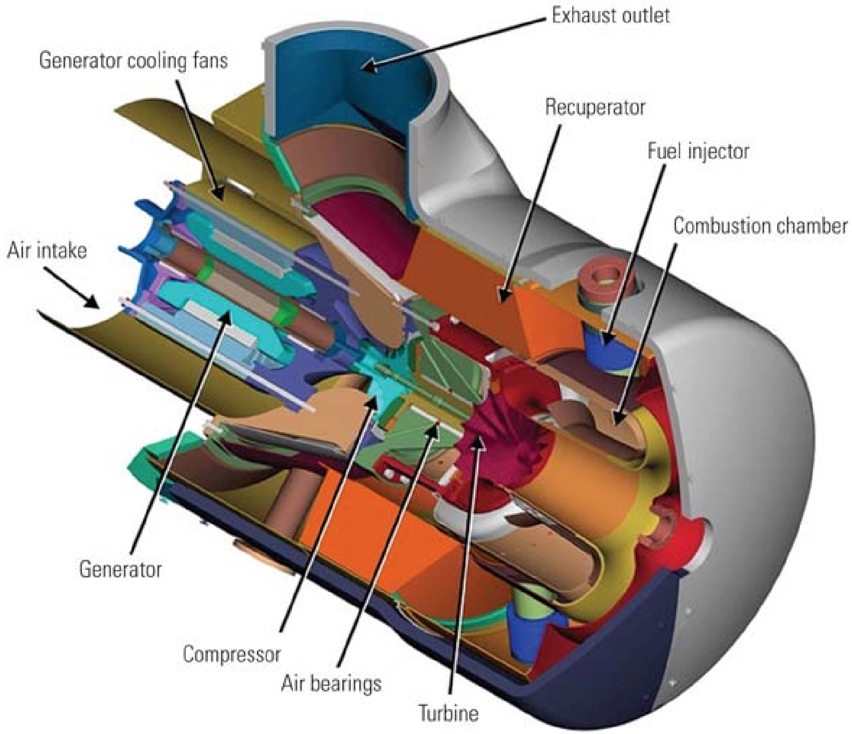
An external regenerative heat-exchanger transfers heat from the turbine exhaust to the compressor discharge air (before fuel is introduced).

Regenerative Configuration:

- Saves fuel
- Increases efficiency
- Low exhaust energy



Examples: ***Solar Mercury 50 / Abrams M1 / Micro-Turbines***



Turbine Cycle Variations – of the basic cycle:

Inter-Cooled Gas Turbines

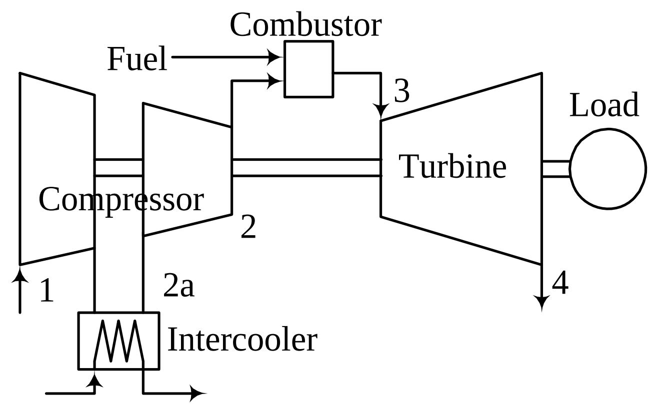
For high-pressure ratio multi-shaft GT units.

LP compressor air is directed to an external heat exchanger.

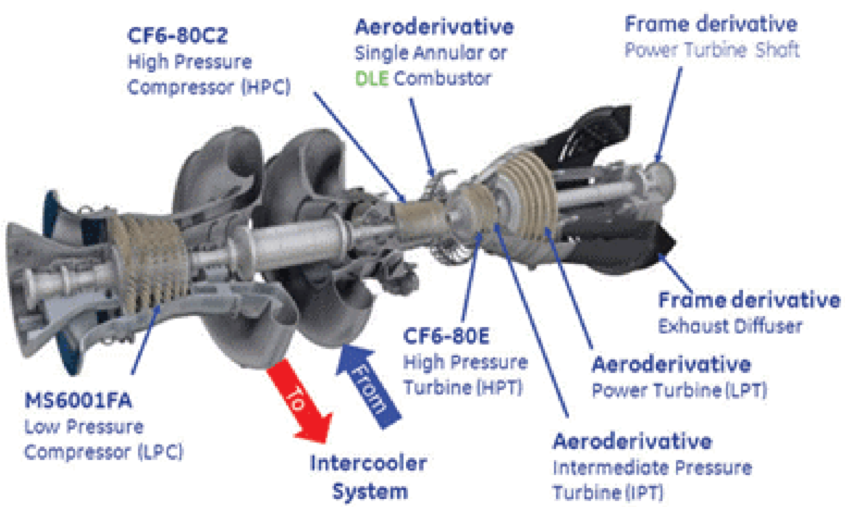
Cooling medium (water or air) decreases air temperature and increases flow density. The cooled air re-enters the HP compressor.

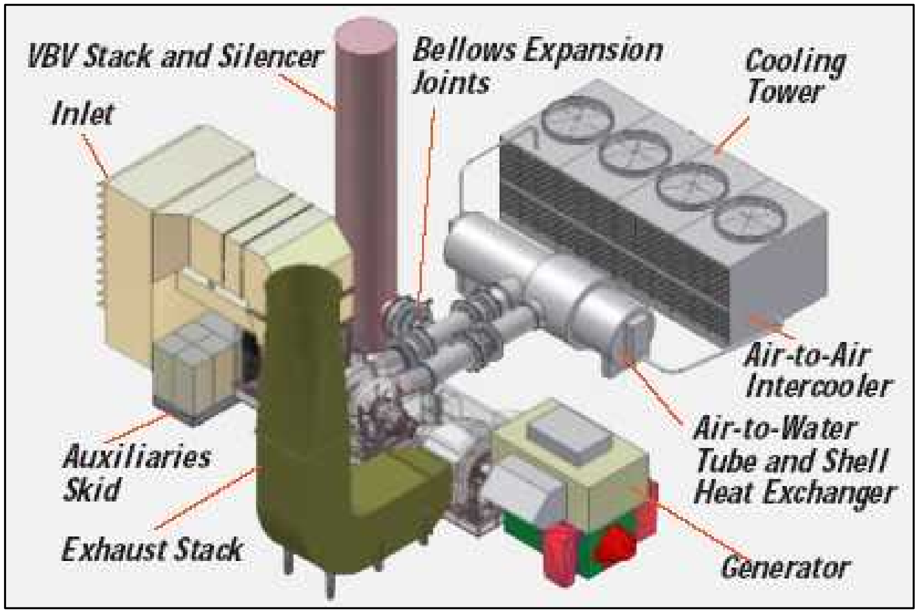
Intercooled Configuration:

- decreases HP compressor power
- improves efficiency & specific output



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

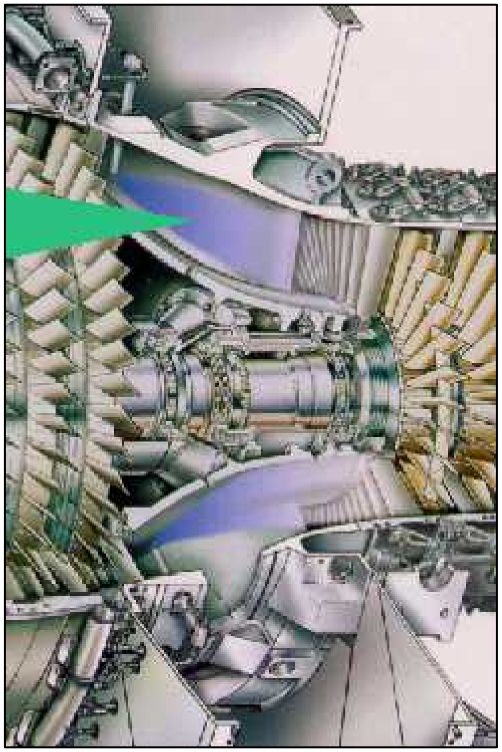




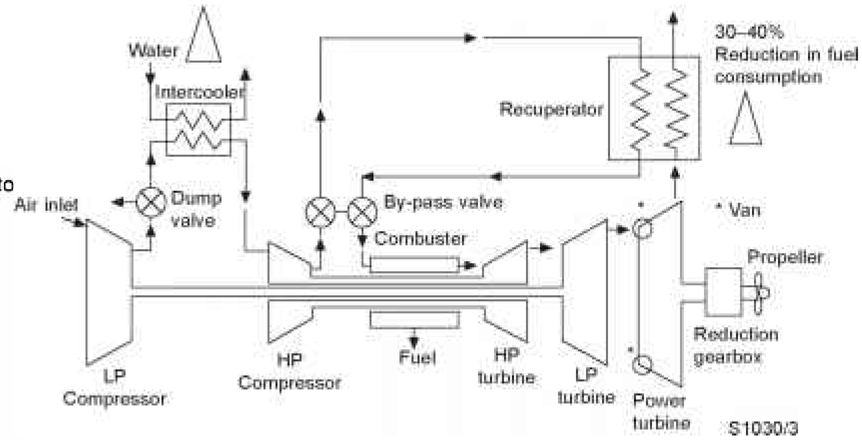
Turbine Cycle Variations – of the basic cycle:

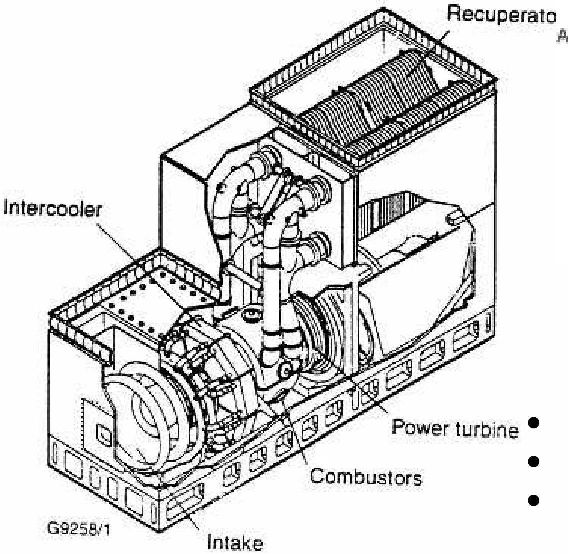
Spraywater Cooling – similar to intercooling, evaporative cooling and/or fogging

Very clean water injected before the LP compressor, and between the LP & HP LM6000 compressor sections of the multi-shaft aero-derivative ***GE LM6000 Sprint***. Systems are also available on ISI versions of the ***Siemens / 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 (other than possibly trains).

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.

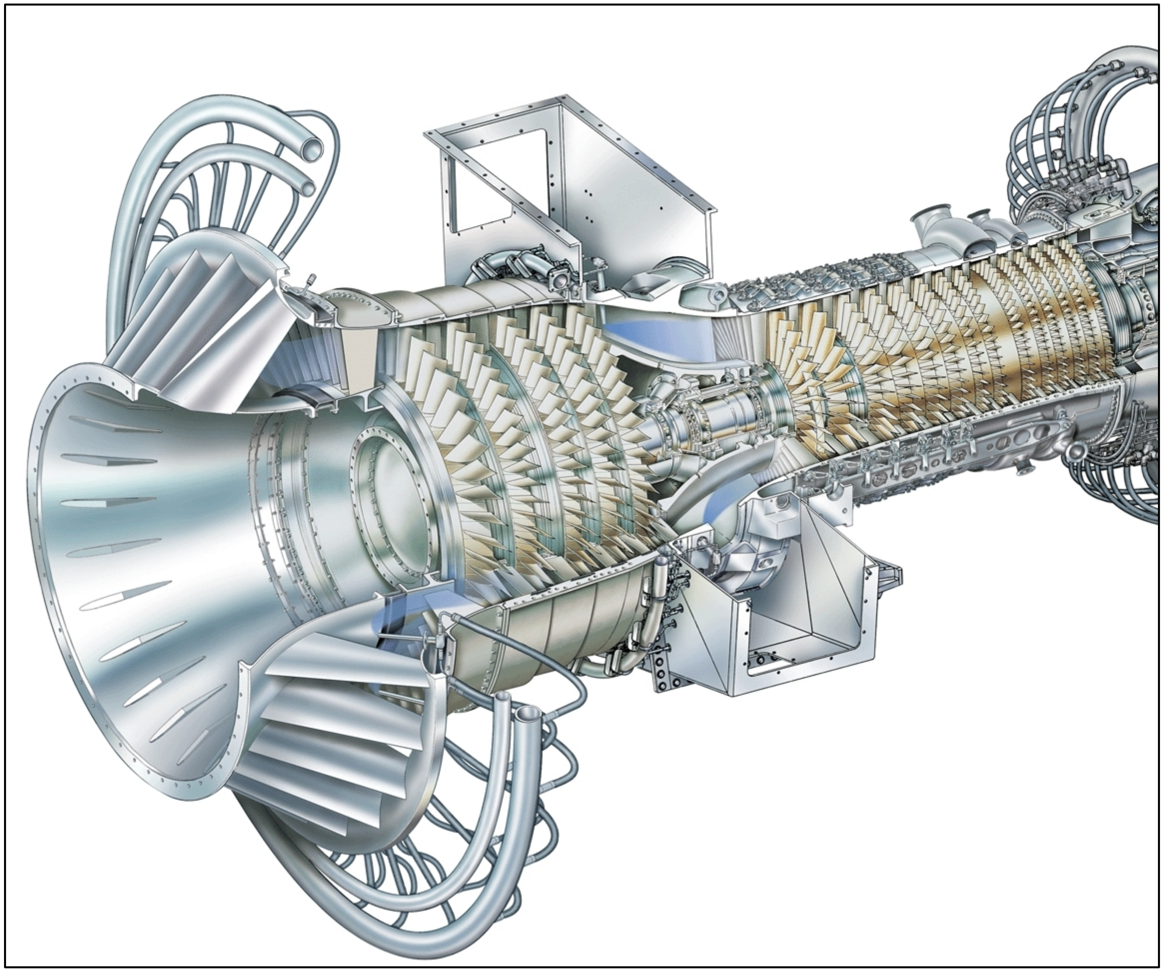
Outlet Guide Vanes (OGV) & diffuser – straighten & slow air stream prior to entry into the combustor section.

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.

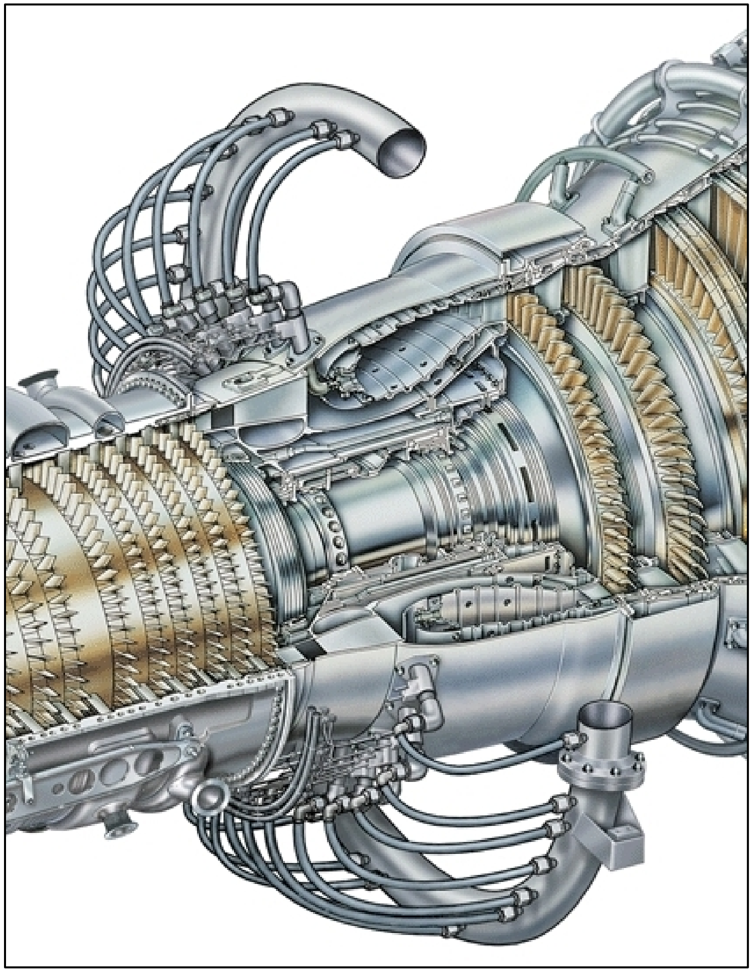
Many aero-derivative units employ Variable Stator Vanes (VSV) to control air flow and rotor speed in the higher-pressure section.



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

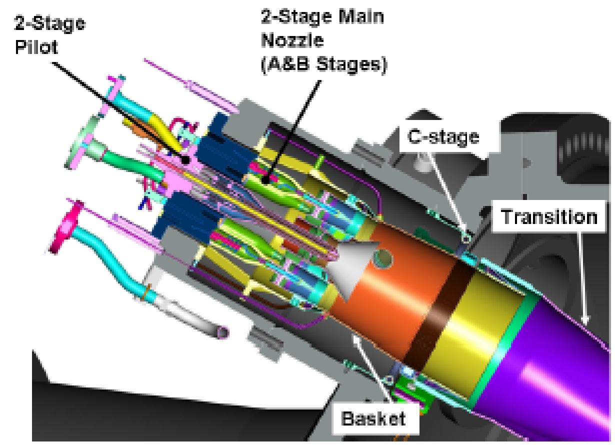
For standard diffusion-combustion systems (i.e. non dry emissions), gaseous or liquid fuels is introduced via nozzles located at the head of each combustor can, or front of combustion annulus chamber.

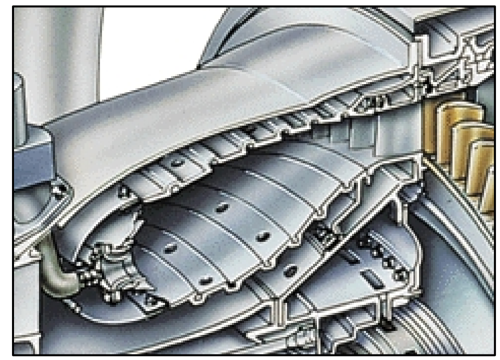
Portion of compressor air introduced directly into the combustion reaction zone (flame); remainder introduced afterwards – for flame shaping and quenching to T3.

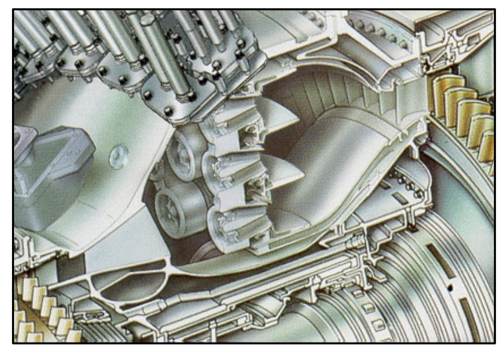
Water or steam injection: for environmental or power enhancement

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

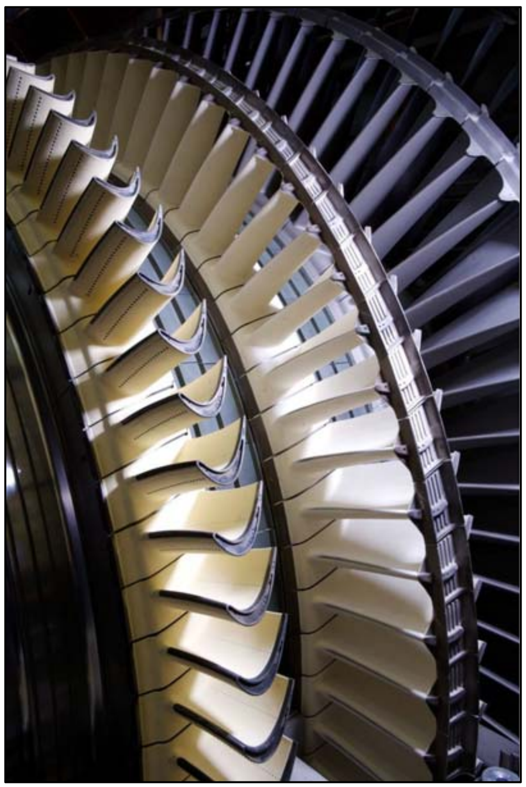
Turbine Section:

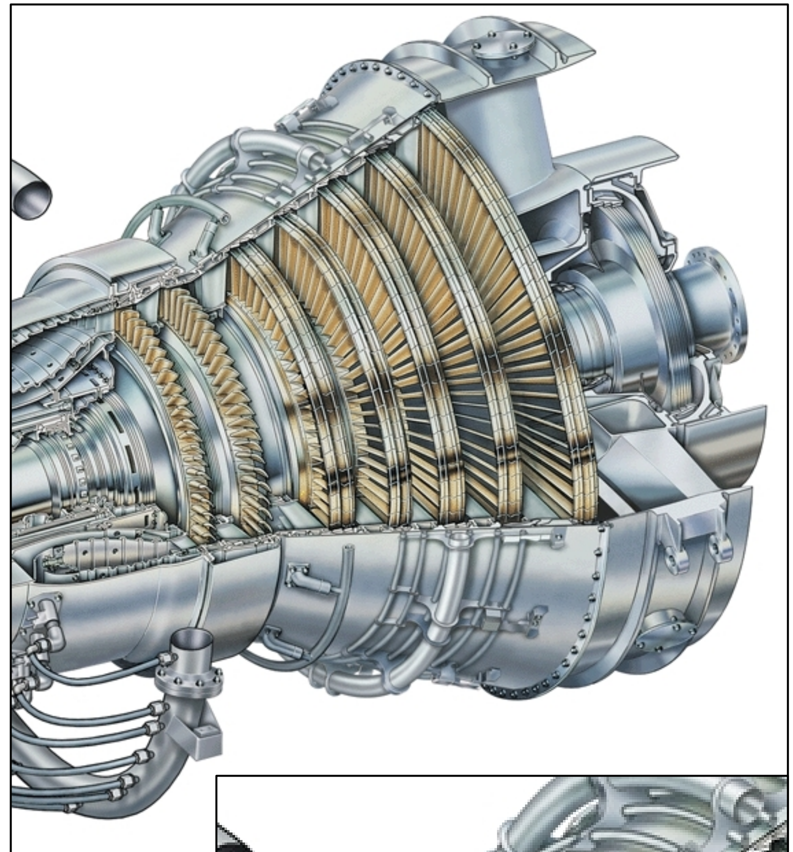
Usually a multi-stage axial design.

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.

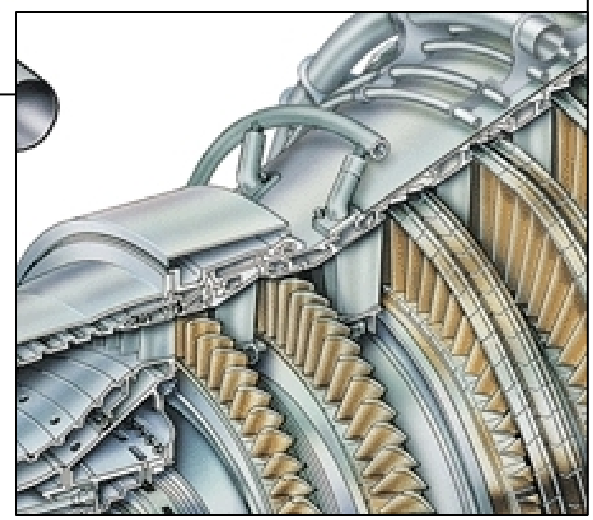


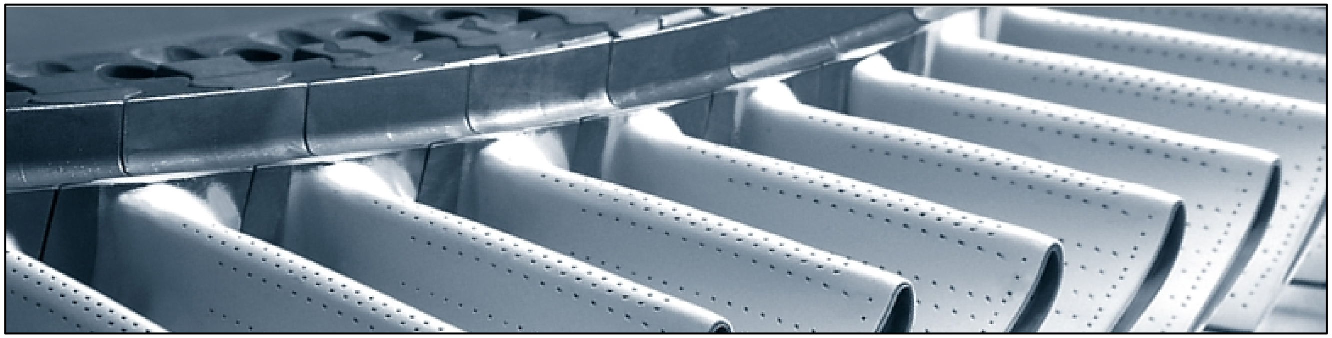


Plus, the rotating blade is required to survive under high centrifugal & mechanical stresses.

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.

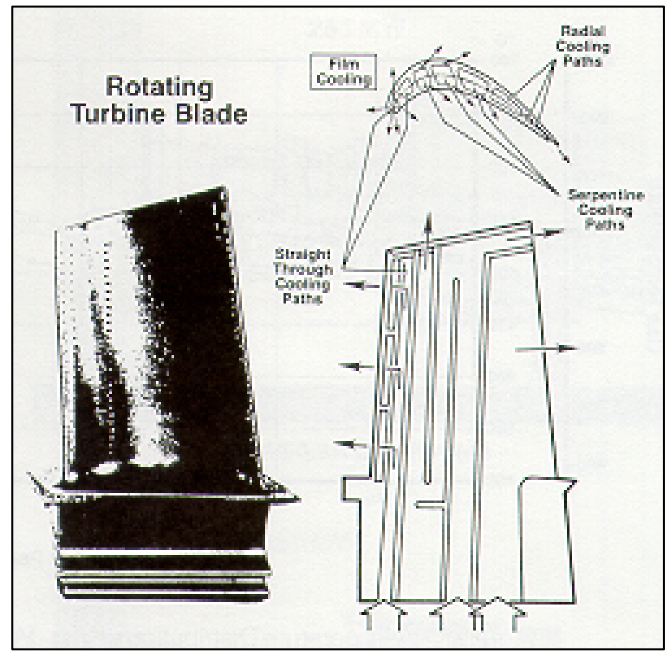




Turbine Section Blades & Discs:

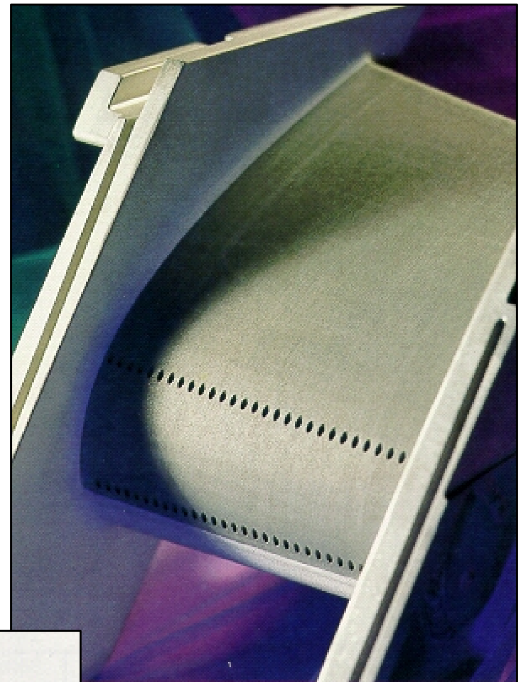
Creep-resistant directionally-solidified (DS) & single-crystal (SC) blade production technology – introduced from the aircraft / jet gas turbine world.

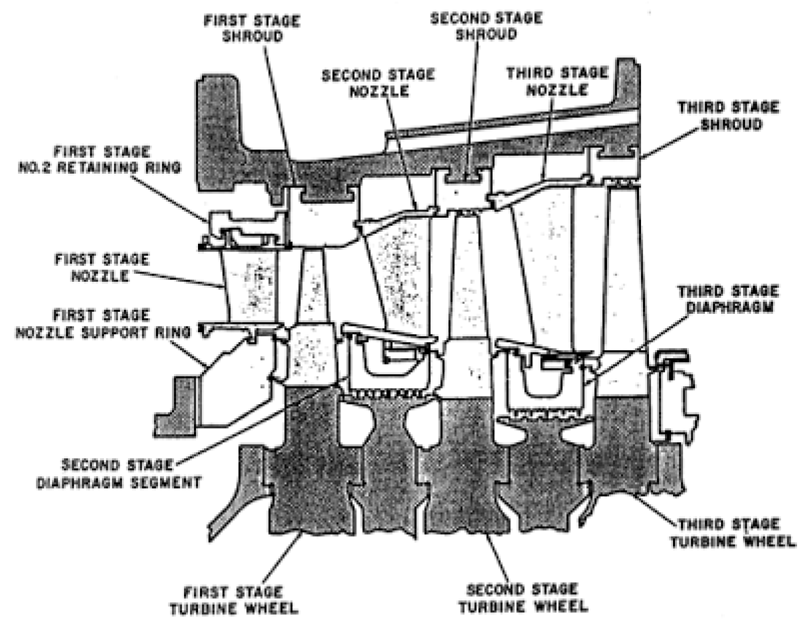
Thermal barrier coatings (TBC) employed to protect aerodynamic surfaces & materials from corrosion, oxidization and erosion.

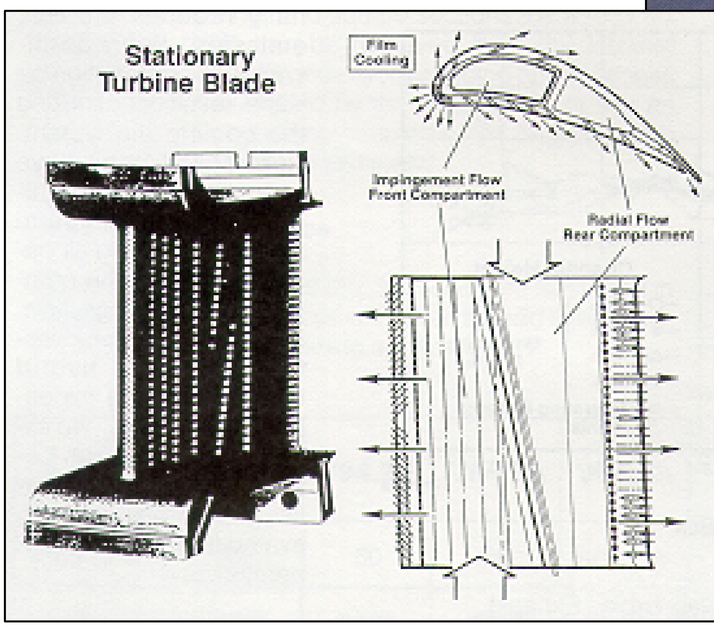


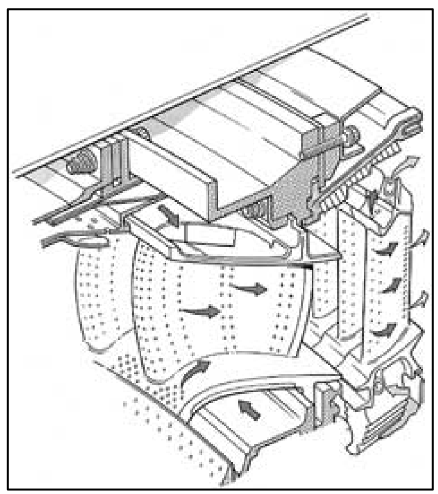
Turbine Section
Stationary Sections:
Turbine row assembly, showing blade attachments to the rotating disk, and blade cooling air exit holes

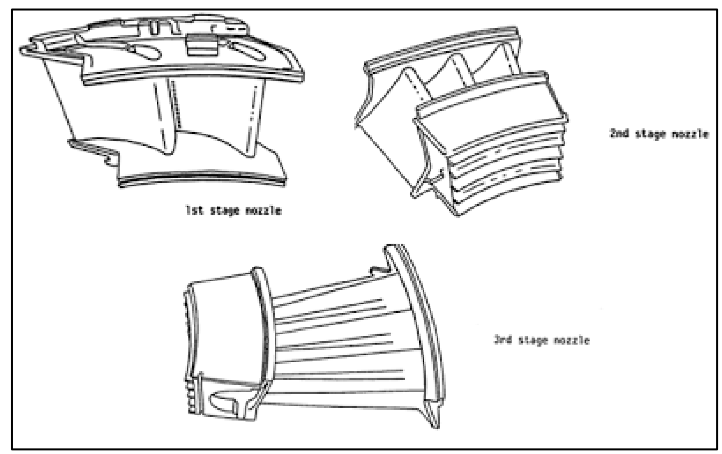
Turbine Nozzle w/ TBC & cooling air exit holes

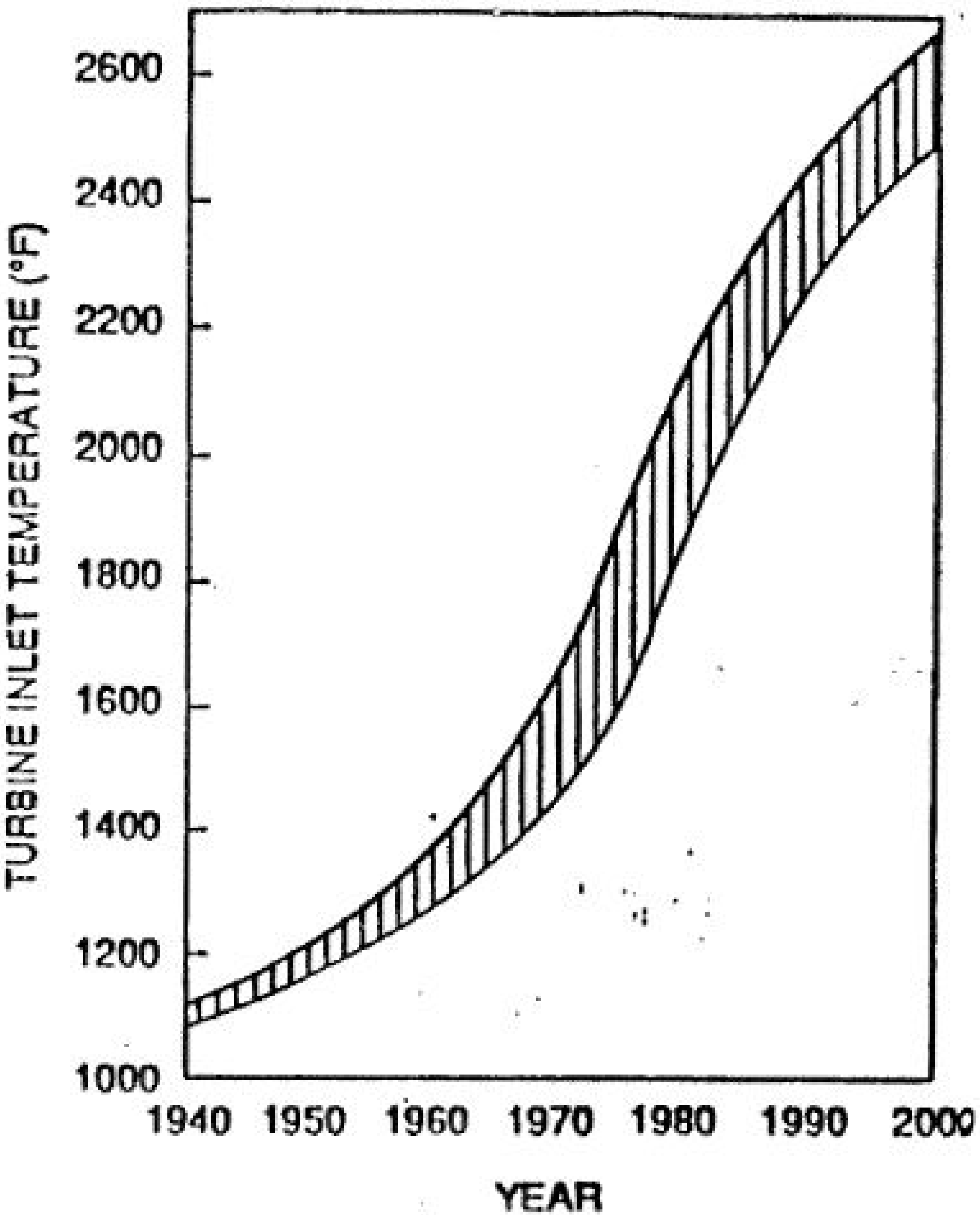




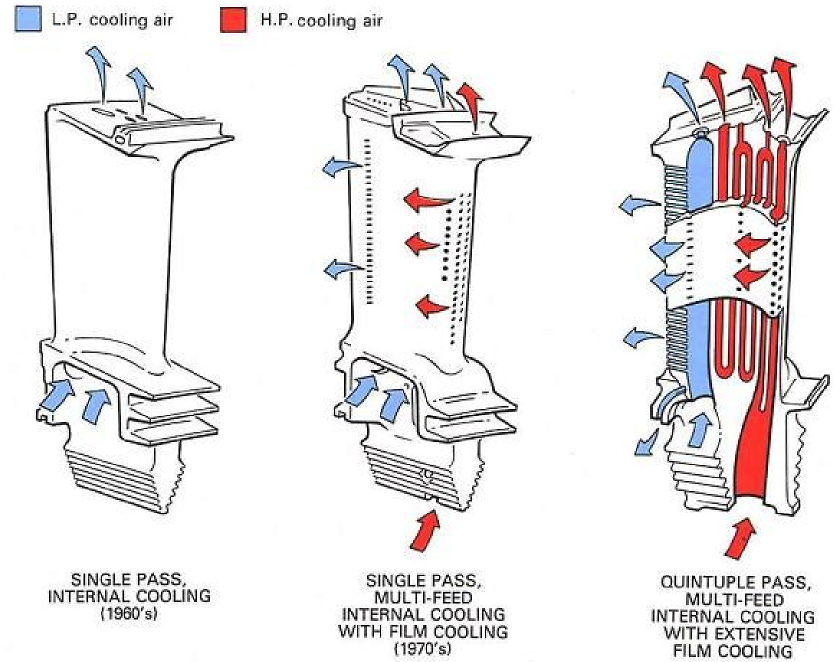


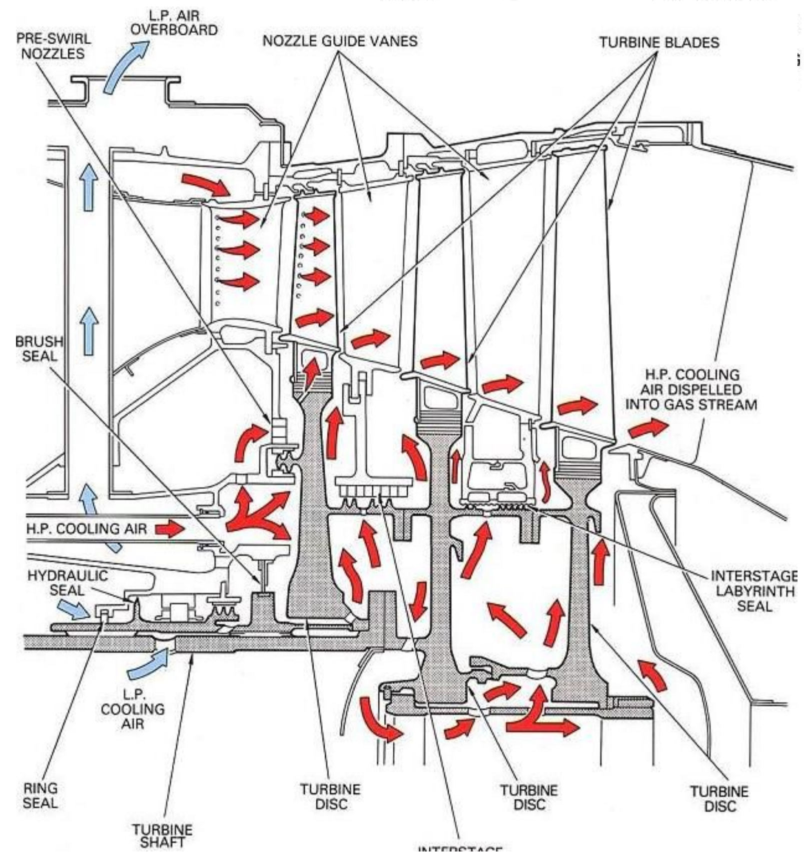




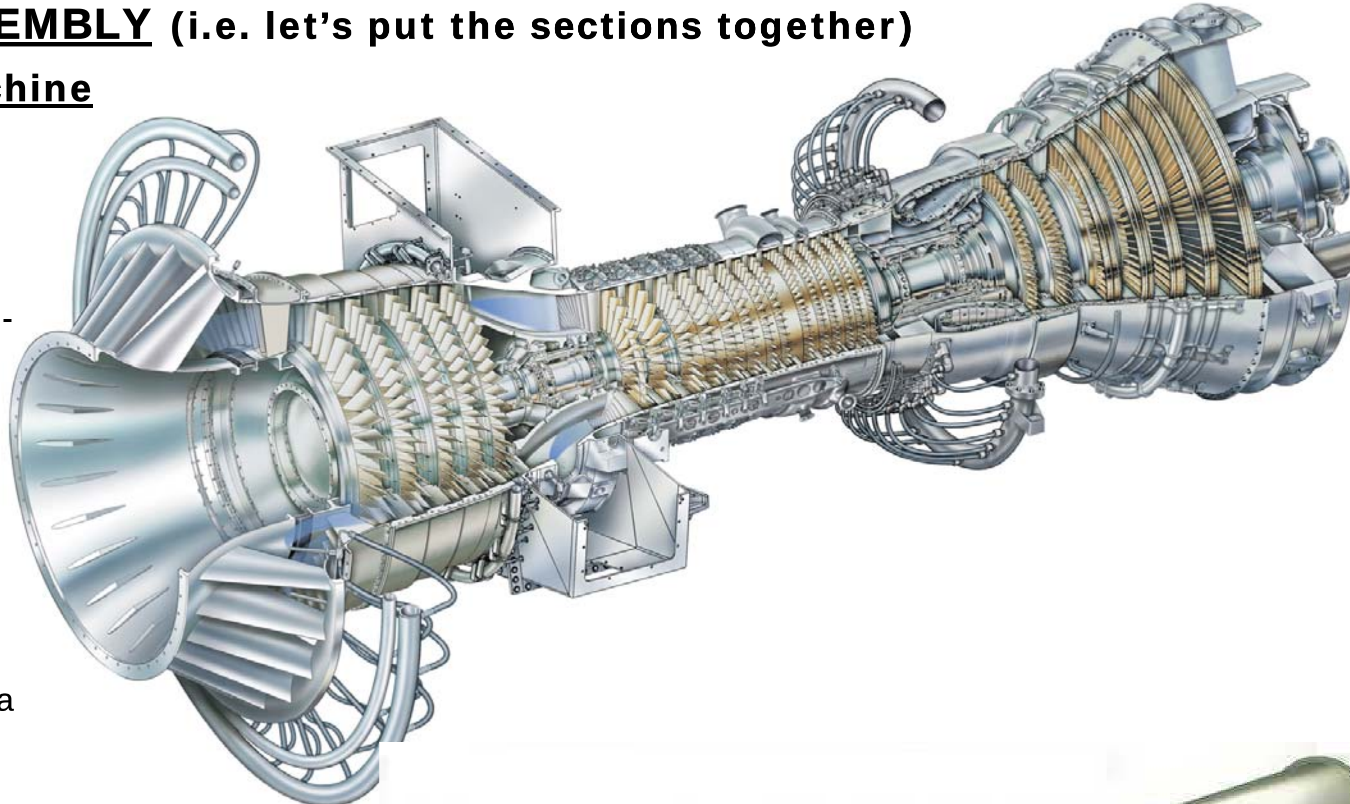


Gas Turbine Inlet Temperature Trend





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



The Basic Gas Turbine <u>Machine</u>

Individual **<u>Compressor</u>**, **<u>Combustor</u>** & **<u>Turbine</u>** 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.

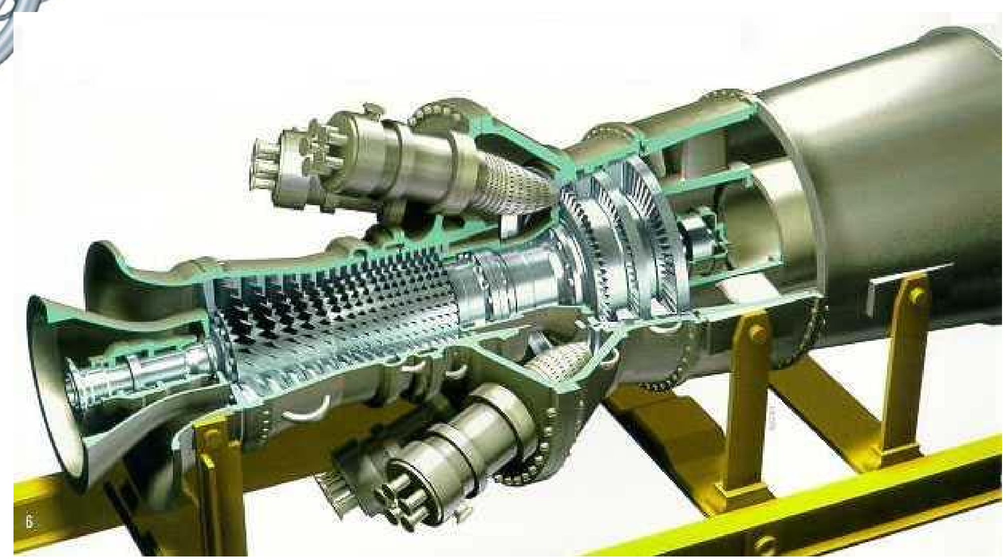
Compression power is provided by turbine section's power output. Excess turbine shaft power drives pump, compressor or generator via an output shaft:

- Cold-end drive
- Hot-end drive

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

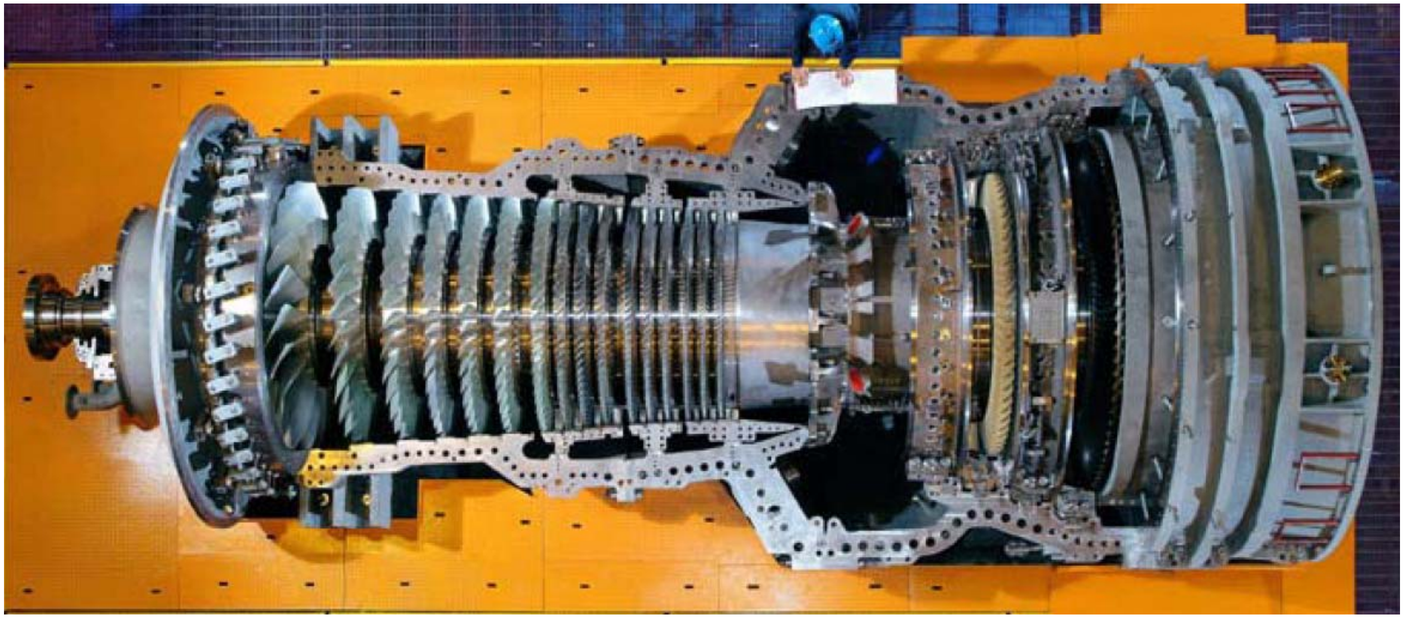
60~70% of the Turbine Section's power output is used by the Compressor Section to drive it.

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.

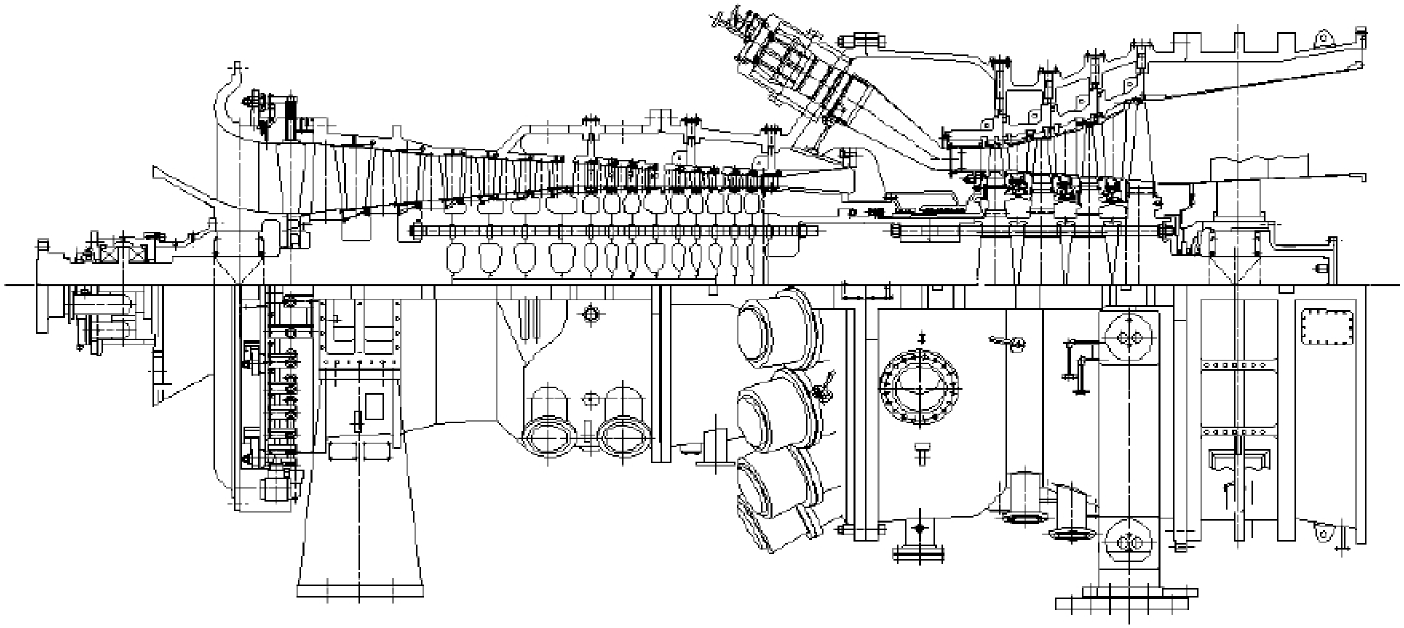


F-Class Gas Turbine Assembly
(175~225 MW)

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

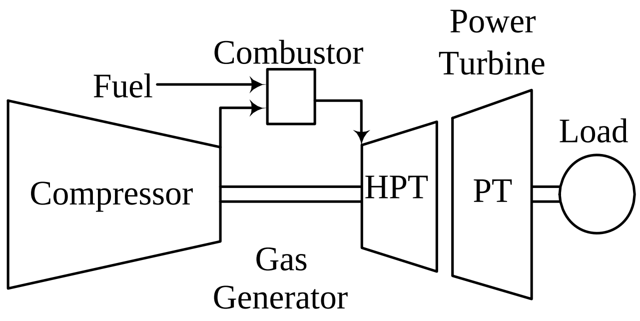


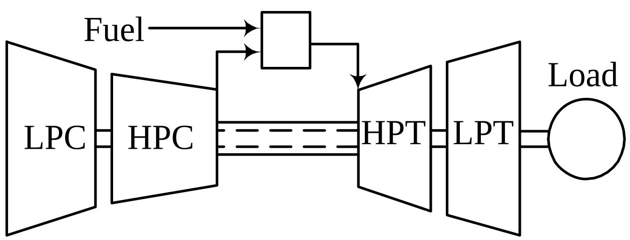
Gas Turbine Variations – from the single-shaft design

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

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.



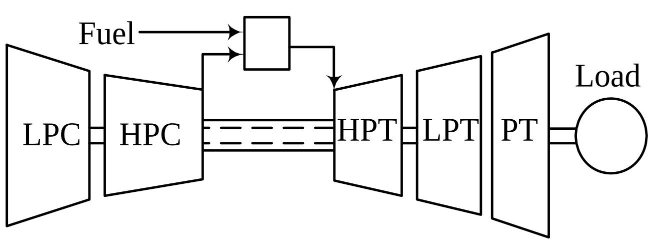


Multi-shaft, with & without PT

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).

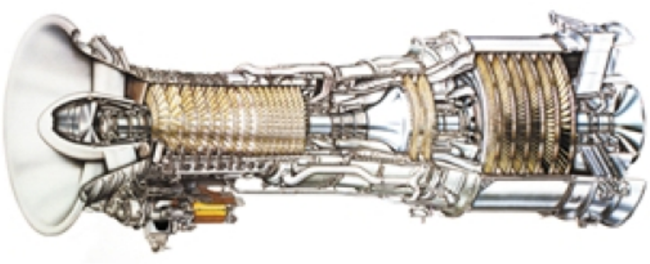
In some three-shaft machines, an intermediate compressor (IPC) & turbine (IPT) also used, in between LP & HP sections (configuration not shown).



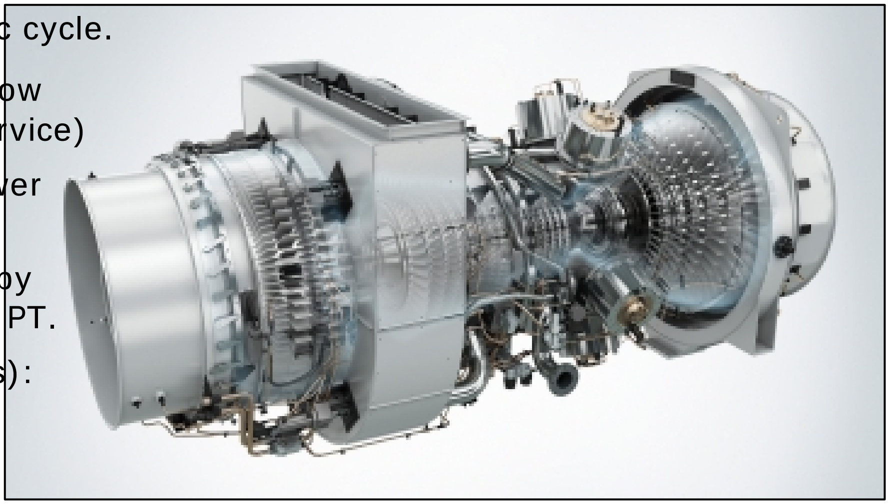
Fixed or variable-speed loads are driven off LP shaft.

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

In some cases, 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.

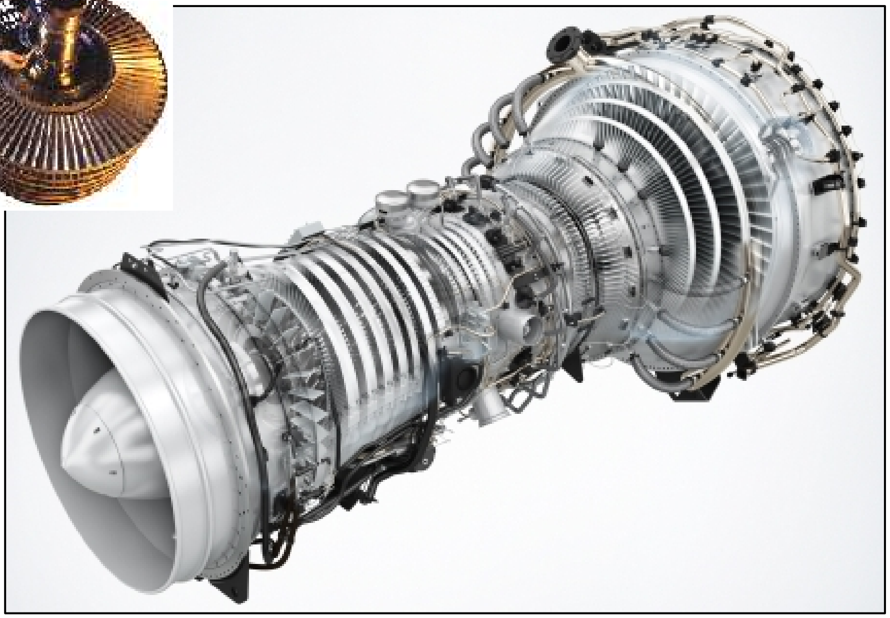
Major Maintenance – generally conducted by complete removal of gas turbine from package – special lifting frames required.

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.

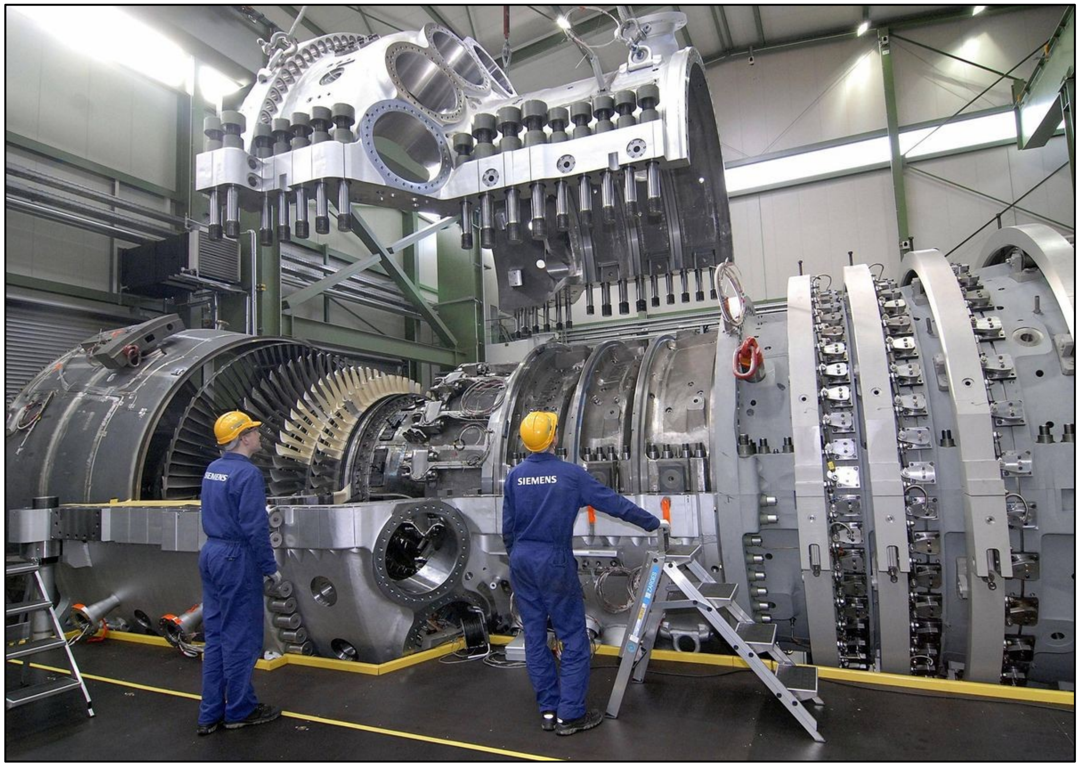
Lease engines available – replaces original engine while under repair.



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.

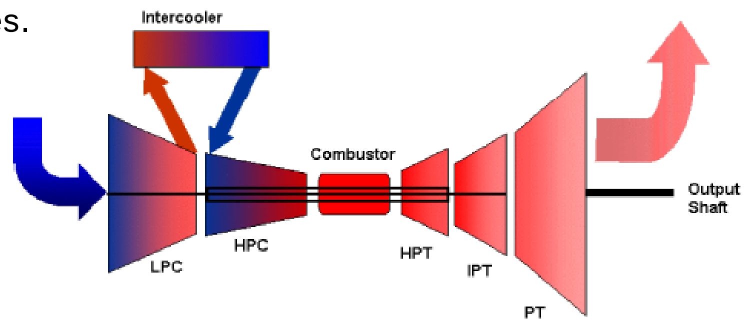
Major Maintenance – usually done at site**:**

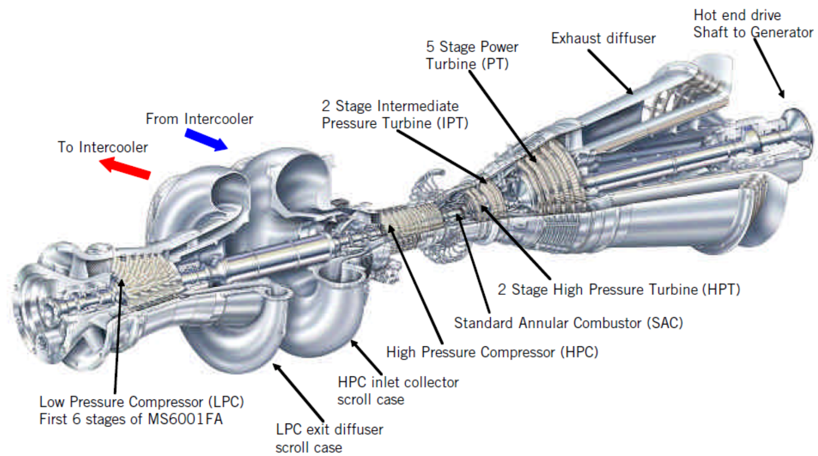
- removal of top half cylinder
- removal of diaphragms and blade rings
- lifting and removal of the turbine rotor
- subsequent blade removal.

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

	Aero-Derivative	**Heavy-Duty Industrial**
Performance	Up to 50~65 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

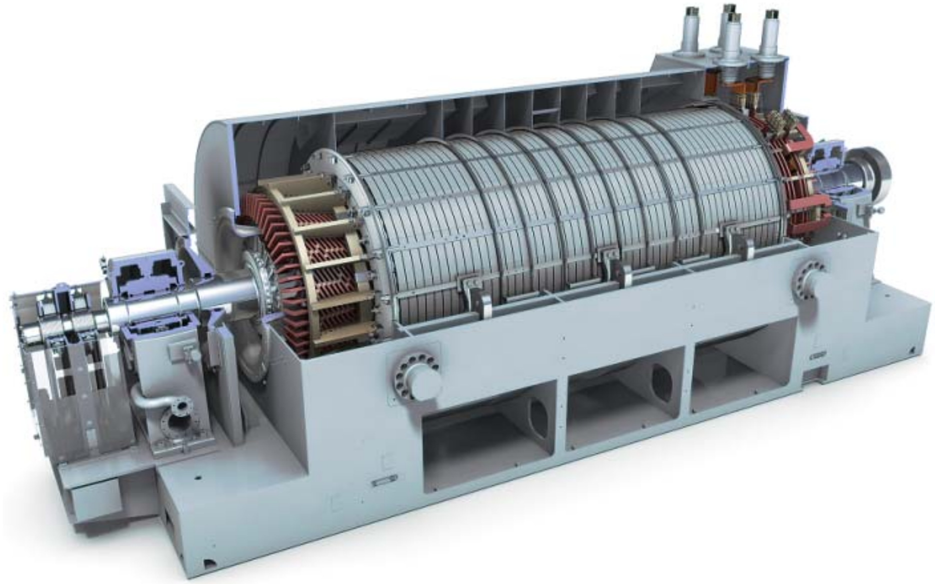
Some GT units like the GE LMS100 combine aero-derivative and heavy-duty industrial aspects, utilizing sections from their LM and industrial lines.





THE GAS TURBINE PACKAGE

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



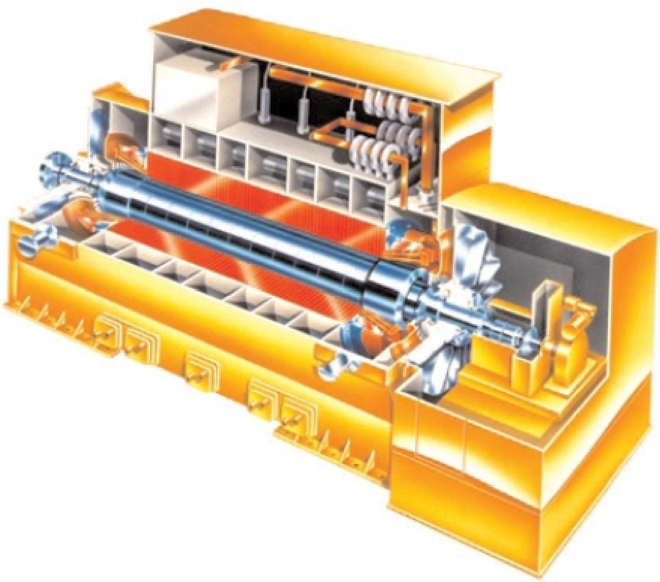
Driven Equipment

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).

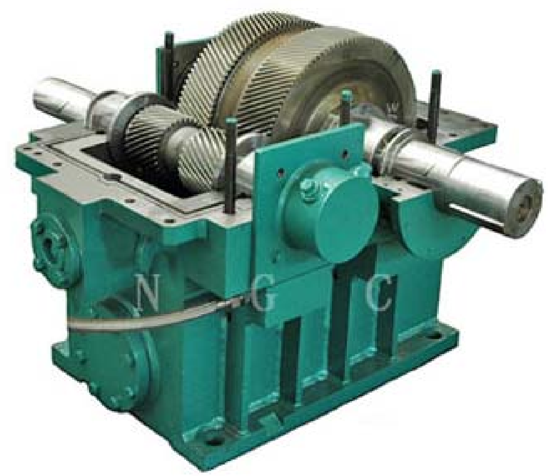


Generator output voltages:

- 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 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 bladepath

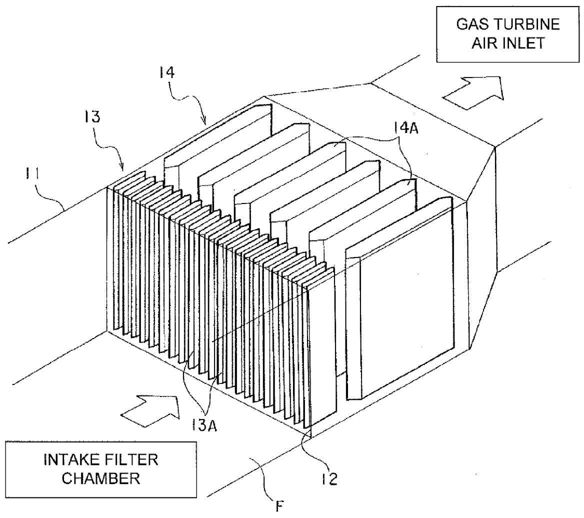
Inlet Air Heating: via coils or bleed air systems - for anti-icing; inlet temperature / performance optimization; DLE control

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



Lubricating Oil Systems

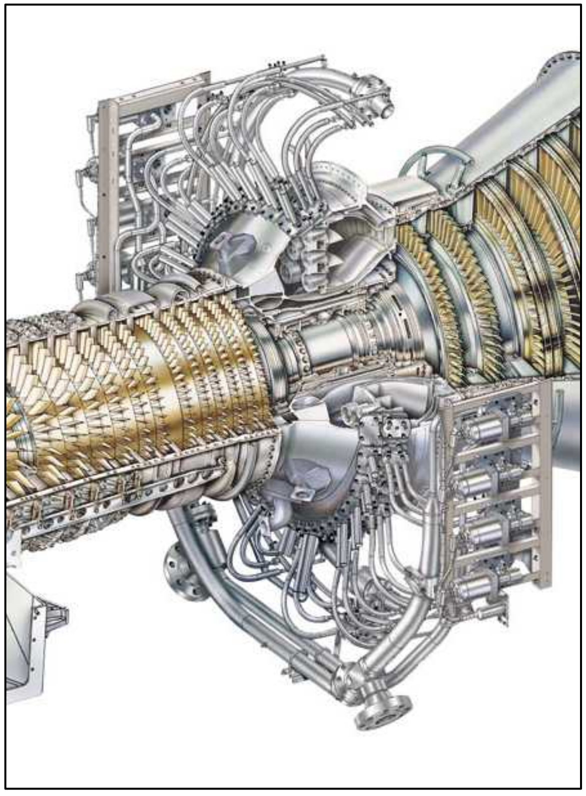
Main, auxiliary and emergency lubricating and control oil (as required) systems – provided for gas turbine and driven equipment.

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 – turbine, gearbox & generator.

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



Fuel Systems

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

Only the 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.

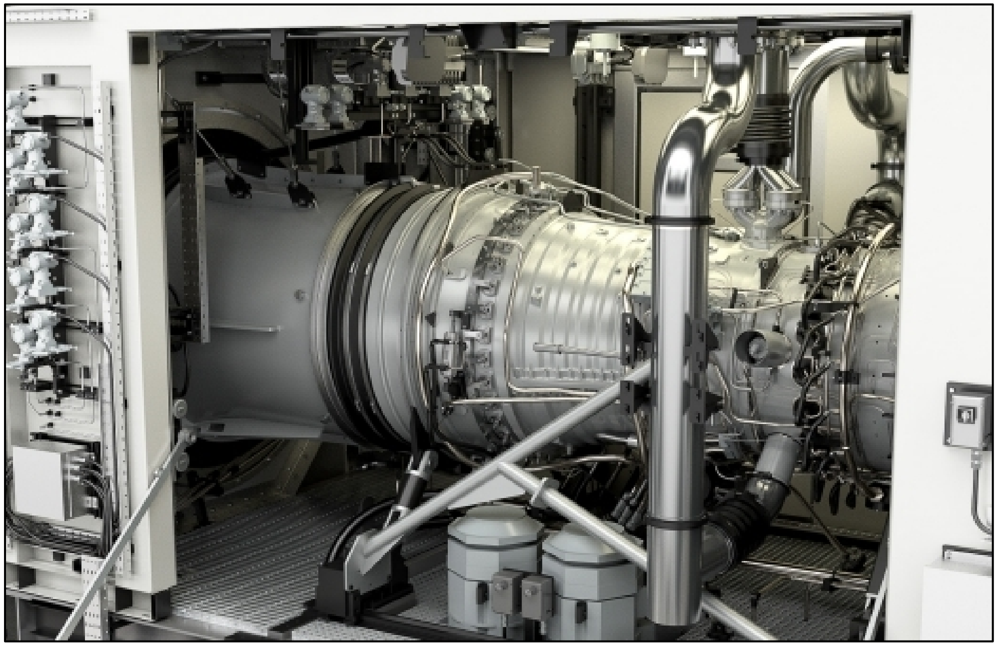
For natural gas duty – sometimes reciprocating or centrifugal gas compression equipment required, plus pulsation dampening equipment.

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

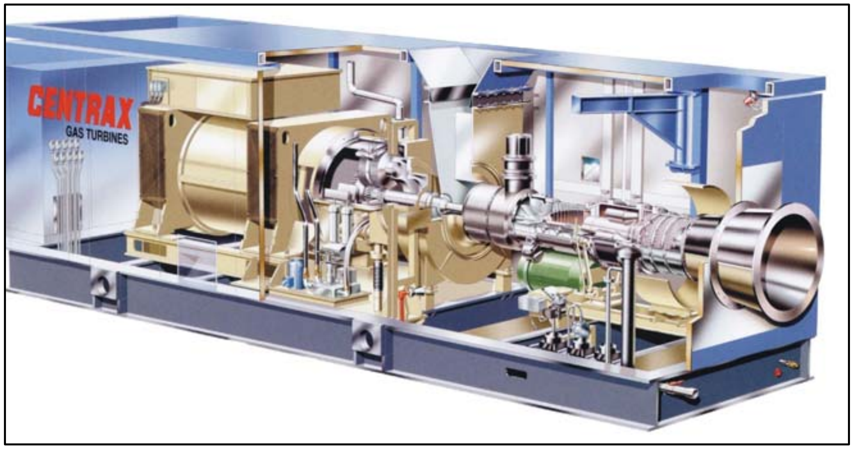
- pilot / ignition,
- primary,
- secondary and/or tertiary nozzle and basket sections (as applicable) of the DLE combustion system;

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

Acoustic and Weatherproof Enclosures



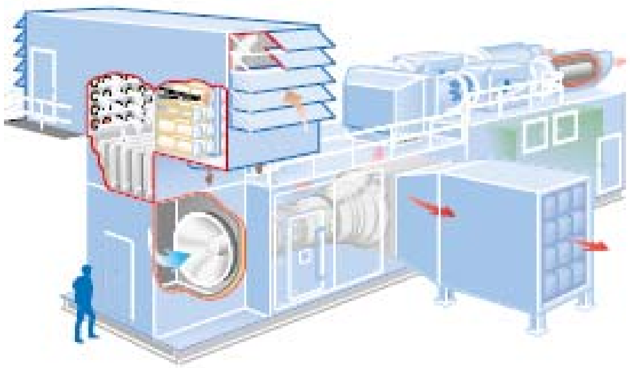
Most smaller industrial & almost all aero-derivative GTG packages are pre-packaged - complete drivetrain enclosed in acoustic enclosure(s); quicker & easier to install. The turbine & generator compartments are separately ventilated.



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.

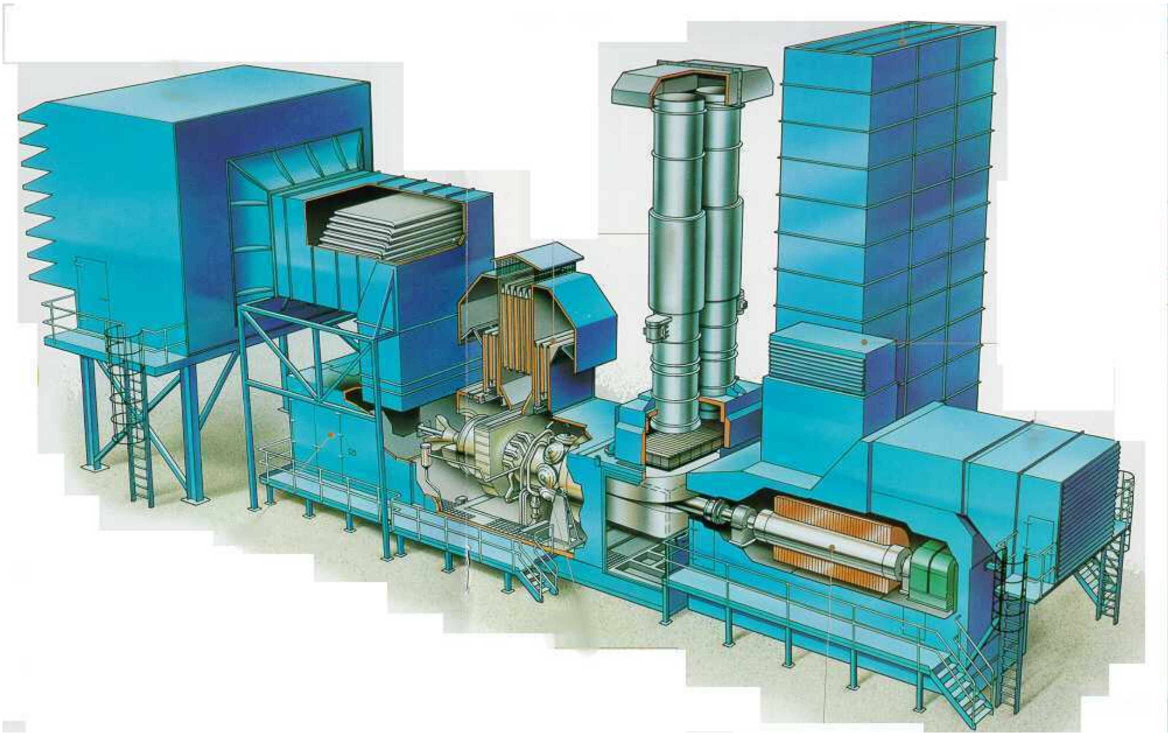


Controls and Monitoring

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 / var control
- breaker synchronization, relay protection
- auxiliaries
- vibration, temperature & pressure monitors
- sequence of events recorders
- certified metering systems
- communication to plant DCS.

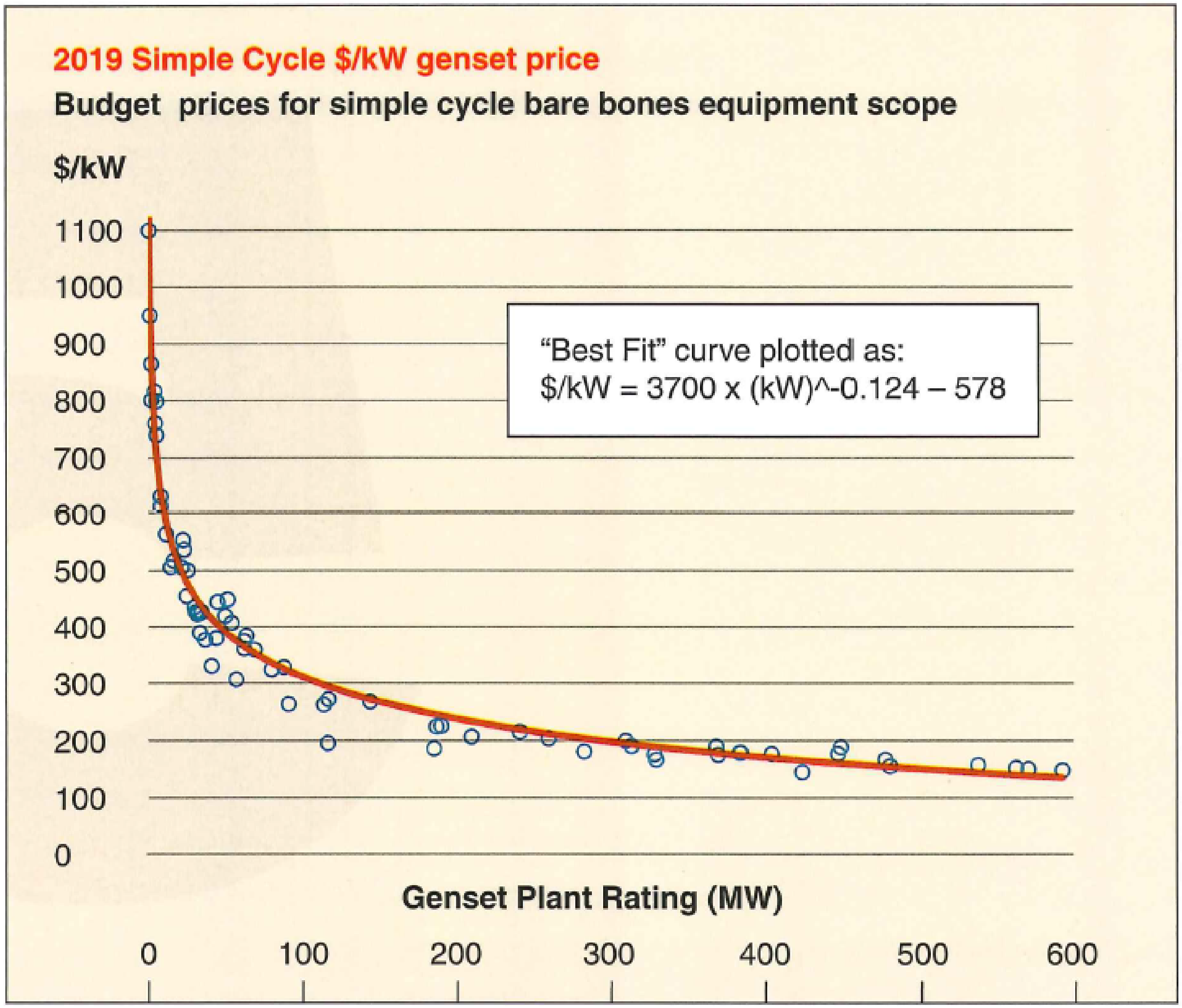


Miscellaneous Auxiliaries

- 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 CO_2 suppression systems
- battery and charger systems
- ventilation and heating
- exhaust expansion joint
- silencer & stack systems (simple-cycle)
- HRSGs for steam production (cogeneration or combined-cycle)

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

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



2019 Simple Cycle Genset Price

Equipment-only budget price for standard bare bones genset without add-on options

The price of a simple cycle gas turbine generator package depends on unit size, design technology (frame vs. aero) and scope of equipment supply.

Besides factors directly affecting manufacturer's costs, market dynamics also come into play in determining prices; continued depressed demand, especially for large utility units, has taken a toll.

GTW's simple cycle plant budgetary prices are based on standard bare bones single-fuel (gas only) packaged units. With none of the options and customized design features offered by OEMs at additional cost.

All prices are quoted in US dollars, FOB factory, for single-unit purchases. They are for equipment only, and do not cover transportation, plant engineering, construction, project-specific options or owner's project costs.

Price update

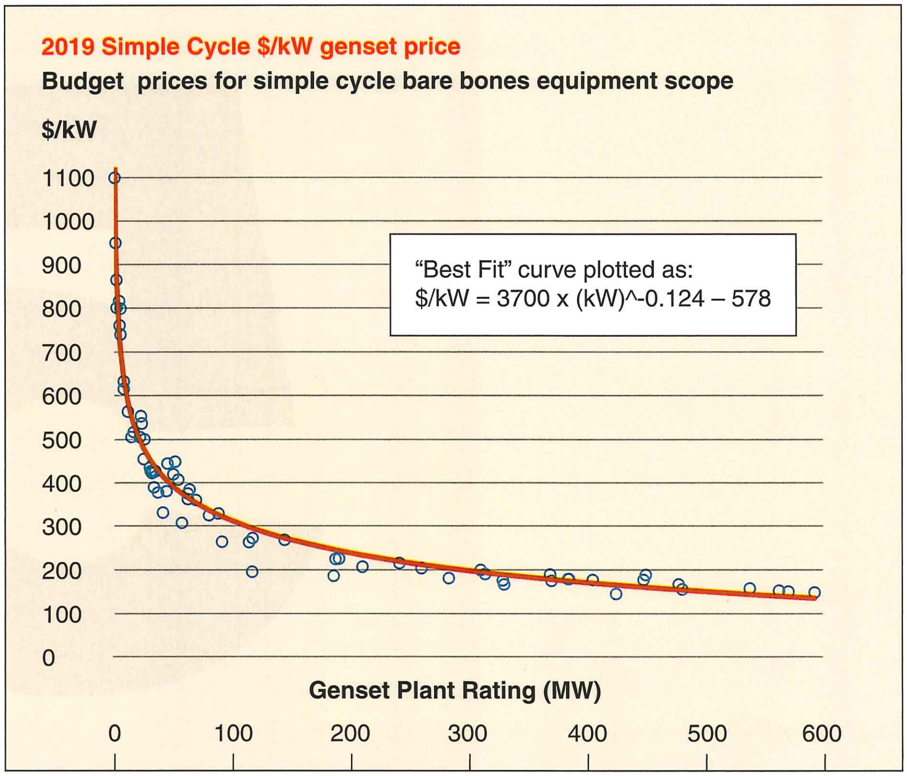
This year's estimated gas turbine prices generally show a steep reversal from last year's slight uptick. Depressed utility market environment, caused largely by increased use of renewable energy sources, has OEMs competing for a larger share of a smaller market.

Weapons include lower prices, lenient contract terms and financing, especially for large utility-sized units. Smaller industrial gensets are not seeing the same downward price pressures, especially with recovery of the oil & gas sector, promising an upturn in aeroderivative unit orders.

Continued low price levels for natural gas fuel, increased LNG supplies, and a steady flow of coal-plant retirements in North American and Europe help prop up the market and prices.

Overall, however, GTW estimates prices for large utility power generation units in 2019-2020 will decline upwards of 10% from those seen in 2017-2018.

This downward trend was forecast last year by GTW, considering the significant over-capacity of manufacturing space for larger gas turbines. The major OEMs have all announced strategic corrective measures including temporary shutdowns, permanent closures and repurposing factories.



Equipment scope

Limited to minimum scope of supply for simple cycle power generating plant packages built around a gas turbine, generator, associated mechanical and electrical auxiliaries, systems, operational control system. Scope includes:

- **Gas turbine.** Skid-mounted gas turbine engine, starting motor, reduction gearbox (if any), lube oil, hydraulic fluid and pneumatic systems, compressor water wash, fuel forwarding and control (w/o booster compressor), external turbine cooling (if any), interconnect piping.
- **Generator.** Standard air-cooled generator package; hydrogen or enclosed water-air cooling (TEWAC) options usually offered for larger units. Generator exciter is typically included in the standard package.
- **Balance of plant.** Standard auxiliaries such as air intake filter, inlet ducting and silencer, exhaust ducting and stack (short) with silencer, vibration monitoring, digital control system, mechanical and electrical auxiliary packages.

Acoustic enclosures for gas turbine, with ventilation and fire protection systems, are usually included.

Mechanical and electrical auxiliaries, essential for gas turbine and generator operation, are supplied in separate skid-mounted enclosures.

Mechanical packages include lube oil and hydraulic fluid, sumps, pumps, controls and coolers. Electrical auxiliaries include batteries, motor control center, voltage regulator and surge protection.

Auxiliary transformers for conditioning power supply for plant motors (starting, lube oil pump and cooling fans) are usually optional, as is main power step-up transformer.

Price and performance

Power output, heat rate and efficiency ratings in GTW simple cycle pricing tables are OEM-specified design ratings for base load operation at ISO standard (59°F ambient and sea level) conditions on natural gas fuel.

Estimated price ($ per kW), based on base load ratings, makes it possible to review and evaluate differences in equipment cost of similarly sized units.

A best-fit relationship between $-per-kW and kW rating for listed models is provided and plotted to assist in calculating the cost of comparably sized models not listed.

Besides unit size, other factors that enter GT package price are gas turbine type (i.e., frame vs. aero), standard design features (e.g., DLN combustion system, adjustable inlet guide vanes, etc.) and engineering design factors such as firing temperature and pressure ratio.

Higher $/kW prices of advanced class (G, H, J, etc.) units reflect more expensive materials and manufacturing processes. However, their increased power output capability more than offset the expense.

Bid quotes

Actual real-world OEM bid prices are quoted for customer-specified scope and with guarantees on net power and heat rate (efficiency) at site-specific conditions and specified fuel composition.

OEMs strategically hedge their bids with some performance margin, i.e. slightly lower power output and higher heat rate, to allow for normal variations in manufacturing tolerances and test uncertainties.

Quotes are always bid based on "factory new and clean" condition without allowance for degradation in performance with usage. Contract language usually specifies a limit in operating time before performance testing must be conducted.

Other factors entering into a project price quote include number of units ordered (i.e., quantity discounts), scope of equipment supply, site-specific requirements, duty cycle, geographic location and OEM's local market share position

Gas turbine gensets designed for onshore oil and gas pipeline operation typically are priced around 10% higher than industrial or utility power plants. Due to the cost of compliance with special packaging and safety requirements such as found in API specifications.

Offshore platform gas turbine packages command an additional price premium to cover costs such as specialized mountings and housing, marine-resistant coatings, and ultra-efficient intake filter systems designed to handle salt-water laden air.

Benchmark

This pricing section of the GTW Handbook serves as a benchmarking tool for assessing the equipment cost for different size and type plants.

To allow for uncertainties, the estimated budget prices should be treated as having a plus or minus 15% range of accuracy.

The data plot and best-fit curve show the strong relationship of cost to unit size, clearly displaying the economies of scale which allow OEMs to reduce manufacturing costs (per kW) as unit physical size and power ratings increase.

This effect is most pronounced with smaller units. For example, a 2MW plant may be priced at around $800 per kW compared to $500 per kW for a 10MW plant.

From around 20MW to 100MW, cost per kW falls less steeply, from around $500/kW to $300/kW.

Beyond 100MW, the $/kW trend continues to decrease gradually, down to around $200/kW. Even lower pricing is seen for the largest G, H and J class units where discounts of some 10%-20% may be observed compared to earlier F-class technology.

This is despite the higher cost of more exotic materials, manufacturing technologies, coatings and cooling techniques needed for machines operating in the 2700°F to 2900°F firing temperatures range. Result of significant economies gained by the increase in power output and power density achieved with these large 400-500MW-class units.

Data spread

Note that the spread in the pricing data for comparably rated units is due partly to the effect of 50Hz vs. 60Hz direct drive machines, where the 60Hz units are more compact (increased power density) due to higher engine operating speed, and to differences in design technology (aero vs frame machines).

Aeroderivative units cost considerably more ($/kW) than heavy frame units. Also, note that the data plot excludes the LMS100 series since their inclusion of an intercooler puts them in their own price class (see table), where a premium is paid for even higher efficiency than the typical aeroderivative genset.

Regardless of gas turbine design and rating, however, remember that the cost of engineering, construction services and other project costs can add from 60% to 100%, and more, to the cost of the equipment alone.

A practical rule of thumb is to double the equipment price for a rough estimate of the total installed cost. ■

2019 Simple Cycle Genset Price

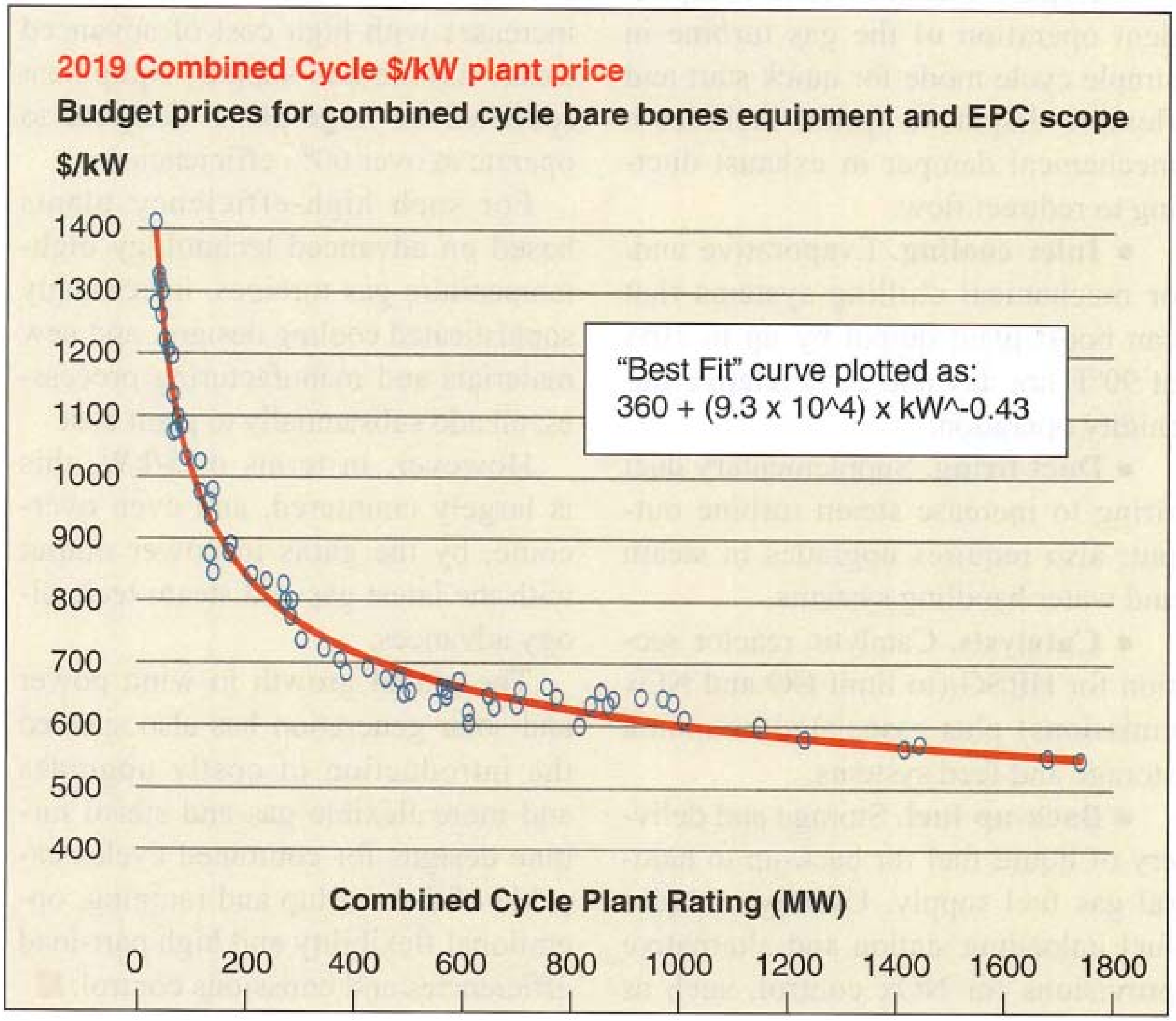
Equipment-only budget price for standard bare bones gas turbine genset without add-on options (in fixed 2019 dollars)

Gas Turbine Model	Freqency Hz	ISO Base Output	Heat Rate Btu/kWh	Efficiency	Budget Price	$/kW
C200	50/60	200 kW	10300 Btu	33.1%	$ 220,000	$ 1100
C1000S	50/60	1,000 kW	10300 Btu	33.1%	$ 950,000	$ 950
M1A-17D	50/60	1,810 kW	12160 Btu	28.1%	$ 1,450,000	$ 801
OP16-3C	50/60	1,850 kW	13800 Btu	24.7%	$ 1,600,000	$ 865
501-KB5S	50/60	3,980 kW	11504 Btu	29.7%	$ 3,250,000	$ 817
Centaur 50	50/60	4,600 kW	11630 Btu	29.3%	$ 3,500,000	$ 761
501-KB7S	50/60	5,380 kW	10570 Btu	32.3%	$ 4,300,000	$ 799
SGT-100	50/60	5,400 kW	11008 Btu	31.0%	$ 4,000,000	$ 741
SGT-300	50/60	7,901 kW	11158 Btu	30.6%	$ 5,000,000	$ 633
Taurus 70	50/60	7,965 kW	9955 Btu	34.3%	$ 4,900,000	$ 615
Mars 100	50/60	11,350 kW	10365 Btu	32.9%	$ 6,400,000	$ 564
SGT-400	50/60	14,326 kW	9647 Btu	35.4%	$ 7,250,000	$ 506
Titan 130	50/60	16,450 kW	9605 Btu	35.5%	$ 8,500,000	$ 517
Titan 250	50/60	21,745 kW	8775 Btu	38.9%	$ 11,000,000	$ 506
LM2500DLE	50	22,417 kW	9636 Btu	35.4%	$ 12,400,000	$ 553
LM2500DLE	60	23,200 kW	9317 Btu	36.6%	$ 12,450,000	$ 537
SGT-600	50/60	24,480 kW	10161 Btu	33.6%	$ 11,150,000	$ 455
1x FT8 SP25 DLN	50/60	25,455 kW	8960 Btu	38.1%	$ 12,750,000	$ 501
SGT-A35(GT62) DLE	50/60	29,845 kW	9089 Btu	37.5%	$ 13,000,000	$ 436
1 x FT8 SP30	50/60	30,892 kW	9327 Btu	36.6%	$ 13,200,000	$ 427
LM2500+ DLE	60	31,900 kW	8785 Btu	38.8%	$ 13,500,000	$ 423
RB211-GT61 DLE	50/60	32,130 kW	8681 Btu	39.3%	$ 13,750,000	$ 428
MS5002E	50/60	33,310 kW	9517 Btu	35.9%	$ 13,000,000	$ 390
LM2500+ G4 DLE	60	34,500 kW	8709 Btu	39.2%	$ 14,750,000	$ 428
SGT-750	50/60	37,031 kW	8456 Btu	40.4%	$ 14,000,000	$ 378
H-25	50/60	41,030 kW	9432 Btu	36.2%	$ 13,600,000	$ 331
6B.03	50/60	44,000 kW	10180 Btu	33.5%	$ 16,750,000	$ 381
LM6000PF DLE	60	45,000 kW	8097 Btu	42.1%	$ 20,000,000	$ 444
LM6000PF Sprint	60	50,000 kW	8109 Btu	42.1%	$ 21,000,000	$ 420
2xFT8 SP50 DLN	50/60	51,235 kW	8905 Btu	38.3%	$ 23,000,000	$ 449

Gas Turbine Model	Freqency Hz	ISO Base Output	Heat Rate Btu/kWh	Efficiency	Budget Price	$/kW
LM6000 SAC (57)	60	54,000 kW	8162 Btu	41.8%	$ 22,000,000	$ 407
SGT-800	50/60	57,000 kW	8502 Btu	40.1%	$ 17,500,000	$ 307
SGT-A65 DLE (TRENT)	50	61,900 kW	7874 Btu	43.3%	$ 23,250,000	$ 376
2xFT8 SP60	50/60	62,086 kW	9281 Btu	36.8%	$ 22,500,000	$ 362
LM9000	50/60	63,700 kW	8100 Btu	42.1%	$ 24,500,000	$ 385
1xFT4000 SP60	50/60	68,747 kW	8305 Btu	41.1%	$ 24,750,000	$ 360
AE64.3A	50/60	80,000 kW	9374 Btu	36.4%	$ 26,000,000	$ 325
6F.03	50/60	88,000 kW	9277 Btu	36.8%	$ 29,000,000	$ 330
7E.03	60	91,000 kW	10060 Btu	33.9%	$ 24,000,000	$ 264
M501DA	60	113,950 kW	9780 Btu	34.9%	$ 30,000,000	$ 263
LMS100 Wet	60	118,000 kW	7628 Btu	44.7%	$ 40,000,000	$ 339
SGT6-2000E	60	117,000 kW	9705 Btu	35.2%	$ 31,900,000	$ 273
H-100	50	116,450 kW	8909 Btu	38.3%	$ 22,800,000	$ 196
M701DA	50	144,090 kW	9810 Btu	34.8%	$ 38,600,000	$ 268
AE94.2	50	190,000 kW	9400 Btu	36.3%	$ 43,000,000	$ 226
M501F	60	185,400 kW	9230 Btu	37.0%	$ 34,500,000	$ 186
SGT5-2000E	50	187,000 kW	9426 Btu	36.2%	$ 42,000,000	$ 225
GT13E2	50	210,000 kW	8980 Btu	38.0%	$ 43,500,000	$ 207
7F.05	60	241,000 kW	8580 Btu	39.8%	$ 52,000,000	$ 216
SGT6-5000F	60	260,000 kW	8530 Btu	40.0%	$ 53,000,000	$ 204
M501GAC	60	283,000 kW	8531 Btu	40.0%	$ 51,200,000	$ 181
SGT6-8000H	60	310,000 kW	<8530 Btu	40.0%	$ 62,000,000	$ 200
9F.05	50	314,000 kW	8930 Btu	38.2%	$ 60,000,000	$ 191
SGT5-4000F	50	329,000 kW	8322 Btu	41.0%	$ 58,000,000	$ 176
M501J	60	330,000 kW	8105 Btu	42.1%	$ 55,000,000	$ 167
GT26	50	370,000 kW	8322 Btu	41.0%	$ 65,000,000	$ 176
GT36-S6	60	369,000 kW	8067 Btu	42.3%	$ 70,000,000	$ 190
7HA.02	60	384,000 kW	8009 Btu	42.6%	$ 69,000,000	$ 180
M701F	50	385,000 kW	8144 Btu	41.9%	$ 68,900,000	$ 179
SGT6-9000HL	60	405,000 kW	8010 Btu	42.6%	$ 72,000,000	$ 178
M501JAC	60	425,000 kW	7775 Btu	44.0%	$ 61,900,000	$ 146
M701JAC	50	448,000 kW	7755 Btu	44.0%	$ 79,500,000	$ 177
SGT5-8000H	50	450,000 kW	<8322 Btu	>41 %	$ 85,000,000	$ 189
M701J	50	478,000 kW	8067 Btu	42.3%	$ 79,700,000	$ 167
SGT5-8000HL	50	481,000 kW	8034 Btu	42.5%	$ 75,000,000	$ 156
GT36-S5	50	538,000 kW	7972 Btu	42.8%	$ 85,000,000	$ 158
M701JAC (2015)	50	563,000 kW	7826 Btu	43.6%	$ 85,900,000	$ 153
9HA.02	50	571,000 kW	7740 Btu	44.1%	$ 86,000,000	$ 151
SGT5-9000HL	50	593,000 kW	7972 Btu	42.8%	$ 88,000,000	$ 148

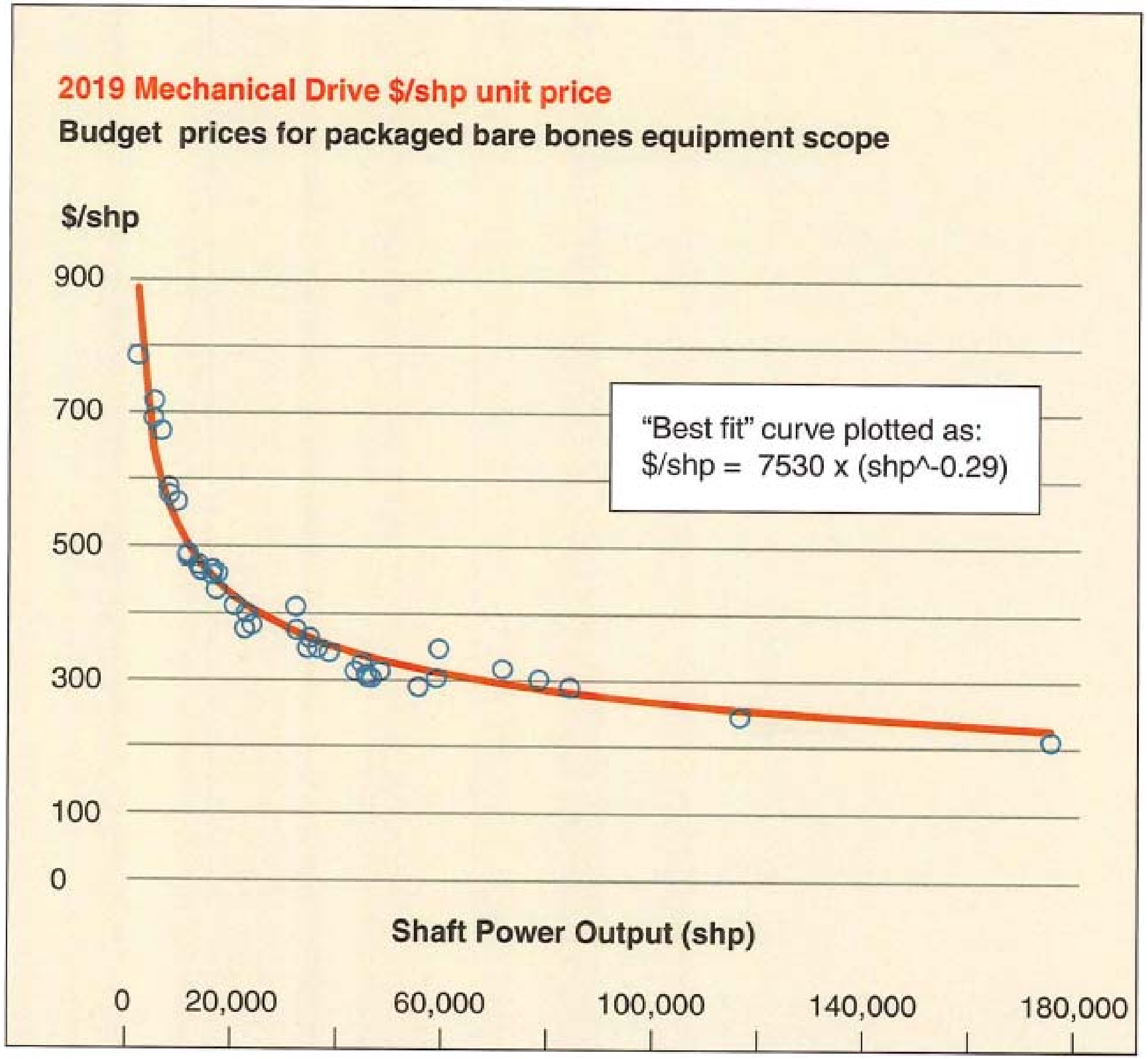
GAS TURBINE PRICING - from the *2019 Gas Turbine Handbook*© ($USD)

Combined-Cycle (CCGT) Prices – approximately the project cost for a “reference plant” without typical options and site specific factors.



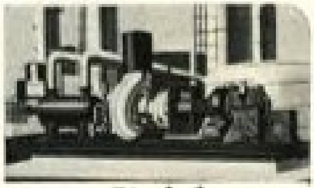
GAS TURBINE PRICING - from the *2019 Gas Turbine Handbook*© ($USD)

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

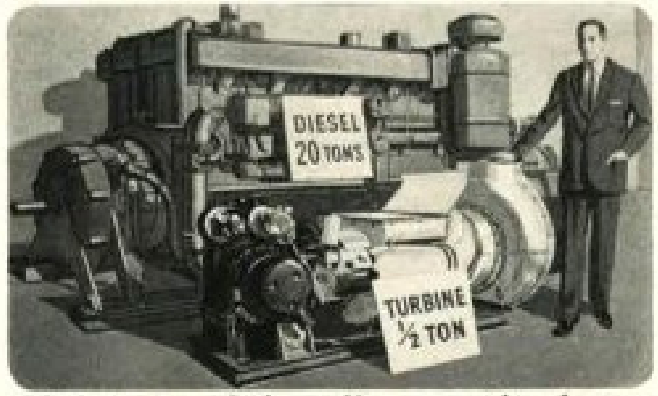
Gasoline—any kind.



Diesel oil

Kerosene.

Natural gas.



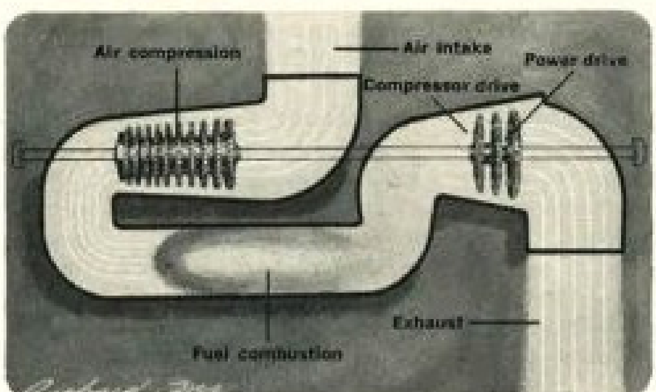
The Jupiter is completely portable—saves weight and space.

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.

SOLAR
AIRCRAFT COMPANY
SAN DIEGO
DES MOINES

2200 PACIFIC HIGHWAY • SAN DIEGO 12, CALIFORNIA