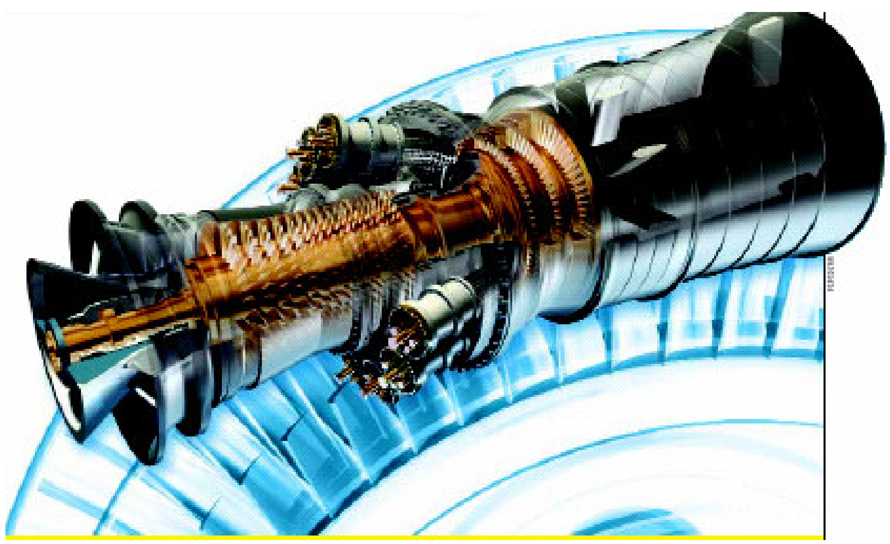
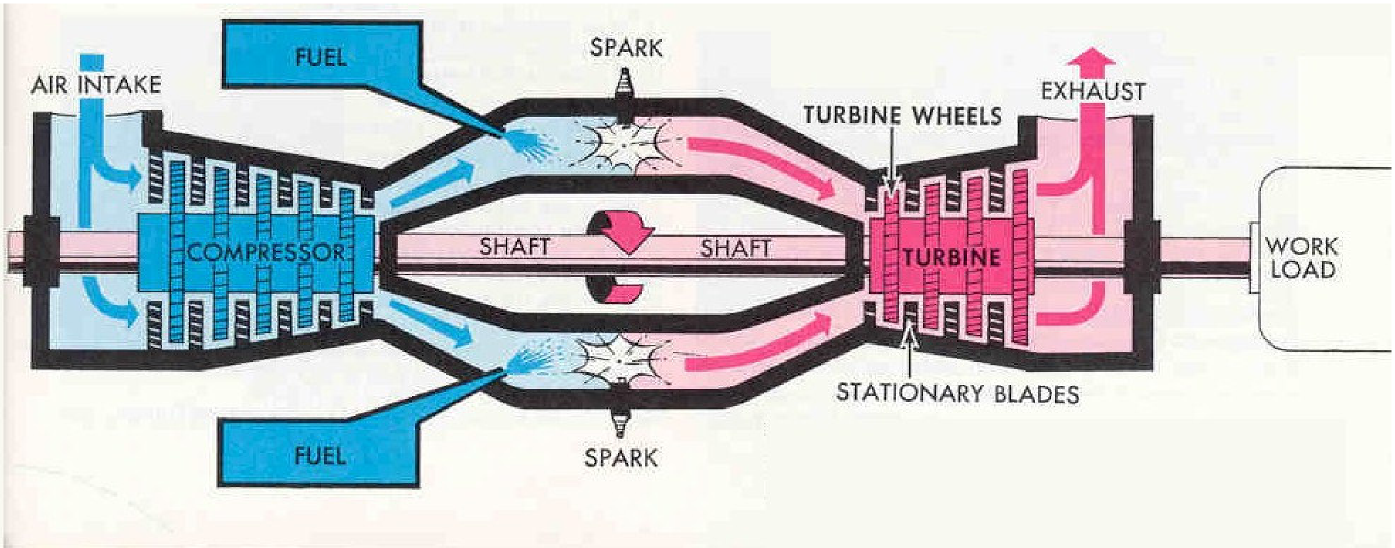
GAS TURBINES

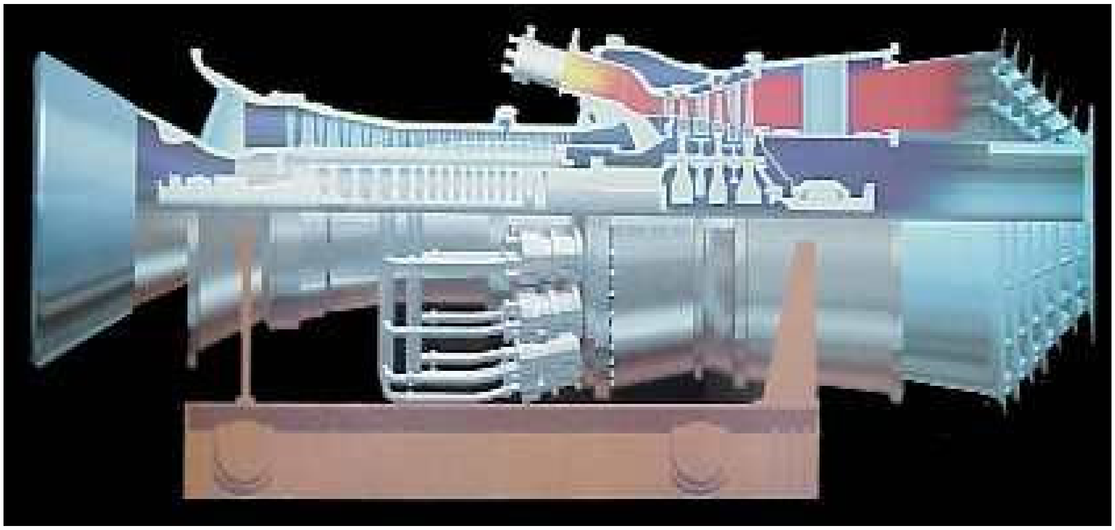
An Introduction

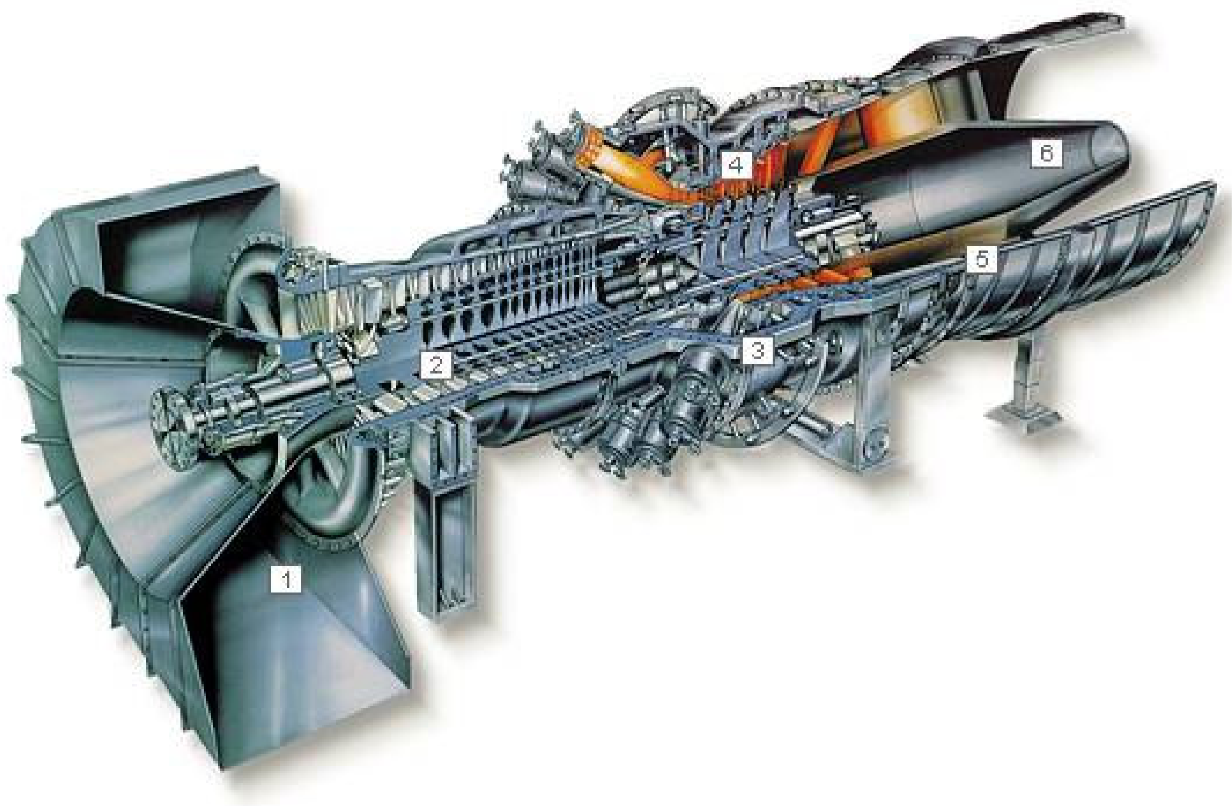


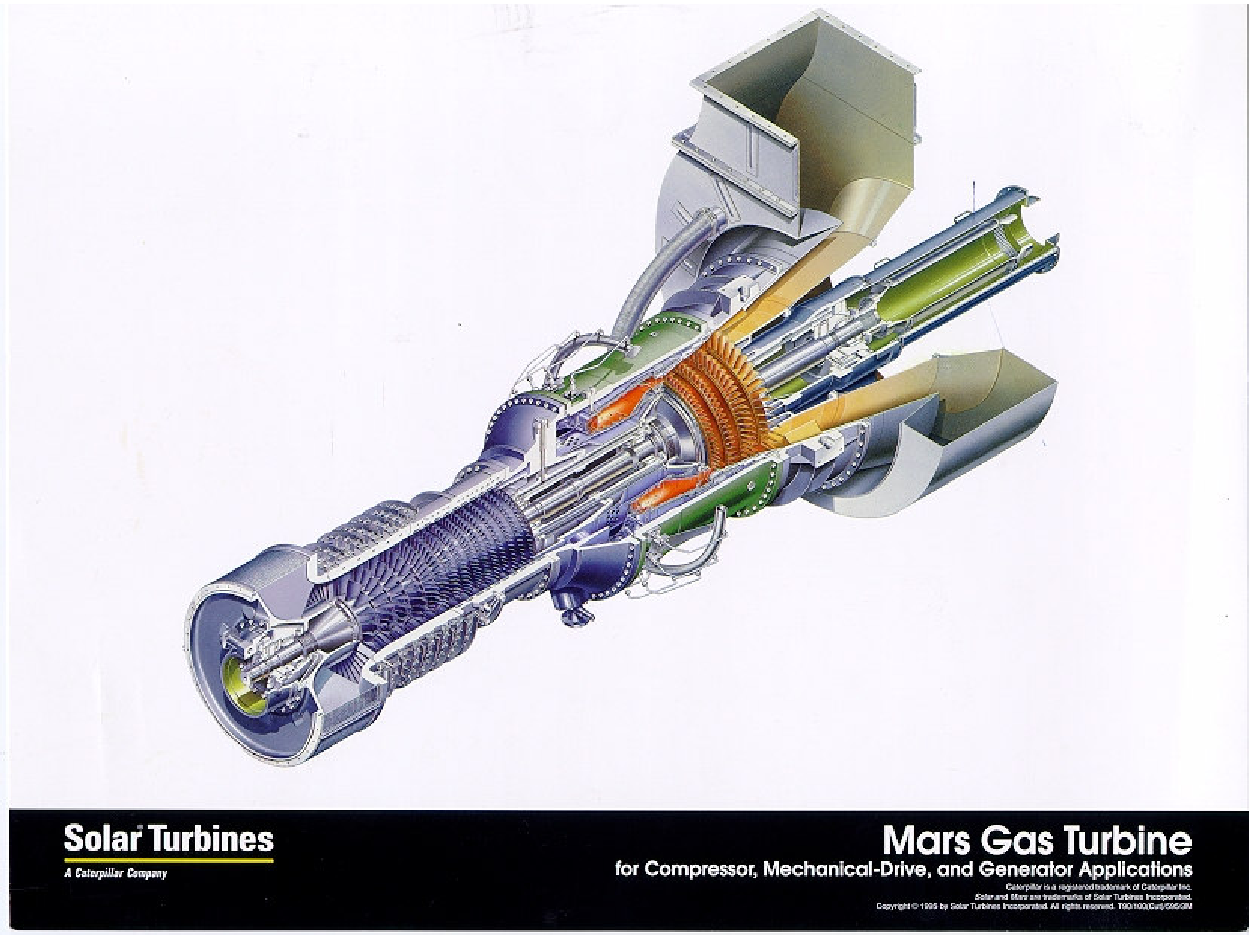
CONTENTS



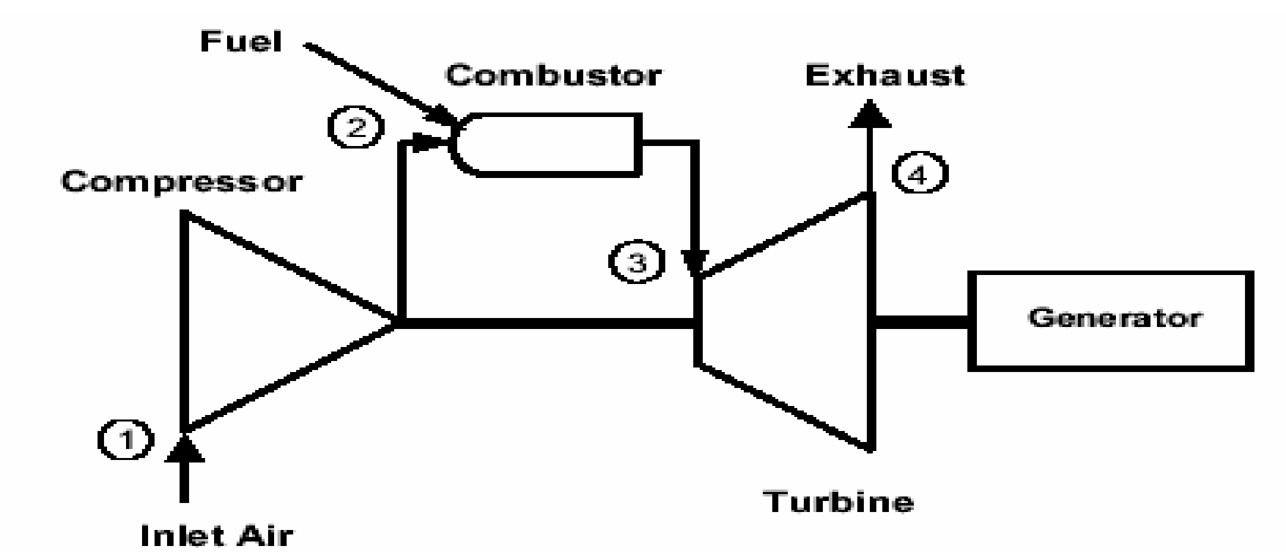
In a Gas Turbine, a compressor forces air into a combustion chamber where it mixes with fuel. A spark ignites the fuel-air mixture, creating hot high-pressure gas that powers the turbine.



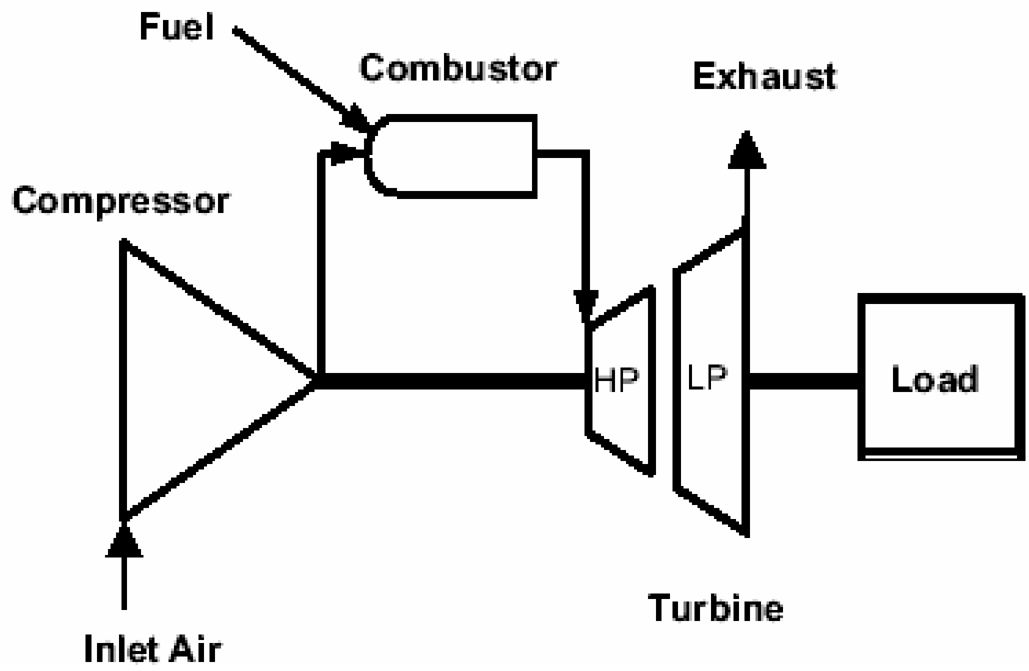

1
2
3
4
5
6



Simple-cycle, single-shaft Gas turbine



Simple-cycle, Twin-shaft Gas turbine



Gas turbine thermodynamics

- Air enters the axial flow compressor at point 1 at ambient conditions.
- These conditions vary from day to day and from location to location. Hence Turbine Industry uses standard ISO conditions for comparative purposes.

  Inlet Temp 59 F/15 C
  Inlet Pressure 14.7 psia/1.013 bar
  60% relative humidity

- Air entering the compressor at point 1 is compressed to some higher pressure. No heat is added; however, compression raises the air temperature so that the air at the discharge of the compressor is at a higher temperature and pressure.
- The air enters the combustion system at point 2, where fuel is injected and combustion occurs.
- The combustion process occurs at essentially constant pressure.

- Although high local temp. are reached within the primary combustion zone (approaching stoichiometric conditions), the combustion system is designed to provide mixing, burning, dilution and cooling.

- Thus, by the time the combustion mixture leaves the combustion system and enters the turbine at point 3, it is at a mixed average temperature.

- In the turbine section of the gas turbine, the energy of the hot gases is converted into work. This conversion actually takes place in two steps.

- In the nozzle section of the turbine, the hot gases are expanded and a portion of the thermal energy is converted into kinetic energy.

- In the subsequent bucket section of the turbine, a portion of the kinetic energy is transferred to the rotating buckets and converted to work.

- Some of the work developed by the turbine is used to drive the compressor, and the remainder is available for useful work at the output flange of the gas turbine. Typically, more than 50% of the work developed by the turbine sections is used to power the axial flow compressor.

- Single-shaft gas turbines are configured in one continuous shaft and, therefore, all stages operate at the same speed. These units are typically used for generator drive applications where significant speed variation is not required.

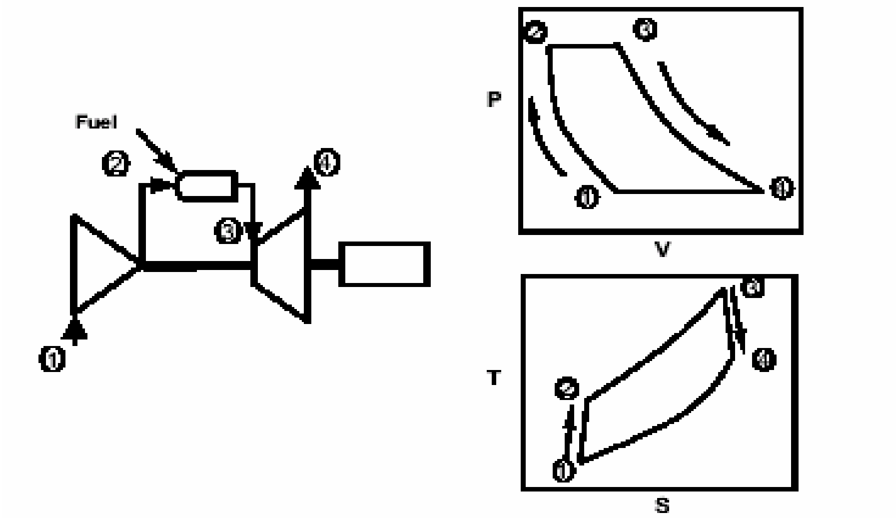
- Simple-cycle, twin shaft gas turbine is typically used for Mechanical drive applications.
- The LP or power turbine rotor is mechanically separate from the HP turbine and compressor rotor. The LP rotor is said to be aerodynamically coupled.

- This unique feature allows the power turbine to be operated at a range of speeds and makes two shaft gas turbines ideally suited for variable speed applications.

- All of the work developed by the power turbine is available to drive the load equipment since the work developed by the high-pressure turbine supplies all the necessary energy to drive the compressor.

- On two-shaft machines the starting requirements for the gas turbine load train are reduced because the load equipment is mechanically separate from the high-pressure turbine.

Thermodynamic Cycle



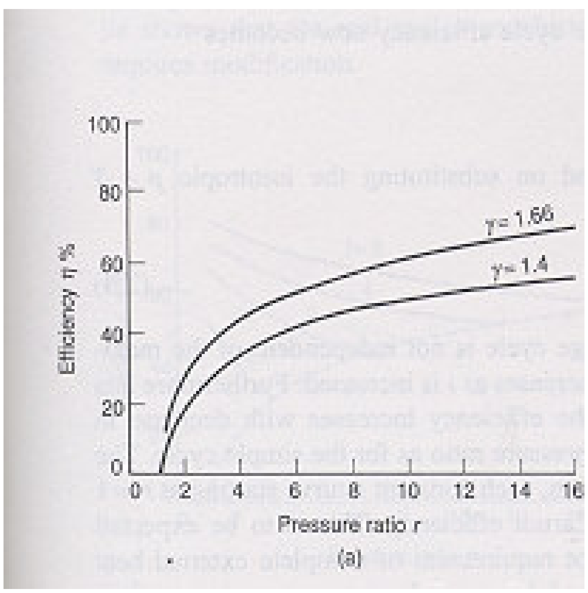
- Shows the four primary states on a gas turbine.
- The systems operation is treated as a cycle, the Brayton cycle.
- The air enters the compressor at state 1. As the air travels through the compressor, which consists of many section called stages, it's pressure and temperature increase.
- At state 2 the air leaves the compressor and enters the combustor. Inside the combustor the air is mixed with fuel and ignited. This results in a constant pressure heating of the combustion products.
- These products exit the combustor at a high temperature and enter the turbine at state 3. While traveling through the turbine, the thermal/potential energy of the combustion products is transformed into mechanical work. A portion of this work is used to drive the compressor while the majority is output to whatever the turbine package is connected to. The combustion products exit the turbine at state 4.
- For an ideal Brayton cycle the following equations are used for first law analyses:
  Turbine work = $h3 - h4$
  Combustor work = $h3 - h2$
  Compressor work = $h2 - h1$
  Cycle output = $(h3 - h4 - h2 + h1)$

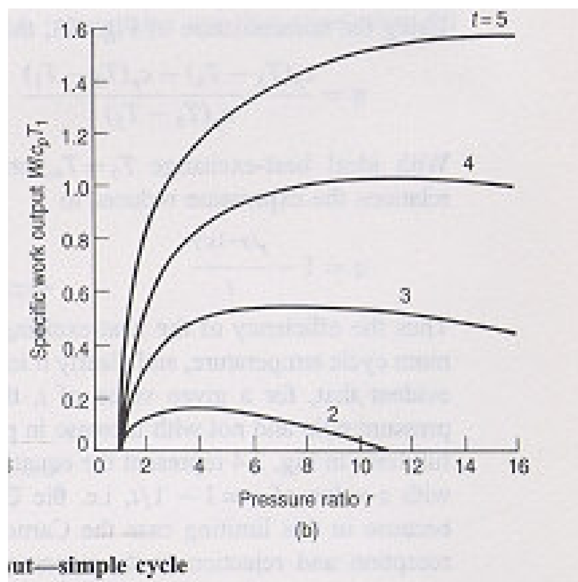
- Thermal efficiency
  (Net cycle Output/Heat supplied)

$$\eta = \frac{cycle \cdot output}{h_3 - h_2}$$

$$ThermalEfficiency = 1 - \frac{1}{[p_2 / p_1]^{(\frac{k-1}{k})}}$$

h = enthalpy at given state, kJ/kg
p = pressure at given state, N/m^2
k = specific heat ratio



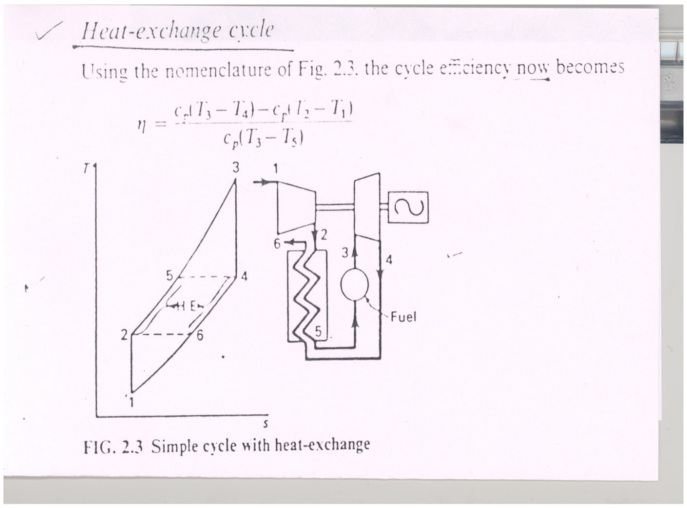


- Plot (a) : how thermal efficiency changes with pressure ratio for a given type of fluid.

- Plot (b) :the change in specific work output as a function of pressure ratio and temp ratio, T3/T1.

- Notice that in some instances it is possible that an increase in pressure ratio will increase efficiency at a cost to specific work.

Heat Exchange Cycle

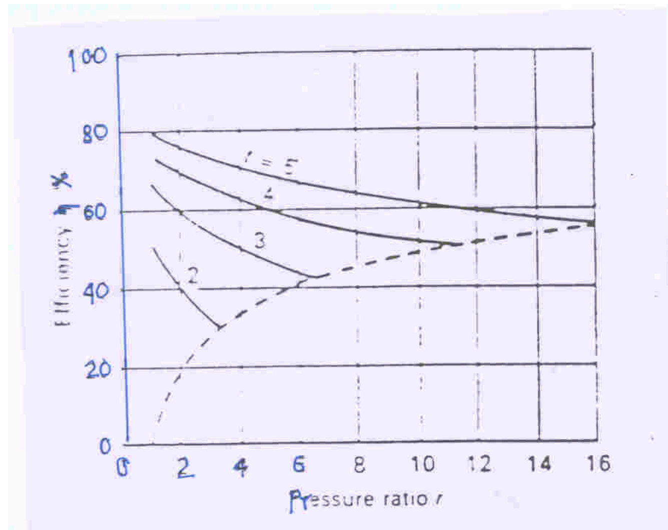


Heat-exchange cycle

Using the nomenclature of Fig. 2.3, the cycle efficiency now becomes

$$\eta = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_5)}$$

FIG. 2.3 Simple cycle with heat-exchange



The cycle efficiency now becomes.

- $\eta = \dfrac{Cp(T3-T4)-Cp(T2-T1)}{Cp(T3-T5)}$

- with ideal heat exchange T5 = T4
- substituting the isentropic p-T relations the expansion reduces to

  $\eta = 1- \dfrac{r^{(k-1)/k}}{t}$

  Where t = T3/T1
  r = P2/P1

- Thus the efficiency of the heat exchange cycle is not independent of the maximum temperature.

- It increases as t is increased.

- for a given value of t, the efficiency increases with decrease in pressure ratio and not with increase in pressure ratio, as for the simple cycle.
- the efficiency curve falls with increasing pressure ration and touches with dotted simple cycle curve.
- the specific work output is unchanged by addition of heat exchanger, simple cycle curves are still applicable.

Reheat Cycle

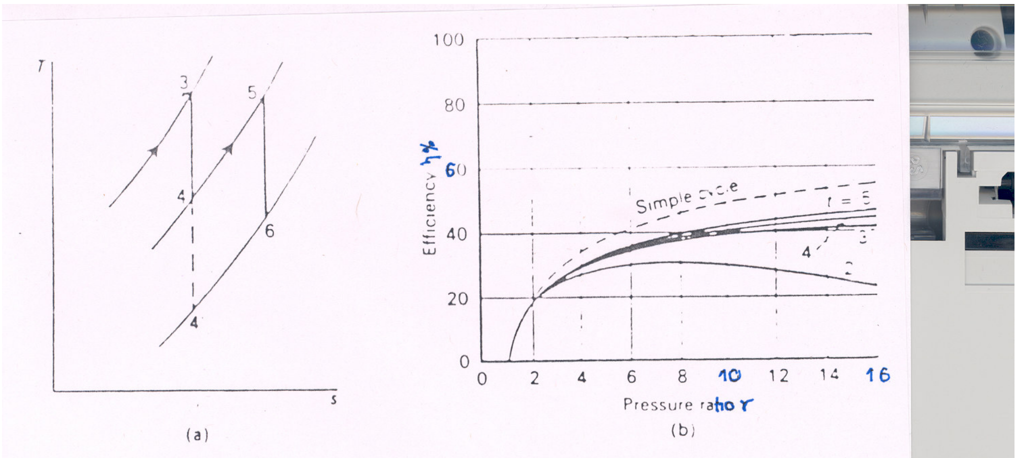


FIG. 2.5 Reheat cycle

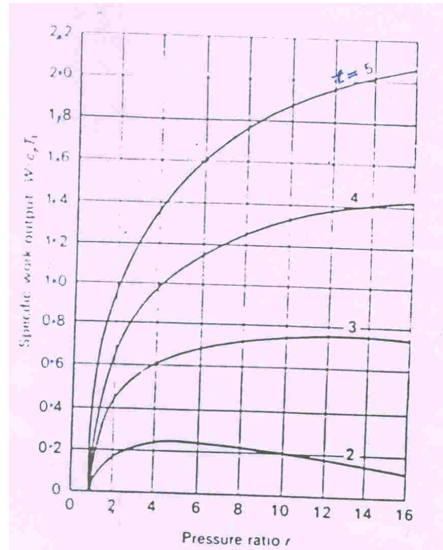


FIG. 2.6 Work output—reheat cycle

- A substantial increase in specific work output can be obtained by splitting the expansion and reheating the gas between the HP and LP turbines.

- (T3-T4) + (T5-T6) > (T3-T'4)

- Assuming that the gas is reheated to a temperature equal to T3

- The differentiation of the specific work output shows that the optimum point in the expansion at which to reheat is when pressure ratios (and hence temperature drops and work transfer) for HP & LP turbine are equal.

- Assuming above

$$\frac{W}{C_pT_1} \text{ (=Specific work output)} = 2t - C + 1 - \frac{2t}{\sqrt{c}}$$

$$\eta = \frac{2t - C + 1 - 2t/\sqrt{c}}{2t - C - t/\sqrt{c}}$$

where $C = r^{(k-1)/k}$ & $r = P2/P1$

Shows reheat increases specific work output. However efficiency is reduced.

Cycle With Reheat And Heat Exchange

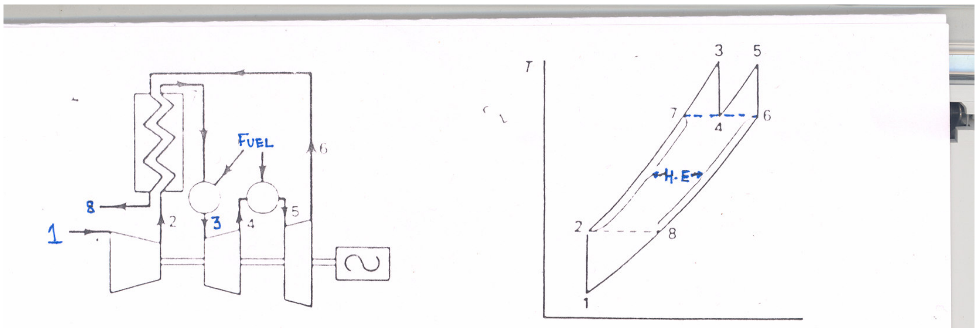


FIG. 2.7 Reheat cycle with heat-exchange

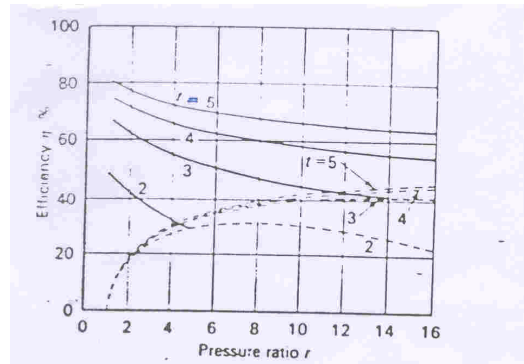


FIG. 2.8 Efficiency—reheat cycle with heat-exchange

- The reduction in efficiency due to reheat can be overcome by adding heat exchange.
- The higher exhaust temperature is now fully utilized in the heat exchanger.
- Increase in work output is no longer off set by increase in heat supplied.

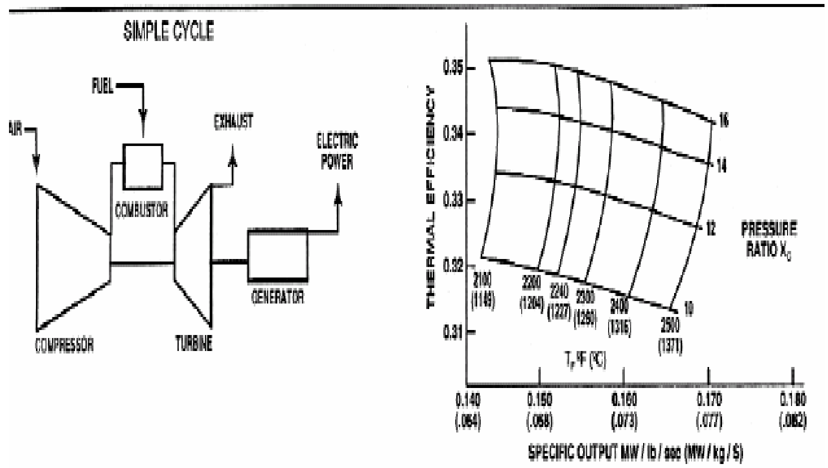
When a heat exchanger is employed, the efficiency is higher with reheat than without.
The dotted curves show efficiency of reheat cycle without heat exchange.

Cycle With Inter-Cooled Compression

- Similar improvement in specific work output to that obtained by reheat can be achieved by splitting the compression.
- And inter-cooling the gas between HP and HP compressor.
- Specific work output is a maximum when the pr. ratios of the LP and HP comprs are equal.
- However use of intercoolers is seldom contemplated in practice, as they are bulky and need large quantities of cooling water. Compactness of Gas Turbine is lost.
- Reduction in efficiency. Increase in specific work output.
- As with reheat inter-cooling increases the cycle efficiency only when a heat exchanger is also incorporated.

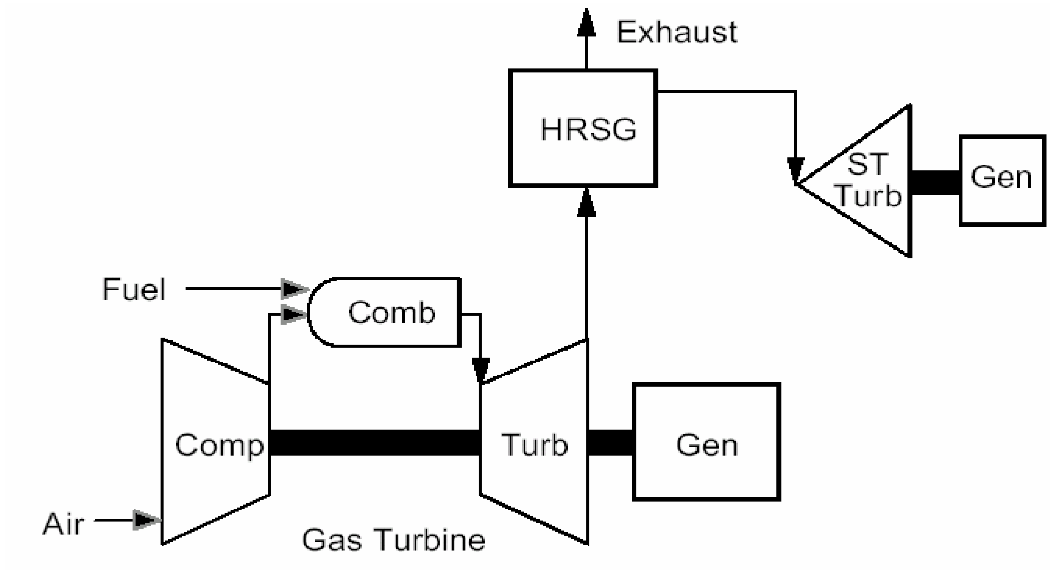
Simple Cycle

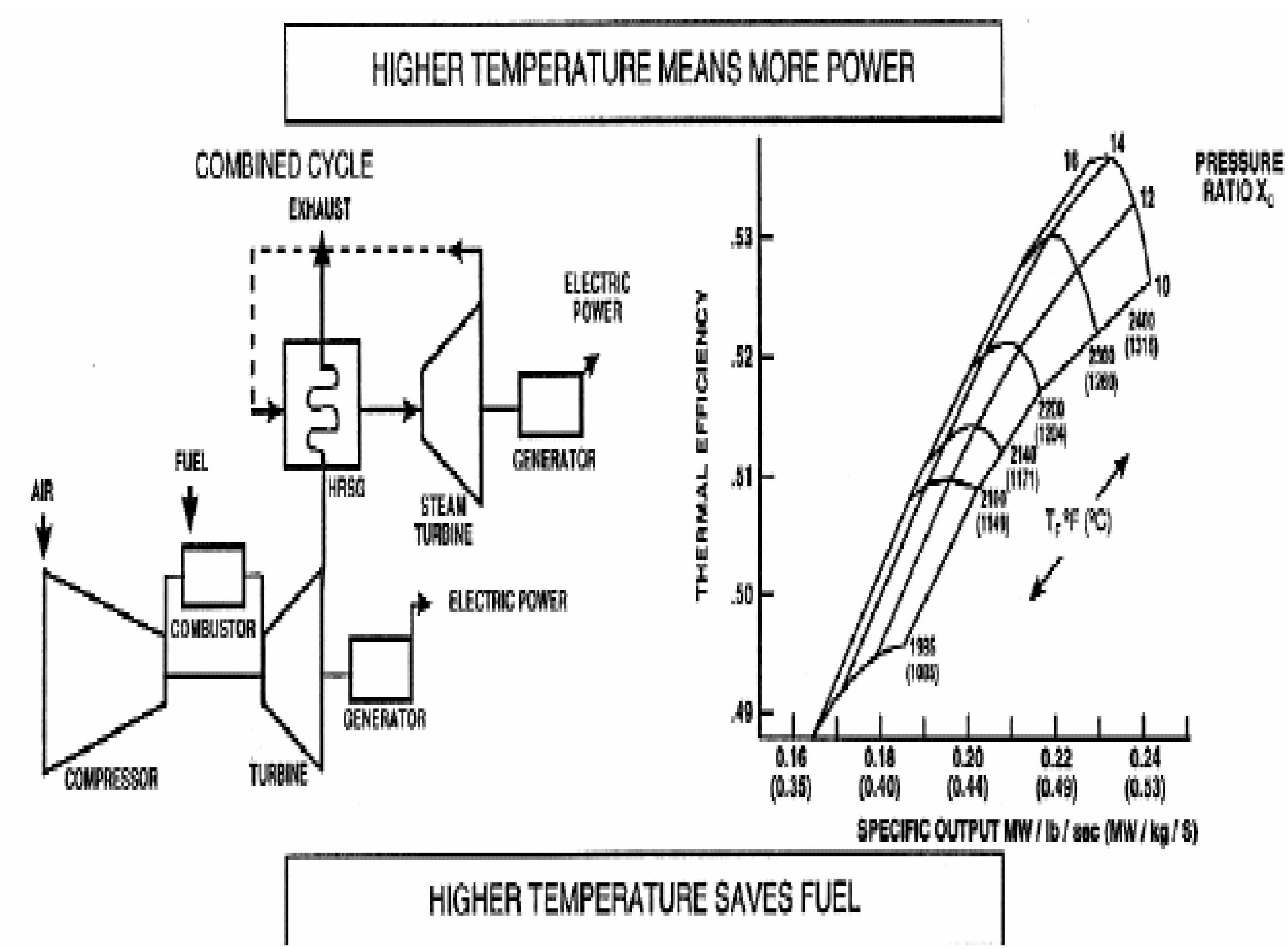
- A typical advance simple-cycle gas turbine will convert 30% to 40% of the fuel input into shaft output.
- Simple-cycle efficiency is achieved with high pressure ratios.



Combined Cycle

- The combined cycle is generally defined as one or more gas turbines with heat-recovery steam generators in the exhaust, producing steam for a steam turbine generator, heat-to-process, or a combination thereof.
- High utilization of the fuel input to the gas turbine can be achieved with some of the more complex heat-recovery cycles, involving multiple-pressure boilers, extraction or topping steam turbines, and avoidance of steam flow to a condenser to preserve the latent heat content.
- Attaining more than 80% utilization of the fuel input by a combination of electrical power generation and process heat is not unusual.
- Combined cycles producing only electrical power are in the 50% to 60% thermal efficiency range using the more advanced gas turbines.

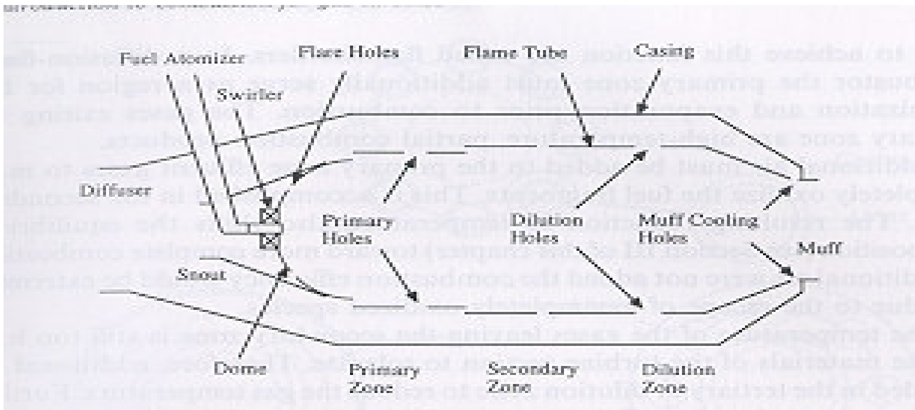

Exhaust
HRSG
ST
Turb
Gen
Fuel
Comb
Comp
Turb
Gen
Air
Gas Turbine


HIGHER TEMPERATURE MEANS MORE POWER
COMBINED CYCLE
EXHAUST
ELECTRIC
POWER
HRSG
GENERATOR
STEAM
TURBINE
FUEL
AIR
COMBUSTOR
ELECTRIC POWER
GENERATOR
COMPRESSOR
TURBINE
PRESSURE
RATIO
THERMAL EFFICIENCY
SPECIFIC OUTPUT MW / lb / sec (MW / kg / S)
HIGHER TEMPERATURE SAVES FUEL

Combustion System: Definitions

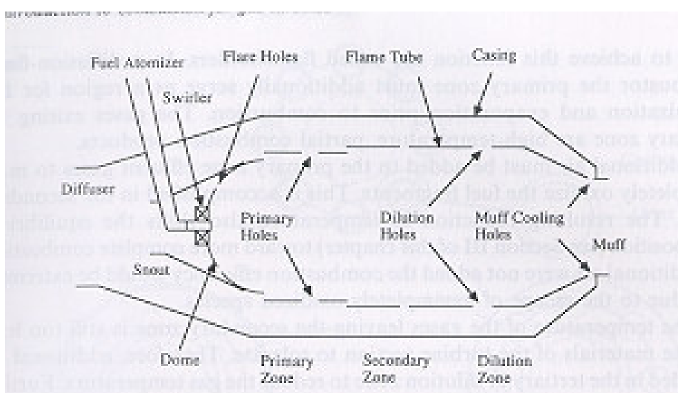
Combustion systems Geometries

'Can' or tubular
Annular,
Can-Annular



- Diffuser - This is where the air first enters the combustor. The primary function of the diffuser is to slow down the incoming air to prevent extinguishing the flame.

- Snout - The snout effectively splits the incoming air-stream; directing part of it into the Can and part of it around the flame tube.



- Swirler - This is part of the injector. It causes the incoming air to swirl.

- Primary Holes - These holes allow air from outside the flame tube to enter the primary combustion zone

- Flame Tube - This is a perforated casing that basically constrains the flame and hot combustion products while at the same time letting in air to feed the reaction. The flame tube is sometimes called a combustion liner.
- Dilution Holes - Air used to cool the combustion products enters through these holes.
- Muff Cooling Holes - Air enters here to further aid in cooling
- Muff - The combustor Can outlet.
- Flare Holes - Used to cool down the dome.

Combustion System - Can Type

- In a ''can' type combustor a series of individual combustion chambers are arranged around the centerline of the turbine package.
- Advantages
  problems associated with aero-dynamics and combustion, such as non-uniform outlet temperatures, are minimized.
- Disadvantages
  Multiple ignitors and fuel lines are required and also that the 'Can' setup is not the most efficient use of space in an annular volume.

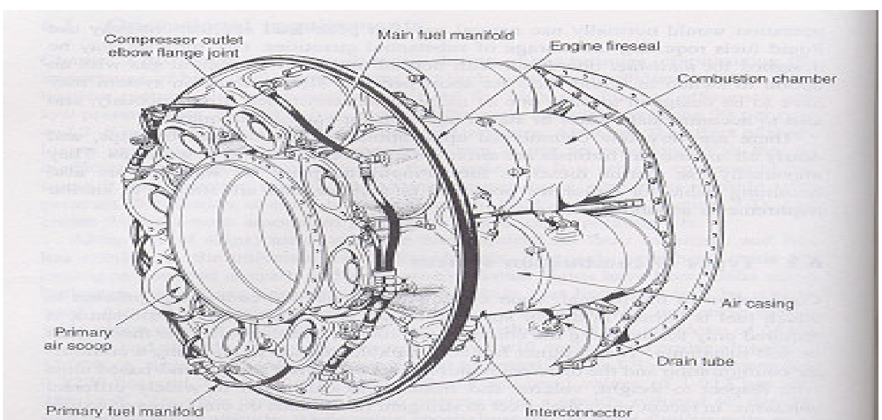
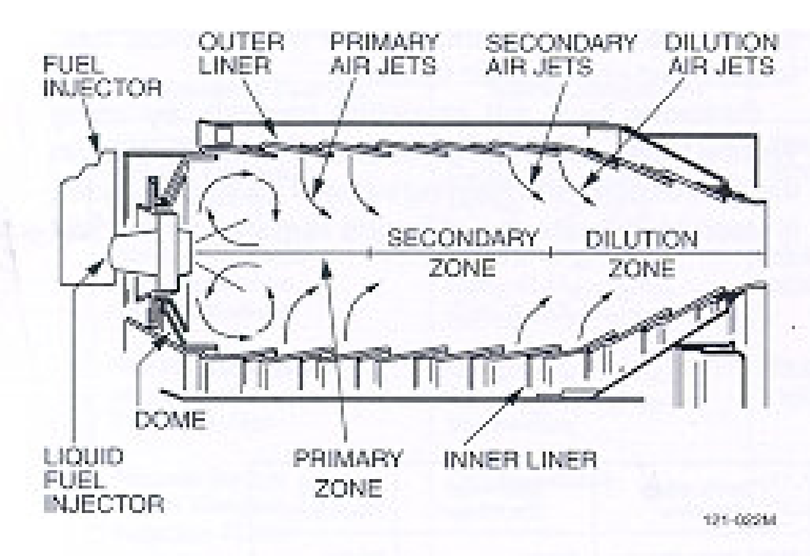


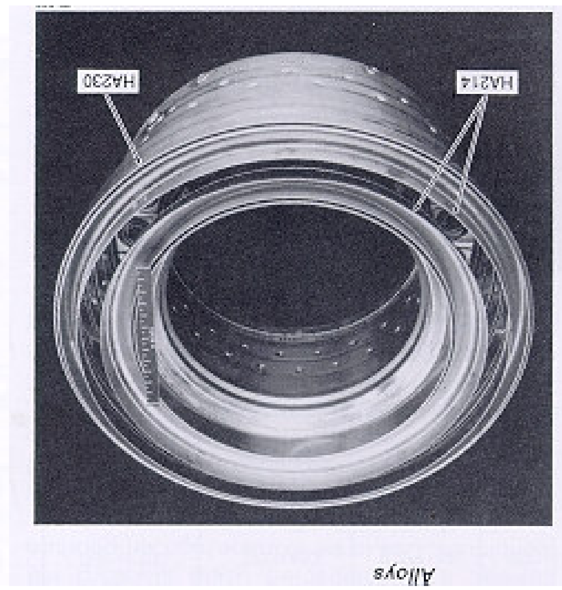
FIG. 6.1 Can type combustor [courtesy Rolls-Royce]

Combustion System *Annular Combustor*

- The annular combustor has the advantage of efficient use of available space. However, ignition and fuel distribution problems are common. Despite these problems annular combustors are widely used in industrial turbines.

- The Can-Annular type of combustor is a hybrid of the two other types. Can-annular setups consist of a series of flame tubes mounted in an annular space between casings. The result is a 'Can' combustor using the maximum amount of volume relative to what is available.





Gas Turbine Fuels

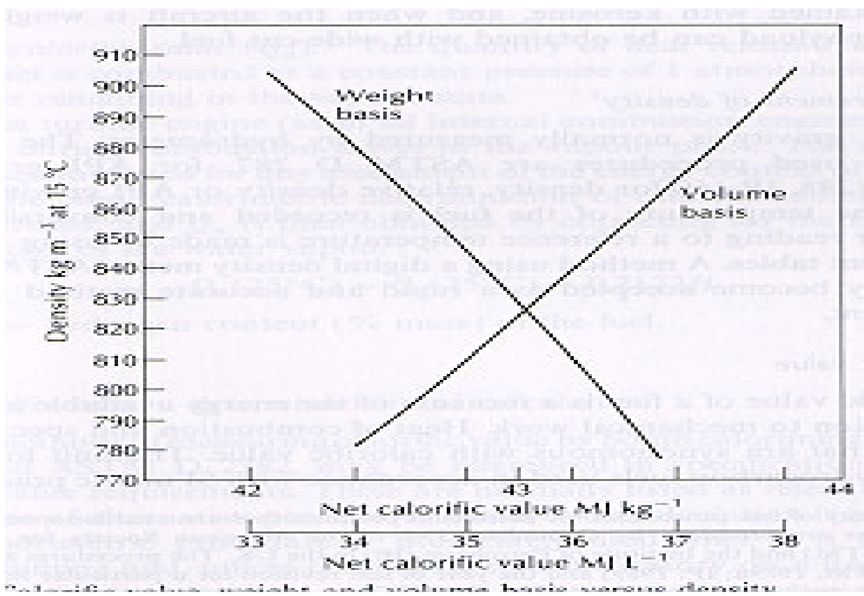
- Main categories
  Liquid Fuels
  Gaseous Fuels
  Alternative Fuels

- -all some type of hydrocarbon. With the possible exception of burning hydrogen gas which is rarely done.

- **Liquid Fuels**
  Liquid fuels can be used in most types of gas turbines (marine, aero, industrial) but are essential for aerospace applications. The reason being is that they have a higher energy density compared to, say, gaseous fuels.

- Typically a liquid fuel, as well as any other, should have the following properties:
  - *High energy density,*
  - *ability to flow at a range of possible temperatures*
  - *sufficient volatility to provide quick vaporization and reaction.*

- Liquid fuel energy content, or calorific value, can be related to the fuel density as shown in the following chart.



<u>Gaseous Fuels</u>

- Natural gas is the fuel of choice for many industrial (stationary) gas turbines.

- Since these types of turbines are not subject to weight or energy density constraints they can be run on a variety of fuels.

- Natural gas is commonly used because it mixes readily with air, produces a fairly clean combustion, and is readily available.

- Hydrogen has also been used as a fuel in industrial turbines. It would seem that this is the ultimate clean fuel. Unfortunately, even though there are no carbon products to worry about, NOx is still going to be an issue. In addition, the use of hydrogen can also result in the embritlement, and eventual failure, of metal turbine components.

Alternative Fuels

- 'Alternative' means extracting hydrocarbon fuels from the earth other than by conventional refining practices.

- Some of these alternative energy sources include: *coal, shale oil, tar sands (heavy oil).*

- These energy sources are currently not used because they usually have a low hydrogen to carbon ratio and also because it is difficult to convert the fuels to a useable form.

- For instance, to burn coal in a turbine it must be converted to either a liquid or a solid. This can be done with processes such as pyrolysis, carbonization, or gasification. In gasification the coal can be reacted with steam to produce hydrogen gas or reacted with hydrogen to produce methane gas.

Combustion Thermo-chemistry

- Most gas turbines operate by reacting a gaseous or vaporized hydrocarbon fuel with air. A typical reaction is given below. This one is for propane reacting with air.

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$$

- just enough air to react fully with the fuel. In reality the may not be the case.

The air / fuel ratio gives an idea of how much fuel and air are being reacted. It can be defined on a molar or mass basis. The air/fuel mass ratio for the above reaction is given below.

$$(\frac{A}{F})_s = \frac{5(32 + 3.76 \cdot 28)}{1(44)} = 15.6 \frac{kgair}{kgfuel}$$

- The above air / fuel ratio is called Stoichiometric Air / fuel ratio, denoted by the subscript s.
- The calculation involves converting the moles of the reactants into masses via their molecular weights.
- As a practice gas turbines are usually run fuel lean (excess air). A standard way of indicating the composition of a given mixture is defined as the ratio of the stoichiometric air fuel ratio to the actual air fuel ratio. This is called the equivalence ratio and is defined as:

- An equivalence ratio less than 1 indicates a fuel lean reaction whereas a ratio greater than one is fuel rich.

$$EqRatio = \frac{(\frac{A}{F})_s}{(\frac{A}{F})_A}$$

- The thermodynamics of a combustion reaction in a gas turbine can be modeled with the following first law equation:
- $$Q = \dot{m} \cdot h_p - \dot{m} \cdot h_r$$
- Q is the amount of heat released by the reaction. m' is the mass flow rate and hp and hr are the enthalpies of the products and reactants, respectively.
- It is useful to estimate the heat liberated by a combustion reaction.

- This can be done using eq. 1. Imagine that Q is the amount of heat that needs to be removed to cool the products to the same temperature as the reactants. Solving eq. 1 under this condition yields the following relationship:

$$Q_{react} = h^{\circ}_{f\,(products)} - h^{\circ}_{f\,(reactants)}$$

- The heat of reaction turns out to be the difference in the formation enthalpies of the products and reactants.

- For designing a turbine system, it is very important to make sure that the temperatures reached during operation will not exceed the maximum levels tolerated by the components.

- The most critical temperature is that of the gases exiting the combustor and entering the first stage turbine section. The adiabatic flame temp can be used to estimate the max temp of combustion.

- The adiabatic flame temp corresponds to a situation where no heat is transferred from the combustion reaction. *hp = hr* & *Q = 0*

- Actual temp. of combustion will not be equal to the Adiabatic flame temp because there wll always be some heat transfer.

- *Adiabatic Flame Temp.* is calculated for a stoichiometric mixture, any products not accounted for will effectively decrease the temp. The formation of CO, oxides of nitrogen, or products formed through disassociation will generally lower the temperature as will adding excess air for cooling purposes. The efficiency of a combustion reaction is defined as:
- *Ta = temp entering combustor , Tp = temp of the products*

- This is the actual temperature change divided by the maximum possible temperature change.

Reactions and Dissociation

- Consider the reaction for carbon and oxygen:

$$C + O_2 \leftrightarrow CO_2$$

- At equilibrium this reaction can proceed in either direction. Which direction it goes is dependent on the concentrations of the reactants and products. The relationship between the two concentrations is defined as the equilibrium constant, Kc. Consider the following reaction:

$$aA + bB \leftrightarrow eE + dD$$

- Kc for this reaction is defined as:

$$K_c = \frac{[C_C^c \cdot C_D^d]}{[C_A^a \cdot C_B^b]}$$

- This equation tells us : based on a change in concentration of a given species, how will the reaction change. Will it shift to the right, making more products or to the left, making more reactants.

Flame Temperature

- For the stoichiometric reaction of carbon and oxygen the adiabatic flame temperature is calculated as: Taf = 6715 K or 11627 F

- The combustion products from this reaction would turn a gas turbine into a crusty pile of slag. In reality, dissociation (the formation of products other than CO2) can lower this temperature considerably.

- In order to properly balance a combustion reaction involving high temperatures, consideration must be given to how the reaction is influenced by the equilibrium constant. The value for Kc can be found in various databases. For this reaction Kc is equal to 0.00071. This corresponds to the dissociation of CO2 into CO and O2. So the real reaction might look something like this:

$$CO_2 + 2O_2 \leftrightarrow 0.964CO_2 + 0.036CO + 1.018O_2$$

- In this equation the molar coefficients were found by considering the amount of reactants and also the equilibrium constant. The adiabatic flame temperature is:

Taf = 4021 K or 6778 F

Combustion System *Injectors*

- It's primary function is to deliver fuel, either gas or liquid, and atomizing air to the combustor.

Liquid Fuel Injectors: Necessary to break up or atomize the fuel entering the combustor. Atomization results in a faster, more complete combustion which increases efficiency and decreases the amount of un-burnt fuel and other pollutants.

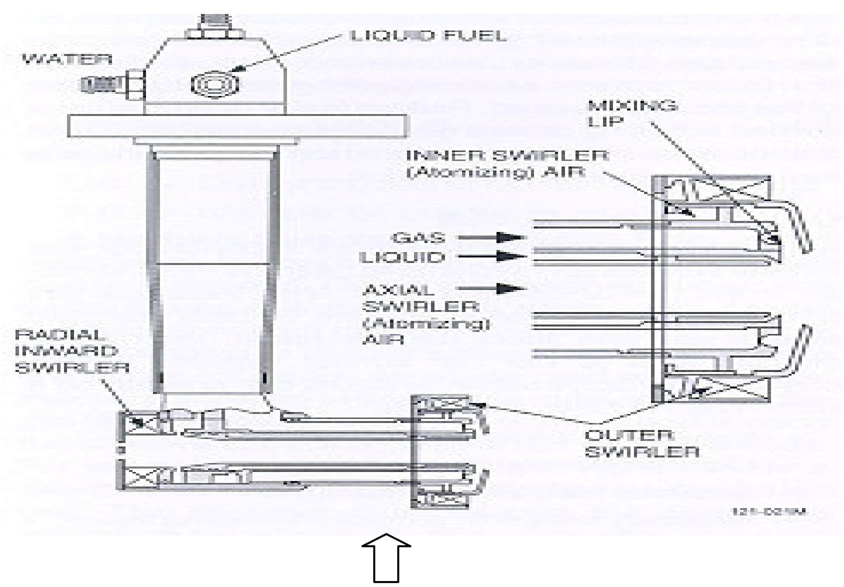
Three primary methods used for atomization:

- *Pressure Atomization:* Fuel is forced under high pressure through a small orifice. The result is a high speed jet of fuel that eventually disintegrates into droplets.

- *Twin-Fluid Atomization:* High velocity air flows across a fuel film on a solid surface. The result is that the fuel is sucked into the air stream and a thin sheet formed.

- *Rotary Atomization:* The fuel is forced over a rotating disc or cup which imparts a centrifugal force that effectively dis-integrate the fuel.

- *Jet Impingement:* The fuel stream emerging from the injector is impinged by high speed air. The result is that the stream is broken into droplets.



Dual fuel injector

- Atomization is quantified by fuel droplet diameter. The Sauter Mean Diameter, or SMD, gives the mean droplet size in microns:

- Increasing mass flow rate increases droplet size and raising the pressure drop across the atomizer decreases it. Controlling these two parameters is one way to control droplet size and consequently flame stability.

- Depending on the atomization technique used, the equation for calculating the SMD will change. The above relation is for pressure-swirl atomization.

Gas Injectors

Gaseous fuels are considered to be ideal for combustion reactions because they are in a 'ready to mix state' and require no special preparation before injection. The gaseous fuel injector must simply distribute the fuel in the combustor in a manner that promotes rapid mixing with the air.

- Things To Consider When Building Injectors:

- Combustion Efficiency - Another way combustion efficiency is measured is by the amount of unburnt fuel in the exhaust. Proper mixing ensures that the amount of un-burnt fuel is minimized.

- Fuel Velocity - Controlling the direction and speed of the fuel jet is important in maintaining a steady and even combustion reaction.

Combustion System *Liner / Flameholder*

- The liner or flame holder performs the following functions: 1. Provide the boundary of the combustion region(s). Contain the flame. 2. Act as a mechanism for the addition of air to the reaction, often by diffusion.

- The image above shows a typical combustor. Notice that there are passageways that allow air to move around the liner. This air not only aids in cooling the liner but also diffuses through holes to become part of the combustion reaction or to cool the combustion products. The holes may also be positioned in such a way as to cause areas of recirculation of the combustion products inside the combustor. This is very important for flame stability.

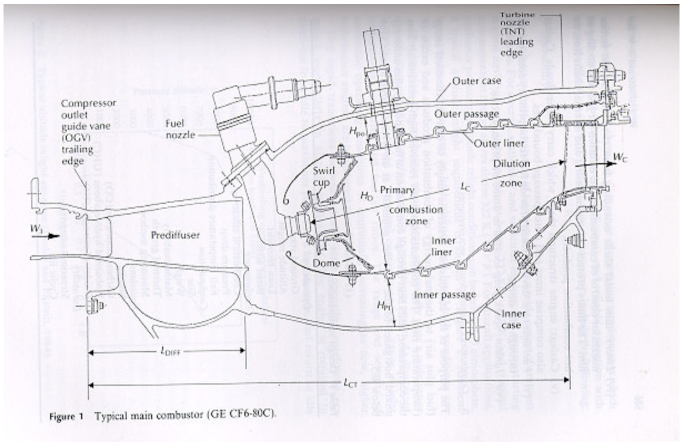


Figure 1 Typical main combustor (GE CF6-80C).

- Currently there is a good deal of research being done on using ceramic components in turbines to allow for and increase in the operational temperatures. On the right is an image of a ceramic combustion liner. The material is called a CFCC or continuous fiber ceramic composite. I know it looks like a toilet paper roll but its not. That liner, assuming it is at least 1.5 ft in diameter, is probably worth about 80K.

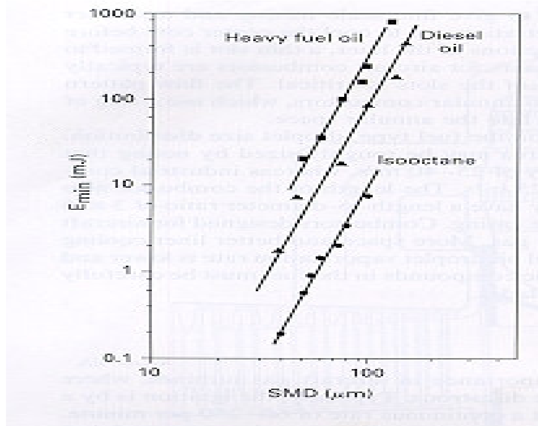
- Notice that there are no holes for air diffusion. This is because at the present ceramics are mechanically very weak. Holes would just make the situation worse. This is also why only certain parts of a turbine can be made from ceramic materials.

<u>Combustion Reaction *Ignition*</u>

- Gas turbine ignition is very important.

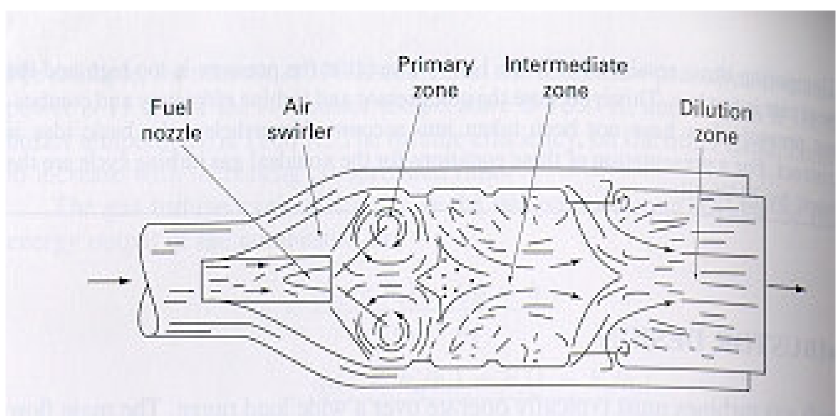
- If jet engine has a flameout at 35,000 feet , make sure that can be started again.

- To start a turbine, the compressor is sped up to a rate that allows for a flow rate sufficient to support combustion. This is usually around 15-20 % of normal speed. At this point gaseous fuels may be ignited with an electric spark. Once combustion begins the ignitor is turned off.



- Liquid fuels differ from gaseous fuels by the amount of energy required to begin the combustion reaction. This 'ignition energy' is proportional to droplet size. Since a spark will typically not be able to initiate a burn in a liquid fuel turbine, a torch ignitor is used instead. The plot on the right shows how ignition energy changes with droplet size for a variety of liquid fuels.

Combustion Reaction *Flame Stabilization*



- If the reactions inside a combustor are much slower than the rate at which fuel and air are moving through the combustion chamber, any flame that is initiated will be blown down stream and the combustion reaction will cease. This is called blow-off. To prevent blow-off, combustors are designed to re-circulate the combustion products in the primary zone thus giving the combustion reaction time to complete and thereby stabilizing the flame.

- Combustion instability can also lead to dangerous aerodynamic vibrations.

- Notice the obstruction downstream from the air swirler. It effectively channels the incoming reactants back into the primary zone thus creating vortices in which the combustion reaction takes place.

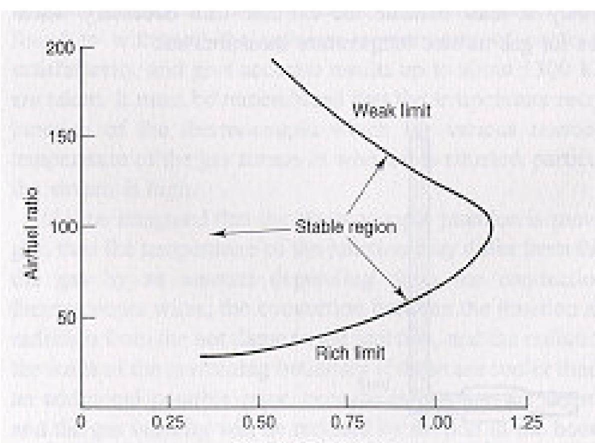
- The action of the air swirler may be enough to create recirculation. When the air is swirled around the axial flow direction the increased speed creates an area of low pressure, as per Bernoulli, which draws combustion products back into the primary zone.

<u>Combustion Reaction *Stability Limits*</u>

- Flame stability can be greatly influenced by both the fuel / air mixture and by the pressure in the combustor. The plot below shows how stability is related to mixture.

- There are limits for both lean and rich mixtures.

- The pr influences combustion stability by changing the speed at which reactions occur. Higher pressures mean higher reaction rates and faster combustion. The following equation can be used to relate the reaction rate to the combustion pressure.



$$r \propto m_j m_k p^2 \sigma^2 T^{1/2} M^{-3/2} e^{\frac{E}{RT}}$$

$$r \propto p^2 f(T)$$

- m = Local molecular concentrations of the reacting species
  Sigma = Mean molecular diameter
  M = Mean molecular weight
  E = Activation energy

R = Universal gas constant, molar
Rho = Density

- The equation can be reduced by substituting pressure and temperature for density.

Emissions and Pollution

- For the most part gas turbines burn hydrocarbons in the presence of air.

- *we get these additional products in Flue gases*

  - Carbon Monoxide
  - UHC
  - Oxides of Nitrogen (NOx)
  - Oxides of Sulfer (SOx)
  - Excess Oxygen

- Carbon Monoxide - Odorless gas that is very lethal if inhaled. Blood would rather absorb CO than O2 which results in oxygen starvation.

- UHC (Unburnt Hydrocarbons) - These cause cancer.

- NOx - NOx control is the focus of a great deal of research. It helps cause smog through a photochemical reaction.

- SOx - When combined with water in the atmosphere SOx produces acid rain.

Pollution *NOx*

- NOx is big problem because, NOx formation increases with combustion temp.

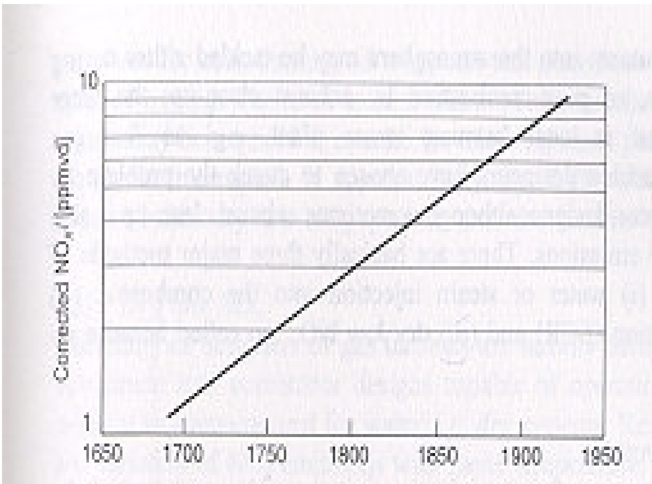
- So does gas turbine efficiency. It is a dilemma.

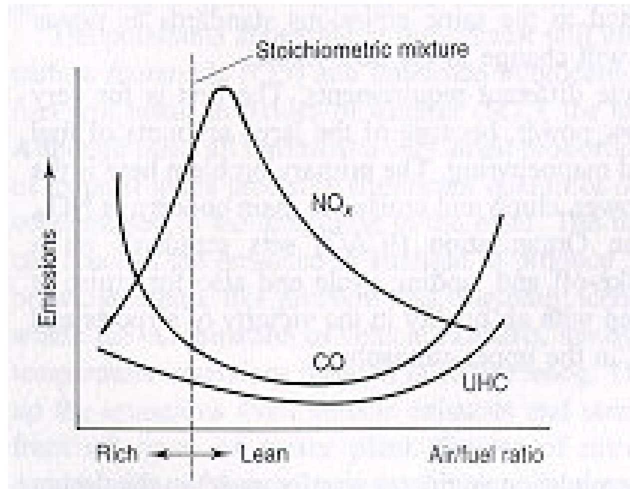
- In order to have an efficient turbine the combustion to should happen at the highest tolerable temp.

- On the other hand the easiest way to control NOx formation is by lowering combustion temp.

- This plot shows how the amount of NOx formation varies with combustion temp.(temp in Kelvin)

- This plot shows how NOx formation varies with the air - fuel ratio





<u>Low NOx Turbine Systems</u>

- It has become increasingly more important to build not only efficient turbines, but also clean turbines.

- There are many methods used to control NOx,

- Dry Control - Operating the turbine with excess air, lean conditions. This lowers the combustion temperature and thereby reduces NOx formation. Reduction is typically around 10 - 20 %.

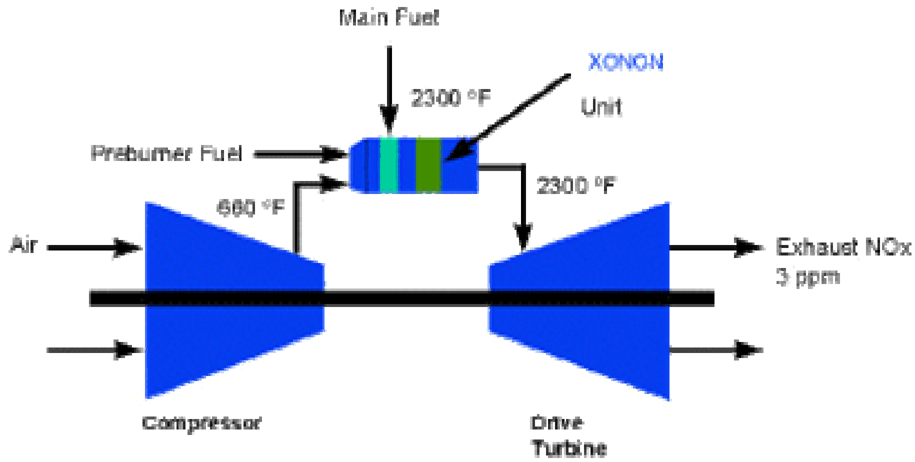
- Wet Control - Inject water or steam into the primary combustion region. This lowers the temp and reduces NOx. Water injection can increase the power output but it also increases fuel consumption and presents corrosion problems. NOx reduction of about 40%.

- Lean Premixed Technology - Similar to dry control. Premix air and fuel in injector to create lean conditions. This substantially reduces NOx but can lead to combustion instability and vibration. Can also substantially increase CO and UHC emissions.

- Selective Catalytic Reduction (SCR) - NOx reacts with an injected reducing agent, such as ammonia, on the surface of a catalyst. These systems require expensive support equipment such as boilers and ammonia recovery systems.

- Catalytic Combustion - This involves the flameless combustion of fuel and air on a catalytic surface. NOx emissions are around 3 ppm.

XONON Low NOx System



- Shows the XONON catalytic combustion system:

- The pre-burner is used during startup to get the catalyst up to operating temperature. This process is not flameless and does produce NOx.

- The main fuel is injected along with air and enters the XONON catalyst module. There, a portion of the fuel is combusted flamelessly. This reaction produces no NOx since the reaction temp is below that required for NOx formation.

- The last section of the combustor is the burnout zone in which the remaining fuel is combusted and CO as well as UHC are burned out. This process is also flameless but NOx is produced since the reaction occurs at sufficiently high temperatures.

- The end result is a gas turbine with ultra low NOx emissions.

Concepts

- Radial Flow turbomachines

  -For low flow rates & higher pressure ratio.
  -e.g. PGT2 Simple cycle Gas Turbine (M/S Nuovo Pignone)
  -Capacity 2MW,
  -Exhaust flow 10.2 Kg/s
  -Exhaust temp 550 deg
  -Efficiency 25% (with 98.5% gear efficiency and 95.5% generator efficiency).
  -having two stage centrifugal Compressor and two stage axial flow turbine.

- Axial Flow turbomachines

  -For large flow rates.
  -per stage pressure rise is low
  -Mostly turbines are axial flow machines.

- Airoderivative Gas Turbines

  -These turbines are derived from Air craft engines
  -Compact turbines
  -High Pressure ratio
  -Less flow rate

- Industrial

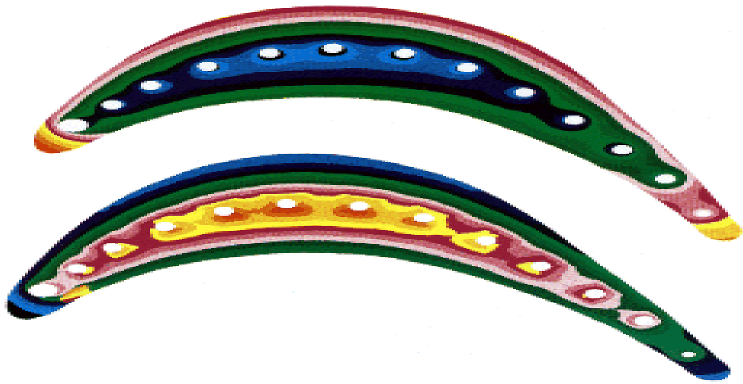
  -Rugged medium & heavy duty Gas turbines

Blade profile

P1

P1< P2 for compressors

Adverse pr gradient



P2

P1> P2 for turbines

Favorable Pr gradient

Surging in Compressors

- The above is a figure of aerofoil placed in a fluid field.
- In the far region the viscous effects are negligible.
- However there exists a boundary layer, where viscous effects can not be considered negligible.
- In a compressor Flow is **from low pressure P1 to Higher pressure P2**
- Hence the flow is against the adverse pressure gradient.
- The phenomenon is similar to climbing to a hill. It is a **"Up-Hill"** flow.
- There is a minimum flow at which the boundary layer gets separated.
- The separation of boundary layer causes reversal of flow.
- The fluid from downstream shall rush back, causing pressure waves.
- This phenomenon is called surging.
- Very dangerous phenomenon, can damage internals.
- It is avoided by controlling the operating point on Head vs Flow curve.
- Centrifugal compressor is having a wide operating band on Head vs Flow curve.
- Hence speed variation can be effectively done.
- An axial flow compressor operates in a narrow band on Head vs Flow curve. On minor speed variation it may go to surging.
- Since most gas turbines are having Axial flow compressors, the speed of the Axial air compr. (HP) shaft is kept constant to avoid surging of the axial Air compr.
- Hence for mechanical drive applications 2 (twin) shaft turbines are used.
- The Axial compr, mounted on HP shaft run at a constant speed, Centrifugal compr, mounted on LP shaft runs at varying speed as per load requirement.
- In Turbines the flow is from high pr to low pr against favorable pr. gradient.
- It is a down hill flow.
- Hence separation of boundary layers does not occur.

Alphabetical List of Major Manufacturers/ International Suppliers

ABB	ALLISON	COOPER ROLLS
DRESSER RAND	EGT	FIAT AVIO
GE	JOHN BROWN	KAWASAKI
KVAERNER ENERGY AS	MAN Gutehoffnungshutte AG	
MHI	MITSUI	MTU MOTOREN
NUOVO PIGNONE	PARSONS TURBINE	PRATT & WHITENY
ROLLS ROYCE	SIEMENS	SOLAR TURBINES
STEWART & STEVENSON	TEXTRON LYCOMING	THOMASSEN
TUMA TURBOMACH	TURBO POWER	TURBOMECA
U S TURBINE CORPORATION		WESTINGHOUSE

Gas Turbines Installed In Our Processing Plants

- **UPPC**

  Fr-5 MS 5002 (M5382C)
  2 nos GE make

- **LPG Vijaipur**

  LPG

  Fr-3 MS 3002 (M3142J)
  2 nos GE make

  Propane unit

  Fr-1 MS 1002 (PGT5)
  2 nos GE/Nuovo Pignone

  LEF O/H

  Fr-1 MS 1002 (PGT5)
  2 nos GE/Nuovo Pignone

- **LPG Lakwa**

  Fr-3 MS 3002
  1 nos GE make

- **LPG Usar**

  Fr-3 MS 3002
  1 nos GE make

- **LPG Gandhar**

  Mars 100 15000 S
  2 nos from M/S Solar

In processing plants mostly GE make turbines are installed.

So we shall look more deeply for GE gas turbines.

PGT5-Details

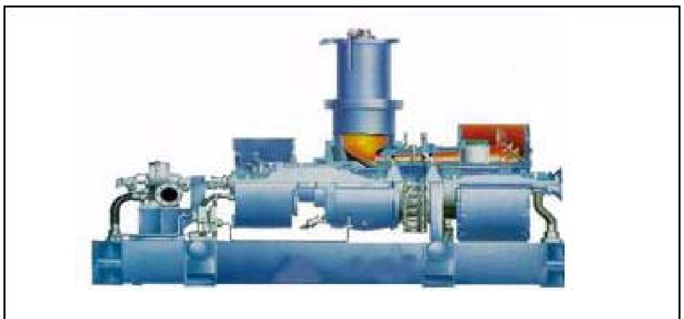
General details

Heavy duty gas turbine, highly modular to enhance accessibility and maintainability.

- 15-stage, high efficiency, axial-flow compressor & single stage turbine on HP shaft.
- The LP section (two-shaft version) is a single-stage, high-energy turbine, with variable second stage nozzles that provide flexibility for mechanical drive service.
- Single combustion chamber which is rugged, reliable, and able to burn a wide range of fuels, from liquid distillates and residuals to all gaseous fuels, including low BTU gas.
- Typical applications include pump driver for oil pipelines and compressor driver for gas pipelines.

Design Information

- 15-stage axial flow compressor;
  pressure ratio 9.1:1 , RPM HP shaft 11140
- Single, reverse flow combustion can


Gas Turbine

Two-shaft turbine with one reaction stage, RPM LP shaft 10290

The gas turbine module on a single base-plate includes the engine, starting system, auxiliaries, and acoustic enclosure.

The standard configuration, excluding the inlet and exhaust ducts, is 28 by 8 by 10 ft (8.5 by 2.5 by 3 m) and weighs 28 t

Emissions control includes a dry low emissions combustion sys and a steam / water injection sys.

Control System : Speedtronic MARK IV

Performance

Generator drive, single-shaft version, natural gas fuel

Output: 5,220 kWe
Heat rate: 13,422 kJ/kWh
Exhaust flow: 24.6 kg/s
Exhaust temperature: 973 °F (523 °C)

Mechanical drive, two-shaft version, natural gas fuel

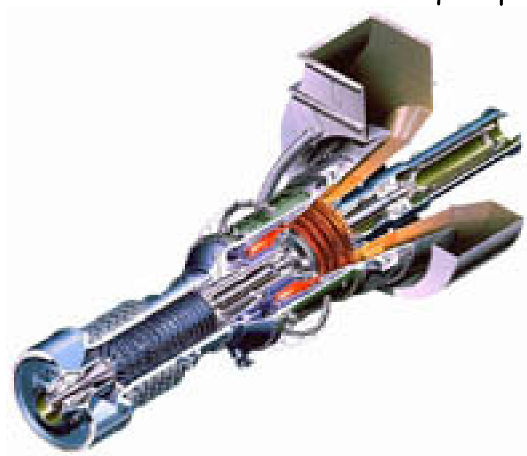
- Output: 7,295 shp (5,440 kW)
- Heat rate: 9,520 btu/shp-h (13,470 kJ/kWh)
- Exhaust flow: 56.9 lb/s (25.8 kg/s)
- Exhaust temperature: 991 °F (533 °C)

Specific to Vijaipur

- Fuel : Gas
- Cycle : Simple
- Starting system : CRANKING MOTOR
- Driven machine : Centrifugal compressor
- Shaft rotation : Anti-clockwise looking at the turbine from suction to exhaust.

MARS 100 -Details

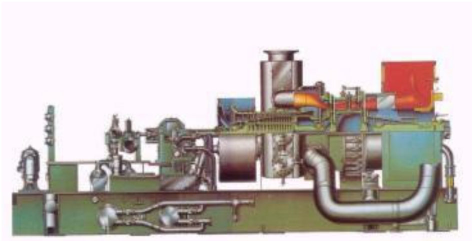
- Completely factory packaged and tested to drive a variety of centrifugal and reciprocating compressors or air, process and refrigeration applications ,drive pumps for water-flooding, gas compression, and transportation of crude oil and other liquid products.



- Model: Mars 100–15000S
- SoLoNOx Emissions Control System
- Compressor Cleaning System, On-Crank
- Compressor Protective Coating
- The standard configuration, excluding the inlet and exhaust ducts, is 28 by 9 by 11 ft (8.6 by 2.7 by 3.4 m) and weighs 23.9 t
- Fuel : Gas
- Output : 11190 Kw (ISO)
- Thermal Efficiency% : 33.9

MS 3002 -Details

- Heavy duty gas turbine, having two shaft configuration.
- Simple or regenerative cycle variants like MS1002.



- 15 stage axial flow compressor
- Reverse flow laterally mounted six combustion chambers.
- In the regenerative cycle unit, air from the axial flow compressor passes through the regenerator where it is heated further and then enters the combustion chambers.
- The turbine exhaust gas passing through the regenerator, after expansion will give away the heat to the incoming air.
- Application as Mechanical drive for gas and oil transportation, industrial co-generation, utility and marine applications.
- The second stage variable angle nozzles have the advantage of limiting over speed and better part. Load heat rate, low starting power and better combined cycle or co-generation operation.

Specific to Vijaipur

Model	:MS 3142J Simple Cycle
Rotation	:Counterclockwise
Shaft Speed	: 7100 for HP shaft
	: 6500 for LP shaft
Control	: Mark IV speedtronic control system
Protection	: Over speed, over temperature vibration, Flame detection.
Sound Attenuation	: Inlet, Exhaust Silencer
Base output	: 14600HP (ISO) with gas fuel
Exhaust temp	: 526 deg C

Heat rate (BTU/HP-hr)	: 9530
Pressure ratio	: 7.1
Exhaust flow	: 53 KG/Sec.
Compressor type	: Axial flow 15 Stages, Horizontal casing split type.
Turbine type	: Axial flow, horizontal casing split type.
Nozzles	: First stage fixed area :Second stage variable.

MS5002- Details

- Designed for mechanical drive applications with a wide operating speed range to meet the operating conditions of the most common driven equipment, centrifugal compressors and pumps.

- It can burn a large variety of gaseous and liquid fuels.

- Almost 500 units (more than 300 of which were manufactured by Nuovo Pignone) have been installed worldwide various environments including arctic, desert, and offshore.

- The simple design and robustness of the machine allows for maintenance to be performed on-site without special tools or service shop assistance.

- Typical applications include gas boosting, gas injection and re-injection, oil and gas pipelines, liquefied natural gas plants, and gas storage.

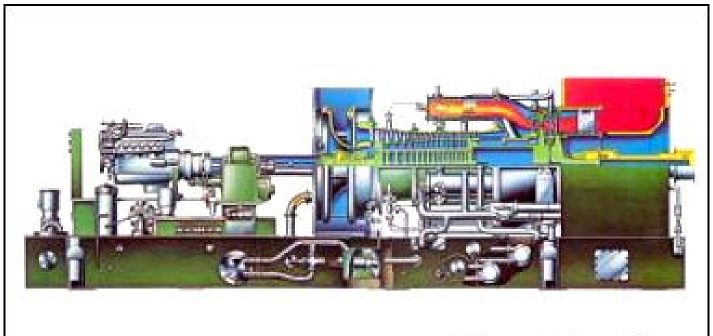
- Two versions are available:

  MS5002C - 38000 HP at ISO condition, and (Installed at UPPC)
  MS5002D - 43700 HP at ISO condition.

Design Information

- MS5002C: 16-stage axial compressor; pressure ratio 8.9:1
- MS5002D: 17-stage axial compressor; pressure ratio 10.8:1
- Reverse flow, multi chamber (can-annular) combustion system (12 chambers)

- Single stage gas generator turbine. (5,100 RPM)
- Single stage power turbine (4,670 RPM) with variable nozzles


Gas Turbine

- Two base plate configurations (Gas turbine flange to flange unit and auxiliary system).
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance.
- The standard configuration, excluding the inlet and exhaust ducts, is 49 by 10 by 12 ft (15 by 3.2 by 3.8 m) and weighs 110 t
- Dry low NOx (DLN) combustion system with Steam or water injection systems.

Performance Information

Mechanical Drive, Fuel - Natural Gas

Model MS5002C

- Output: 38000 hp (28340 kW)
- Heat rate: 8814 btu/shp-h (12470 kJ/kWh)
- Exhaust flow: 274.1 lb/s (124.3 kg/s)
- Exhaust temperature: 963 °F (517 °C)

Model MS5002D

- Output: 43690 hp (32580 kW)
- Heat rate: 8650 btu/shp-h (12239 kJ/kWh)
- Exhaust flow: 311.7 lb/s (141.4 kg/s)
- Exhaust temperature: 948 °F (509 °C)

Solar Turbines- Model Details

Mechanical-Drive Specifications

Gas Turbine Model	Nominal Output, kW	Nominal Output, hp	Thermal Efficiency, %	Length, m	Length, ft-in.	Width, m	Width, ft-in.	Height, m	Height, ft-in.	Weight, kg	Weight, lb
Saturn 20	1185	1590	24.5	4.0	13'2"	1.8	5'10"	1.9	6'4"	3733	8230
Centaur 40	3500	4700	27.9	5.5	18'3"	24	8'0"	27	8'11"	10433	23,000
Centaur 50	4570	6130	29.9	5.5	18'3"	24	8'0"	27	8'11"	10433	23,000
Centaur 50L	4680	6275	30.9	5.5	18'3"	24	8'0"	27	8'11"	10433	23,000
Taurus 60	5740	7700	31.9	5.5	18'3"	24	8'0"	27	8'11"	10433	23,000
Taurus 70	7690	10,310	34.8	6.4	21'1"	2.9	9'8"	3.3	10'11"	13607	30,000
Mars 90	9860	13,220	33.1	8.6	28'3"	27	9'0"	3.4	11'3"	23905	52,700
Mars 100	11190	15,000	33.9	8.6	28'3"	27	9'0"	3.4	11'3"	23905	52,700
Titan 130	14540	19,500	35.6	9.8	32'0"	3.0	10'0"	4.5	14'10"	35444	78,140

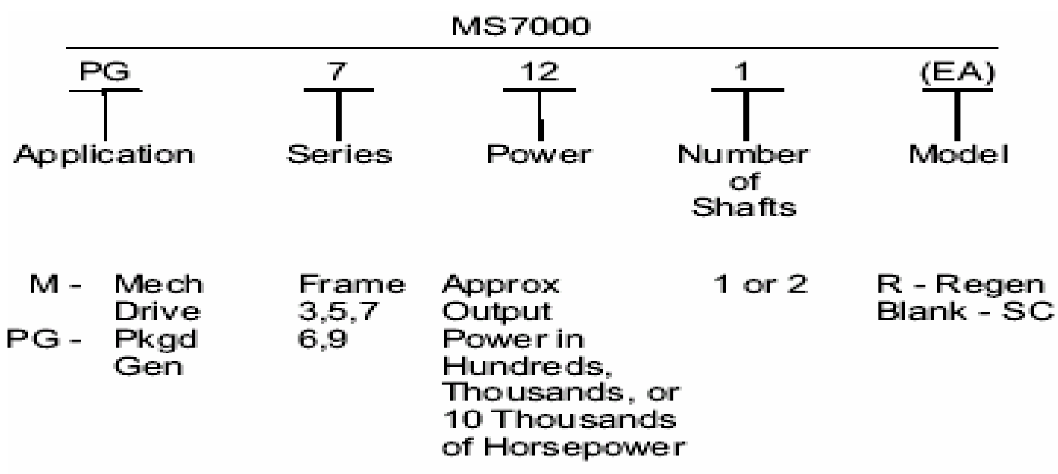
At ISO conditions: 15°C (59°F), sea level, 60% relative humidity, zero inlet or exhaust duct losses. Natural gas fuel.

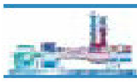
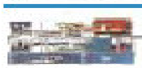
Generator Set Specifications

Gas Turbine Model	Type Duty	Nominal Output, kWe*	Thermal Efficiency, %	Standard Voltages	Length, m	Length, ft-in.	Width, m	Width, ft-in.	Height, m	Height, ft-in.	Weight, kg	Weight, lb
Saturn 20	Continuous	1210	24.3	240-4160	5.8	18' 11"	1.7	5' 5"	2.0	6' 6"	9980	22,000
Centaur 40	Continuous	3515	27.9	3300-13800	8.8	28' 9"	2.5	8' 0"	2.6	8' 6"	26077	57,500
Centaur 50	Continuous	4600	29.3	3300-13800	8.8	28' 9"	2.5	8' 0"	2.6	8' 6"	29025	64,000
Taurus 60	Continuous	5500	30.4	3300-13800	8.8	28' 9"	2.5	8' 0"	2.6	8' 6"	29478	65,000
Taurus 70	Continuous	7520	33.8	4160-13800	11.3	37' 0"	2.7	8' 11"	2.7	8' 11"	47803	105,385
Mars 90	Continuous	9450	31.7	3300-13800	14.5	47' 6"	2.8	9' 2"	3.6	12' 0"	64698	142,500
Mars 100	Continuous	10690	32.4	3300-13800	14.5	47' 6"	2.8	9' 2"	3.6	12' 0"	73028	161,000
Titan 130	Continuous	14000	33.3	11,000-13800	14.6	48' 0"	3.0	10' 0"	3.2	10' 7"	74844	165,000

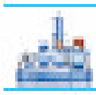
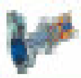
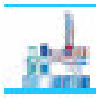
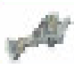
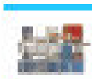
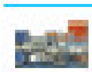
At ISO conditions: 15°C (59°F), sea level, 60% relative humidity, zero inlet or exhaust duct losses. Natural gas fuel.
* Measured at the generator terminals.

GE Turbines-Model Details

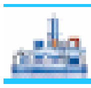
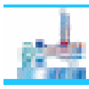
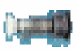
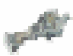
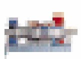
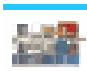


		GENERATOR DRIVE Approx. Weight(**) kg.	GENERATOR DRIVE Approx. Dimensions (**) m.	MECHANICAL DRIVE Approx. Weight(**) kg.	MECHANICAL DRIVE Approx. Dimensions (**) m.
	PGT5	28,000	8.5 x 2.5 x 3.0	30,000	7.7 x 2.5 x 4.3
	GE5	23,900	5.9 x 2.5 x 3.0		
	PGT10	27,000	8.1 x 2.5 x 4.0	32,000	9.1 x 2.5 x 4.0
	GE10	34,000	9.0 x 2.5 x 6.0	38,000	10.5 x 2.5 x 6.0
	PGT16	19,000	8.1 x 2.5 x 3.8	19,000	8.1 x 2.5 x 3.8
	PGT25	37,650	9.1 x 3.5 x 3.5	37,650	9.1 x 3.5 x 3.5
	PGT25+	30,750	6.5 x 3.6 x 3.9	30,750	6.5 x 3.6 x 3.9
	LM6000	31,000	9.3 x 4.2 x 4.4	31,000	9.3 x 4.2 x 4.4
	MS5001	87,430	11.6 x 3.2 x 3.7		
	MS5002C/D			110,000(*)	15.0 x 3.2 x 3.8(*)
	MS6001B	96,000(*)	15.9 x 3.2 x 3.8(*)	96,000(*)	15.9 x 3.2 x 3.8(*)
	MS7001EA	121,000	11.6 x 3.3 x 3.8	121,000(*)	11.6 x 3.3 x 3.8(*)
	MS9001E	217,500(*)	22.1 x 4.5 x 6.3(*)		

(*) including auxiliary skid
(**) gas turbine skid without enclosure

GENERATOR DRIVE (ISO conditions - natural gas - electrical generator terminals)											
	ISO RATED POWER		HEAT RATE		EFFIC.	PRESSURE RATIO	EXHAUST FLOW		TURBINE SPEED	EXHAUST TEMPERATURE	
	KW	-	KJ/kWh	-	%		Kg/sec	lbs/sec	RPM	°C	°F
 PGT5	5,220	-	13,422		26.8%	9.1	24.6	54.2	10,290	523	973
 GE5	5,500		11,740	-	30.7%	14.6	19.6	43.2	16,630	574	1,065
 PGT10	10,220	-	11,536	-	31.2%	13.8	42.3	93.3	7,900	488	910
 GE10	11,250	-	11,481	-	31.4%	15.4	46.9	103.4	11,000	484	903
 PGT16	13,735	-	10,314	-	34.9%	20.1	47.4	104.5	7,900	493	919
 PGT25	22,417	-	9,919	-	36.3%	17.9	68.9	151.9	6,500	525	976
 PGT25+	30,226	-	9,084	-	39.6%	21.5	84.3	185.8	6,100	500	931
 LM6000	43,076	-	8,707	-	41.3%	30.0	131.0	288.8	3,600	449	840
 MS5001	26,830	-	12,687	-	28.4%	10.5	125.2	276.1	5,094	483	901
 MS6001B	42,100	-	11,230	-	32.1%	12.2	145.8	321.7	5,163	552	1,026
 MS7001EA	85,100		11,000		32.7%	12.5	300.0	661.4	3,600	537	998
 MS9001E	123,400	-	10,650	-	33.8%	12.6	412.8	910.0	3,000	543	1,009

MECHANICAL DRIVE
(ISO conditions - natural gas - shaft output)

	ISO RATED POWER		HEAT RATE		EFFIC.	PRESSURE RATIO	EXHAUST FLOW		TURBINE SPEED	EXHAUST TEMPERATURE	
	KW	shp	KJ/kWh	btu/shp-h	%		Kg/sec	lbs/sec	RPM	°C	°F
 PGT5	5,440	7,295	13,470	9,520	26.7%	8.6	25.8	56.9	10,290	533	991
 PGT10	10,660	14,295	11,060	7,817	32.5%	13.8	42.3	93.3	7,900	488	910
 GE10	11,690	15,675	11,060	7,817	32.5%	15.2	46.9	103.4	7,900	484	903
 PGT16	14,252	19,120	9,939	7,020	36.2%	20.1	47.4	104.5	7,900	493	919
 PGT25	23,261	31,200	9,560	6,750	37.7%	17.9	68.9	151.9	6,500	525	976
 PGT25+	31,364	42,060	8,754	6,180	41.1%	21.5	84.3	185.8	6,100	500	931
 LM6000	44,740	60,000	8,455	5,980	42.6%	28.5	127.0	280.0	3,600	456	853
 MS5002C	28,340	38,005	12,470	8,814	28.8%	8.8	124.3	274.1	4,670	517	963
 MS5002D	32,580	43,690	12,239	8,650	29.4%	10.8	141.4	311.7	4,670	509	948
 MS6001B	43,530	58,380	10,825	7,650	33.3%	11.9	145.0	319.7	5,111	544	1,011
 MS7001EA	86,000	115,330	10,900	7,700	33.0%	12.5	300.0	661.4	3,600	538	1,000

Mechanical Drive Gas Turbine Ratings									
Model	Year	ISO Rating Continuous (kW)	ISO Rating Continuous (hp)	Heat Rate (Btu/shp-hr)	Heat Rate (kJ/kWh)	Mass Flow (lb/sec)	Mass Flow (kg/sec)	Exhaust Temp (degrees F)	Exhaust Temp (degrees C)
M3142 (J)	1952	11,290	15,140	9,500	13,440	117	53	1,008	542
M3142R (J)	1952	10,830	14,520	7,390	10,450	117	53	698	370
M5261 (RA)	1958	19,690	26,400	9,380	13,270	205	92	988	531
M5322R (B)	1972	23,870	32,000	7,070	10,000	253	114	666	352
M5352 (B)	1972	26,110	35,000	8,830	12,490	273	123	915	491
M5352R (C)	1987	26,550	35,600	6,990	9,890	267	121	693	367
M5382 (C)	1987	28,340	38,000	8,700	12,310	278	126	960	515
M6581 (B)	1978	38,290	51,340	7,820	11,060	295	134	1,013	545

Aeroderivative Gas Turbines

		Output (kW)	Heat Rate (Btu/kWh)	Heat Rate (kJ/kWh)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (lb/sec)	Exhaust Flow (kg/sec)	Exhaust Temp. (°F)	Exhaust Temp. (°C)
50 Hz Power Gen	LM6000PC Sprint*	49,500	8,471	8,935	30.0:1	3,627	297	135	821	438
	LM6000PC	43,000	8,538	9,006	30.0:1	3,627	285	129	787	419
	LM6000PD Sprint	46,900	8,262	8,715	30.0:1	3,627	292	132	834	446
	LM6000PD	41,700	8,366	8,824	30.0:1	3,627	279	127	838	448
	LM6000PD (liquid fuel)	40,417	8,443	8,721	28.5:1	3,627	272	123	853	456
	LM2500PK	29,300	9,625	10,152	22.8:1	3,000	197	89	911	488
	LM2500PV	33,500	8,920	9,409	23.0:1	6,100	197	89	907	486
	LM2500PH	26,500	8,673	9,148	18.2:1	3,000	167	76	927	497
	LM2500PE	22,800	10,008	10,556	18.9:1	3,000	158	72	956	513
	LM2000	17,600	9,600	10,129	15.6:1	3,000	139	63	885	474
	LM1600PA	13,700	9,760	10,295	20.1:1	7,900	110	50	894	478
60 Hz Power Gen	LM6000PC Sprint*	49,500	8,451	8,914	30.0:1	3,627	300	136	826	441
	LM6000PC	43,500	8,485	8,950	30.0:1	3,627	284	129	792	422
	LM6000PD Sprint	46,800	8,235	8,686	30.0:1	3,627	290	132	837	447
	LM6000PD	42,300	8,308	8,763	30.0:1	3,627	278	126	846	452
	LM6000PD (liquid fuel)	40,212	8,415	8,878	28.1:1	3,627	268	122	857	458
	LM2500PK	30,900	9,288	9,797	22.9:1	3,600	197	89	906	486
	LM2500PH	27,700	8,402	8,862	17.8:1	3,600	167	76	922	494
	LM2500PE	24,000	9,716	10,248	19.0:1	3,600	157	71	955	513
	LM2000	17,600	9,715	10,247	15.4:1	3,600	136	62	917	492
	LM1600PA	13,700	9,760	10,295	20.1:1	7,900	110	50	894	478
Mechanical Drive		Output (hp)	Heat Rate (Btu/shp-h)		Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (lb/sec)	Exhaust Flow (kg/sec)	Exhaust Temp. (°F)	Exhaust Temp. (°C)
	LM6000PC	60,000	5,938	—	29.1:1	3,600	281.9	127.8	825	440
	LM2500PK	40,044	6,702	—	22.6:1	3,000	193.5	87.7	967	519
	LM2500PE	30,400	7,017	—	18.1:1	3,000	153.3	69.5	994	534
	LM2000PA	24,300	7,117	—	16.0:1	3,600	141.9	64.4	894	479
	LM1600PA	19,100	7,016	—	20.2:1	7,900	104.3	47.3	915	491

*Sprint 2002 deck is used with water injection to 25 ppmvd for power enhancement.

NOTE: Performance based on 59° F amb. Temp., 60% RH, sea level, no inlet/exhaust losses on gas fuel with no NOx media, unless otherwise specified.

Gas Path Description

- As the turbine starting system is actuated and the clutch is engaged, ambient air is drawn through the inlet plenum assembly, filtered & compressed in Axial air compressor.

- For pulsation protection during startup bleed valves are installed.

- Compressed air from compressor flows into the annular space surrounding the combustion chambers, through combustion wrapper casing.

- Air flows in to the spaces between the outer combustion casing and combustion liners, enters the combustion zone through holes provided in combustion liners.

- Fuel from off-base source in provided at fuel nozzles centered in the end plate of a separate combustion chambers.

- The nozzles introduce the fuel in to the combustion chambers where it mixes with the combustion air and is ignited by spark plugs. At the instant when fuel is ignited in one combustion chamber, flame is propagated, through connecting cross fire tubes to all combustion chambers.

- After the turbine rotor reaches operating speed, combustion chamber preserve causes the spark plugs to retract, to remove their electrodes from the hot flame zone.

- The hot gases from the combustion chambers expand in to the separate transition pieces attached to the aft end of the combustion liners.

- Hot gases then flow to HP turbine section.

- HP turbine section consist of fixed nozzle & buckets.

- LP turbine section consists of variable nozzle and turbine blades.
- After passing through turbine section , the gases are directed in to exhaust hood and diffuse which contains a series of turning vanes to turn the gases from axial direction to radial direction, thereby reducing exhaust hood loss.
- The gases then pass in to exhaust plenum and are introduced to atmosphere through exhaust stack.

GT Systems

- The Gas Turbine incorporates a number of control protection and support systems associated the unit. These systems vary from turbine to turbine depending on customer requirements.

Control & protection systems

- Typically the control systems include those systems used for control of the gas turbine in normal starting. operation, and loading. They also include the speed control, temperature control, start up control, and fuel control functions.

- The protection systems include those systems required for normal startup and shutdown protection and their associated permissive logic and those systems required for prevention of damage to the turbine due to mal-operation or abnormal or emergency conditions.

- Such abnormal or emergency conditions occasionally occur in systems. They can result from a fault or failure external to the turbine and load systems, or within the control systems of the station.

- Equipped with SPEEDTRONIC™ Mark IV/ V/ VI control system

Support systems

Support systems typically include:

- The lube oil system, for furnishing normal lubrication and absorbing the heat rejection of the gas turbine.

- The hydraulic supply system, which provides the necessary hydraulic flows and pressures for control device on the turbine.

- The control oil (Trip Oil) system, which operates devices for the fuel control, second stage nozzle control, hydraulic trip subsystem.

- The cooling water system, which cools the lube oil. This system is closed and independent of external water.

- The starting system, including the starting device and the required panel logic sequence for starting the gas turbine and bringing it up to operating speed.

- The cooling and sealing air system, which provides the necessary air flow from the turbine compressor to other parts of the excessive temperature buildup and to prevent bearing oil leakage.

- The fuel system which supplies, control the flow of, and directs the fuel to the fuel nozzles in the gas turbine combustors.

- The atomizing air system provides sufficient pressure in the air atomizing chamber of the fuel nozzles to break the fuel jet upto a fine mist, permitting ignition and combustion with increased efficiency.

- The ventilating and heating system provides the ventilation of hot air from compartments so that various devices in these compartments work within the allowable compartments temperatures.

- The fire protection system is provide to extinguish fires in the compartments, in case any fire takes places.

- The inlet and exhaust system provide atmospheric air to be brought into the compressor through inlet ducting and let exhaust gases either to atmosphere or to heat recovery steam generators through exhaust ducting.

Lubrication System

- Lube oil is circulated to the turbine bearings, compressor bearings, couplings, accessory gear box & load gear box. Again a portion of pressurized fluid is diverted and filtered again for use by hydraulic control devices as control fluid and as a supply to other system.

- Major system component include:

    - Lube oil reservoir in the turbine base

- Main lube oil pump (shaft driven from accessory gear)
- Auxiliary Lube Oil Pump
- Emergency Lube Oil Pump
- Pressure relief valve in the main pump discharge
- Lube Oil Heat Exchangers
- Lube Oil Filters (5 micron)
- Coupling Oil Oil Filters (5 micron)
- Coupling Oil Pr. Regulator
- Bearing Header Pressure Regulator

Trip oil system

- It is primary protection interface between the turbine control panel and the components on the turbine which admit or shut off fuel to the turbine.
- Lube oil from turbine bearing header is used for trip functions (abnormal & emergency shutdown) as well as hydraulic signal to the fuel stop valve for normal startup & shutdown.
- LO is passed through a piping orifice to become the trip oil (OLT). The orifice is sized to limit the flow of lube oil in to trip oil system & insure an adequate capacity for all tripping device operation without causing starvation of the Lube oil when the trip oil system is activated.
- The trip oil is supplied to IGV trip device, 2nd stg Nzzle trip device, Turbine over-speed trip device, Fuel stop valves.
- The over-speed trip mechanism mounted on HP & LP rotor. It is a mechanical device, actuated automatically by the over-speed bolt should the turbine speed exceed the bolt setting. As a result, a rapid decay of Trip oil pr occurs, ultimately stopping the flow of fuel to the turbine by action of the Fuel stop valve.

Hydraulic Oil System

- Fluid power required for operating the control componenets of the gas turbine fuel system, is provided by the hydraulic oil system. This furnishes the means for opening or resetting of the fuel stop valves, in addition to the variable IGV & 2 nd stage nozzle, clutch, hydraulic control & trip devices of the gas turbine.

- Major Component Include:

    - Main Hydraulic Oil Pump
    - Auxiliary Hydraulic Oil Pump
    - Hydraulic Oil Filters
    - Accumulator Assembly.
    - Hydraulic Manifold Assembly

Starting System

- Before the Gas turbine can be fired and started it must be rotated or cranked by the accessory equipment. This is accomplished by Diesel Engine/ Cranking motor/Expansion motor etc. through a torque converter to provide power required by the turbine for the startup.

- Major Component Include:

    - Cranking Motor
    - Torque Converter
    - Starting Clutch
    - Accessory Coupling
    - Accessory Gear Box

Torque Converter Assy

This includes the following.

- Torque Converter Assy
- Hydraulic Ratchet Mechanism
- Output Gear Unit

- Torque converter consists of a cranking motor driven pump rotor that supplies oil to a hydraulic turbine connected to the input shaft of the output gear.

- The hydraulic ratchet mechanism is a rack & pinion type rotary actuator connected through a roller- ramp type one-way clutch to the input shaft of the output gear. The output gear unit connects the ratchet mechanism and the output side of the torque converter to the starting clutch.

- Components of the ratchet assy include:

  - Rotary actuator/one way clutch mechanism in the Torque convertor assy, Control valve module, Pump assy & relief valve.

- Oil from the Lube oil system is ported to the starting clutch and the ratchet system.

- Hydraulic self sequencing automatically shifts the oil flow between the forward & rest strokes of the ratchet mechanism. A forward stroke advances the starting clutch about 47 deg during the 10 sec duration. The rest strok is about 4.5 sec duration.

- Once every three minutes the mechanism is operated through one complete cycle. The cycle is terminated in the forward stroke position to lock the clutch in engaged position.

Accessory Drive

- The accessory drive gear, located at the compressor end of the gas turbine, is a gearing assembly coupled directly through accessory coupling to the turbine rotor. Its function is to drive each gas turbine accessory at its proper speed and to connect & disconnect the turbine from the starting device.

- In addition it contains the system main lube oil pump and the HP turbine over-speed trip bolt & mechanism.

- Accessories driven by gear may include:
  - Main Lube oil Pump
  - Main Hydraulic oil Pump
  - Liquid Fuel Pump
  - Water Pump
  - Main Atomizing Air compressor

Atomizing Air System

- For Liquid fuel system.
- Provides sufficient pressure in the air atomizing chamber of the fuel nozzle body to maintain the ratio of atomizing air pr to Compr. Disch. pr at approx. 1.2 or greater over the full operating range of the turbine.
- Major component include:
  - Atomizing air compressor
  - Atomizing Air Heat Exchanger
  - Starting atomizing air compressor

Cooling & Sealing Air System

- Provides the necessary air flow from the Gas Turbine compressor to the other parts of the GT rotor & stator to cool these parts during normal operation. Used to provide the following cooling & sealing functions:
  - Sealing of turbine bearings
  - Cooling of turbine internals

  - Cool the turbine outer shell and exhaust frame
  - Providing an operating air supply for the air operated valves
  - Compressor pulsation protection (Bleed system)
  - Provide pulse air to self cleaning inlet air filters.

- Specially designed air passages are fabricated in the turbine casing, turbine nozzle & rotating wheels.
- Air is extracted from compressor stgs, from compressor discharge etc.
- This extraction also induces the flow of Ambient air for aft shell turbine cooling system through eductors.
- Centrifugal dirt separators are installed for bearing sealing air lines for removal of dirt etc.

Gas Fuel System

- Designed to deliver the gas fuel to the turbine combustion chambers at a proper pressure and flow rates to meet all of the starting, acceleration and loading requirements of the Gas Turbine.
- Major components include:
  - Gas fuel strainer
  - Fuel gas low pr alarm switch. Pressure gauges.
  - Gaseous fuel vent valve.
  - Gas fuel trip valve.
  - Gas stop ratio valve & control valve (SRV & GCV)
  - Stop ratio valve control servo-valve

- Gas control valve control servo-valve
- Gas control valve LVDTs
- Stop ratio valve LVDTs
- Pr transducers
- Gas fuel servo hydraulic filter (in the hyd supply to the SRV & GCV)
- Gas fuel Manifold & Nozzles

- Protection Device
  - Low gas pr switch, installed in the Gas piping ahead of GCV /SRV provides the alarm protection should the gas pr drops below the switch setting.
  - Fuel gas vent valve vent the any accumulated gas in the compartment between GCV/SRV through pipings.
  - Three pr transducers are installed in the fuel gas discharge side of the SRV to provide operational feedback signal to the control system.
  - Three Pr gauges are provided in the fuel gas piping. P1 measures the pr of the fuel gas entering the SRV, P2 measures the pr as it leaves the valve & P3 measures the pressure of the gas leaving the GCV and flowing to the gas manifold.

Inlet & Exhaust System

- Gas turbine performance and reliability is a function of the quality and cleanliness of the inlet air entering the turbine. It is necessary to treat the inlet air entering the turbine & filter out the contaminants.
- Inlet air system with its specially designed equipment & ducting to modify the quality of the air under various temp, humidity and contamination situations.
- Hot exhaust gases produced as a result of the combustion in the turbine are cooled and attenuated in the exhaust system ducting before being released to the atmosphere.

- The noise generated during Gas turbine operation is attenuated by means of absorptive silencing material and devices built in to inlet & exhaust sections which dissipate or reduce the acoustical energy to an acceptable level.

- Major components include:

  - Air inlet filters
  - Inlet ducting
  - Inlet silencers: Silencing is provided by use of vertical baffles consisting of acoustically perforated sheets of encapsulated low density insulation material.
  - Exhaust plenum
  - Expansion joints
  - Exhaust silencer
  - Exhaust duct
  - Stack

Ventilating & Heating System

- Both ventilating & heating capabilities have been incorporated in to the accessory and turbine compartments (enclosure), with each utilizing thermally insulated side panels and roofs.

- Gravity closing dampers are used in the system to automatically provide a tight closure when fire protection system is activated.

- Through independent ductings, Vent fans discharge air is drawn in Accessory chamber, Combustion compartment, Turbine compartment & Exhaust compartment.

- After cooling the air is vented to atmosphere through independent ducts.

Fire Protection System

- CO_2 is designed to extinguish fires by reducing the O_2 content of the air in a compartment from an atmosphere normal of 21 % to less than 15%, an insufficient concentration to support the turbine fuel or Lube oil.

- It provides an extended discharge to maintain an extinguishing concentration for approx 40 minutes to minimize the likelihood of a re-flash condition because of the re-flash potential of the combustibles exposed to high temp metal.

- For CO_2 system to be effective, the compartment panel must be in place and the compartment door must be closed.

- Extremely hazardous to enter the compartments after the CO_2 system has been charged, as it creates an atmosphere that will not support the life.

Speedtronic Control System

- GT control system is designed to crank the turbine, bring it to purging speed (approx 20%), Fire it, and then bring the unit to the operating speed.

- On Compressor or process drive loads the GT to the appropriate point, on generator drive synchronizes to the line.

- This system must occur automatically and is one while minimizing the thermal stresses in the GT Hot gas path parts & associated hardware.

- Following is the chronological order of evolution of the control system:

    - Fuel regulator
    - Mechanical Controls
    - SPEEDTRONIC Mark-I
    - SPEEDTRONIC Mark-II
    - SPEEDTRONIC Mark-II WITH INTEGRATED TEMP SYSTEM

- SPEEDTRONIC Mark-IV
- SPEEDTRONIC Mark-V
- SPEEDTRONIC Mark-VI

The total control system can be divided in to four functional sub-systems:

- Control
- Protection
- Sequencing
- Power supply

Of these the control sub-system is the predominant. It must perform five basic functions:

- Set start-up & normal fuel limits
- Control Turbine Acceleration
- Control Turbine speed
- Limit internal turbine Temp
- Control Air flow/ Load

Only one control function or system can control the fuel flow to the GT at a time. The four control systems feed a "minimum value gate" whose output is used as an input by the fuel control system. A minimum value is used to provide the safest operation of the turbine.

- Protection system is designed to trip the turbine by stopping fuel flow when critical parameters are exceeded or control equipment fails.

  - Over-temperature

- Over-speed
- Loss of flame
- Vibration
- Combustion monitor(not for fr3/fr5 machines)

FUNCTIONAL CONTROL DIAGRAM
TWO-SHAFT GAS TURBINE

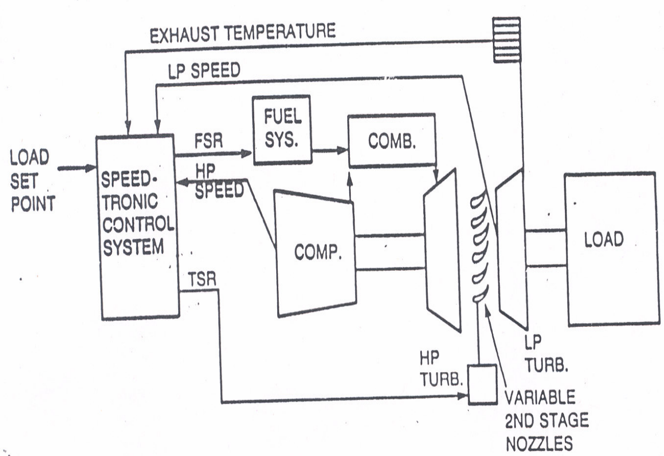


FIGURE TS-1
(103-104)

OVERTEMPERATURE PROTECTION

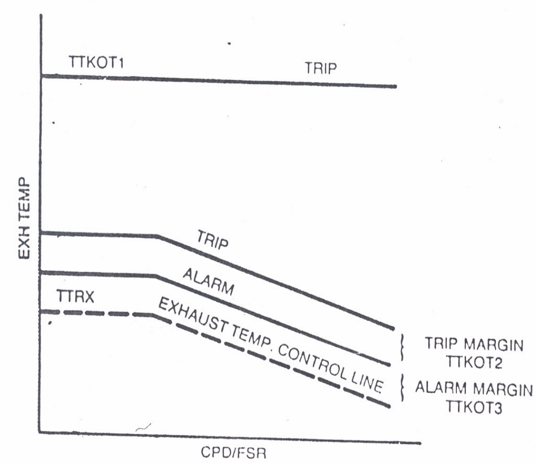


FIGURE OTFR-1
(593)

Gas Turbine Component/Parts

Following are typical major Gas turbine parts

- Combustion chambers
- Cross fire tubes
- Combustion elbows(outer/inner)

Fuel nozzles combustion liners
Spark plugs flame detectors

- Transition pieces

Transition piece packing

- Combustion wrapper casing
- Exhaust plenum

Turbine casing Compressor Casings
Exhaust Frame Exhaust Diffuser

- Hp rotor

LP Rotor

- I st stage nozzle nozzle support

Ist nozzle control ring Ist stage ring IGV Assly 2nd stage VAR Nozzle

- I st stage bucket

Ist stg shroud 2nd stage bucket

- 2 nd stg shroud

2 nd stg diaphragm

- Flex seal plates
- Bearings & bearing housings

Bearing labyrinths

- Accessory coupling

Load coupling guards

Turbine Base

- Structural steel foundation on which GT is mounted.
- Supports basic GT unit, accessory equipment, inlet & exhaust plenums.
- The forward end of the base under the accessory compartment, also functions as a Lube oil tank.

- An oil drain channel is constructed along the web of the left longitudinal I-beam.
- This channel extends from the oil tank to the end of the base, providing a passage for the lube oil header.

Turbine Supports

- Mounted to its base by vertical supports at three locations.
- The forward support is located at the lower half of the forward vertical flange of compressor casing.
- The aft two supports are located on either side of the turbine shell.

Compressor Section

- Consists of the compressor rotor & enclosed casing.
- Included with in the compressor casing are the inlet guide vanes, rotor & stator blading and 2 exit guide vanes.

Compressor Rotor

- Consists of 2 stub shafts, wheels, through bolts and rotor blades.
- The forward stuff shaft is machined to provide active & inactive thrust faces and journal for No. 1 bearing etc.

Compressor Stator : Three major sections:

Inlet Casing :

- Located at the forward end of GT.
- Its prime function is to uniformly directs air in to compressor.,It also supports No.1 bearing assembly.

- IGV are located at the aft end of the inlet casing.

Compressor Casing

Discharge Casing:

- Final portion of the compressor section. It is the longest single casing.

Blading

- Compressor rotor and stator blades are airofoil shaped and are designed to compress air efficiently at high tip velocities.

Combustion Section

- Reverse flow type.
- Includes combustion chambers, combustion elbows etc..
    - Combustion liners.
    - Transition pieces.
    - Cross fore tubes.
    - Spark Plug : Two high voltage, retractable electrode sparkplugs mounted in adjacent combustion chambers.
    - Flame Detectors : Two UV flame scanners are installed on two adjacent combustion chambers.
    - Fuel Nozzels : Emits a metered amount of air in to combustion liners.

Turbine Section

- HP Turbine rotor is of through bolt construction, consisting of distance pieces, turbine wheels, inter stage spacers and aft wheel shaft.

- It is mated to the compressor rotor by the bolted flange connection on the final stage compressor wheel.
- Aft wheel shaft includes No. 2 bearing journal.
- LP turbine rotor consists of turbine wheels, inter stage spacers and aft wheel shaft.
- Aft wheel shaft connects turbine wheel to the load coupling.
- It includes No. 3 & No. 4 bearing journal & active / inactive thrust faces etc.

Buckets

- In fr-6 (power generation) three stage turbine is used. Buckets increases in size from first to third stage.
- Ist & IInd Buckets are internally air cooled.
- The third stage buckets are not internally air cooled, however the tips of these buckets, like 2nd stage buckets, are enclosed by a shroud which is a part of the tip seal.
- Fr-5 turbines buckets are not internally cooled.

Rotor Cooling

- Turbine rotor must be cooled to maintain reasonable operating temperature and therefore, assure a longer turbine service life.
- Cooling is accomplished by means of a positive flow of cool air radially outward through a space between the wheel & buckets and buckets & stator in to main gas stream. This area is called wheel spaces.

Turbine Stator

- Turbine shell and the exhaust frame complete the major portion of the gas turbine stator structure.
- Turbine casing (shell) :

- Controls the axial & radial position of the shrouds and nozzles, thus controlling turbine clearances and relative positions of the nozzles to the turbine buckets.

- First stage fixed nozzle.
- Second stage variable nozzle.
- 2nd stage diaphragm & inter stage gas path.
- Cooling of turbine shell through extraction air, ambient air through eductors.
- Shrouds:
  - Unlike the compressor blading, the turbine bucket tip do not run directly against integral machine surface of the casing but against annual curved segments called shrouds.
  - The shroud's primary function is to provide a cylindrical surface for minimum bucket tip clearance leakage.
  - Shrouds secondary function is to provide a high thermal resistance between the hot gases and comparatively cool shell.
  - By accomplishing this function, the shell cooling load is drastically reduced, the shell diameter is controlled, the shell roundness is maintained, and important turbine clearances are assured.

Exhaust Frame

- It is bolted to the aft flange of the turbine shell.
- Structurally, the frame consists of an outer cylinder and inner cylinder interconnected by the radial struts.
- The exhaust diffuses is located between the inner and outer cylinder.

- At the exit of the diffuser, turbine various assist in directing the gases in to the exhaust plenum.
- Turbine shell cooling air flows through the space between the struts and the wrapper to maintain uniform temperature of the struts.

Bearings

- HP rotor is supported on No. 1 & No. 2 journal bearings. LP rotor is supported on No. 3 & No. 4 journal bearings.
- Each rotor is having thrust bearing assembly

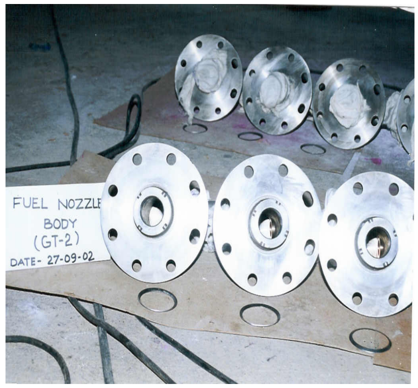
– Bearing No. 1	Journal	Elliptical
	Thrust Active / Inactive	Tilting pad
– Bearing No. 2	Journal	Elliptical
– Bearing No. 3	Journal	Elliptical
– Bearing No. 4	Journal	Elliptical
	Thrust Active / Inactive	Tilting pad

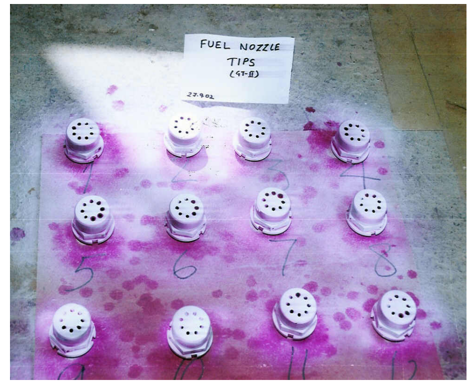
- These bearings and seals are incorporated in bearing housings.

Couplings

- Accessory coupling :
  - Splined, oil filled flexible coupling.
- Load coupling :
  - A rigid hollow coupling connects the turbine rotor shaft to the reduction gear.

Fuel Nozzle





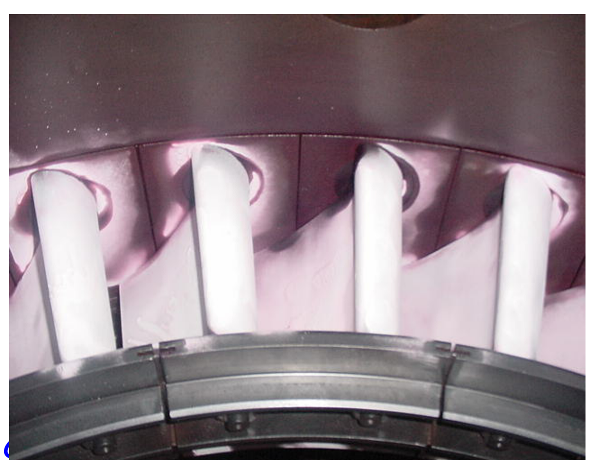
Combustion Liner

CombustionLiner & Cross Fire Tubes

Transition Piece

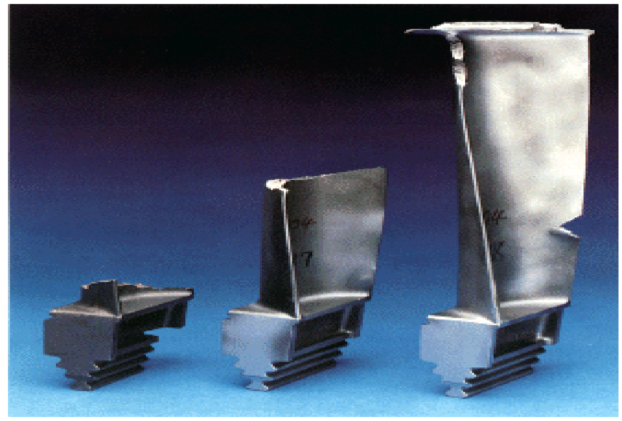
I st Stage Nozzle

2nd Stg Nozzle

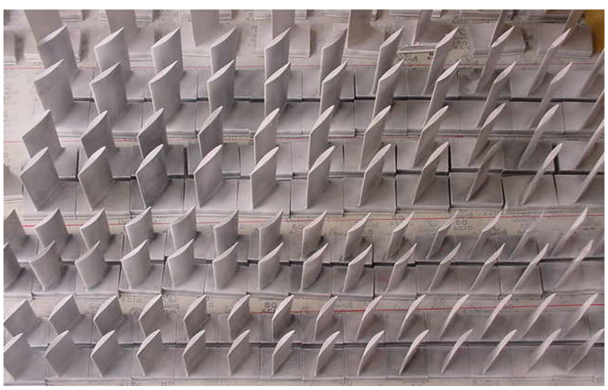


Ist Stage Bucket

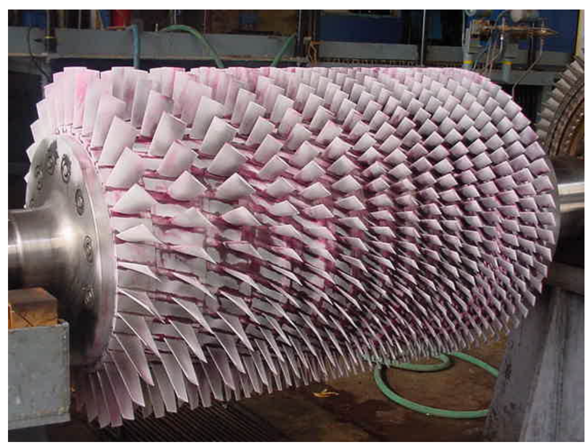
Damaged Buckets



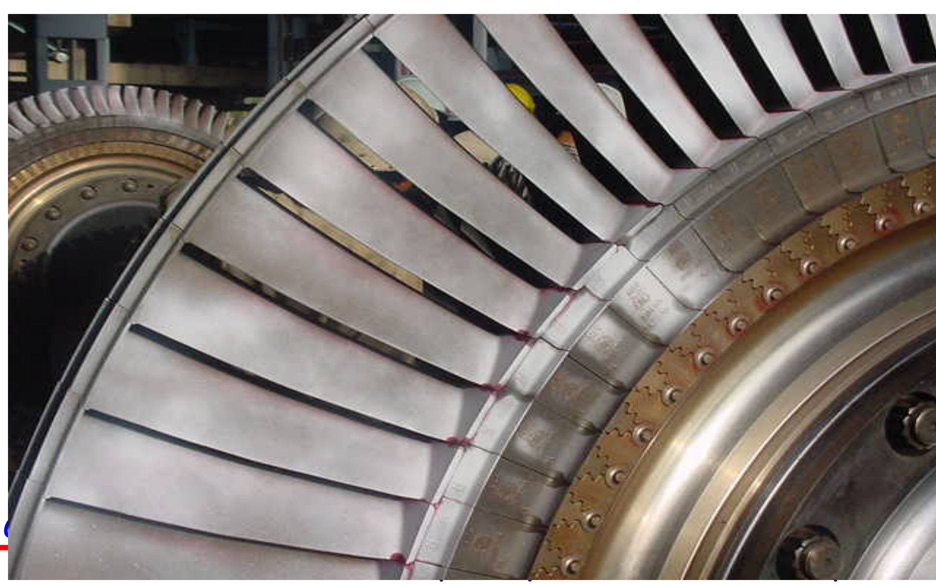
Compressor Stator Blades



HP Rotor



2nd Stg Buckets



Gas Turbine Materials

Casing	: Gray / Ductile Cast Iron
Combustion Liners	: Hest Alloy
Transition Piece	: Hest Alloy
Compressor Wheels	: Cr-Mo-V Steel
Turbine Wheels	: IN 706, M 152 Cr-Mo-V Steel
Compressor Blades	: SS 403 (12% Cr STEEL) With Ni, Cr coating to prevent corrosion
1st Stage Buckets	: IN 738, GTD 111, Coated with Pt-Cr-Al Coating
2nd Stage Buckets	: U 700 (RENO 77), U 500
Nozzles	: FSX 414, N155

Bucket And Nozzles Are Produced By Low Wax Investment Casting.

Modern Alloys

- Turbine blade alloy is complex in that it contains up to ten significant alloying elements, but its microstructure is very simple. The structure consisted of rectangular blocks of stone stacked in a regular array with narrow bands of cement to hold them together. In the alloy case the `blocks' are an inter-metallic compound with the approximate composition $Ni_3(Al,Ta)$, whereas the cement' is a nickel solid solution containing chromium, tungsten and rhenium.

Superalloys

- Titanium in the original inter-metallic has been replaced by Tantalum. This change gave improved high temperature strength, and also improved oxidation resistance.

- The evolution from wrought to conventionally cast to directionally solidified to single crystal turbine blades has yielded a 250°C increase in allowable metal temperatures, and cooling developments have nearly doubled this in terms of turbine entry gas temperature.

- Alignment of the alloy grain in the single crystal blade, which has allowed the elastic properties of the material to be controlled more closely. These properties in turn control the natural vibration frequencies of the blade.

- If metallurgical development can be exploited by reducing the cooling air quantity this is a potentially important performance enhancer, as for example, the Rolls-Royce Trent 800 engine uses 5% of compressor air to cool its row of high pressure turbine blades. The single crystal alloy, RR3000, is able to run about 35°C hotter than its predecessor. This may seem a small increase, but it has allowed the Trent intermediate pressure turbine blade to remain un-cooled.

Thermal Barrier Coatings

- Thermal barrier coatings are used for some years on static parts, initially using Magnesium Zirconate but more recently Zirconia.
- On rotating parts, the possibility of ceramic spalling is particularly dangerous, and strain-tolerant coatings are employed with an effective bond coat system to ensure mechanical reliability.
- Ceramic Matrix Composites further increases in temperature are likely to require the development of ceramic matrix. composites.

IN738	
Cr	16
Co	8.3
Fe	0.2
W	2.6
Mo	1.75
Ti	3.4
Al	3.4
Cb	0.9
C	0.1
B	0.001
Ta	1.75
Ni	REST.

GTD111	
Cr	14
Co	9.5
W	3.8
Mo	1.5
Ti	4.9
Al	3.0
C	0.1
B	0.01
Ta	2.8
Ni	REST.

U700	
Cr	15
Co	17
Mo	5.3
Ti	3.35
Al	4.25
C	0.07
Fe	0.02
Ni	REST

U500	
Cr	18.5
Co	18.5
Mo	4
Ti	3
Al	3
Ni	RES

N155	
Cr	21
Ni	20
Co	20
Fe	REST
W	2.5
Mo	3
C	0.20

FSX414	
Cr	29
Ni	10
Co	REST
Fe	1
W	7
C	0.25
B	0.01

Hest Alloy	
Ni	51
Fe	6
Cr	17
Mo	19
Si	0.1
Mn	1
W	5

Advancement- F Series

- Introduced in 1987, F class gas turbines, including the 7F (60 Hz),the 9F (50 Hz) and the 6F (either 50 or 60 Hz).
- Include an 18-stage axial compressor and a three-stage turbine.
- Features a cold-end drive and axial exhaust, which is beneficial for combined cycle arrangements.
- Firing Temp ~ 1300 deg C

_9FA_ MS9001FA

- Robust Dry Low NOx (DLN) 2.0+ combustor, suited for the diverse fuels.
- Greater than 56% cycle efficiency with less than 25 ppm NOx.
- Can be configured in a single shaft combined cycle arrangement with the generator and steam turbine.
- For large combined cycle or cogeneration power plants, the 9FA can be arranged in a multi-shaft configuration where one or two gas turbines are combined with a single steam turbine to produce power blocks of 390 or 780 MW.

_7FA_ MS7001FA

- Reduced of NOx and CO emissions. GE's DLN 2.6 (Dry Low NOx combustor produces less than 9 ppm NOx and CO, thereby minimizing the need for exhaust cleanup systems.

_6FA_ MS6001FA

- Mid-size version of the 7FA and 9FA. Designed for either 50 or 60 Hz applications.
- Produces 75.9 MW of simple cycle power at 35% efficiency and 117.7 MW of combined cycle power at 54.7% net efficiency..

- Its can-annular combustors are the same size and configuration as the 7FA's, the number of combustion chambers is decreased from 14 to 6.
- Cold-end drive allows exhaust gases to be directed axially into the HRSG.
- Ability to burn a wide spectrum of fossil fuels, including gasified coal, like other F technology units.
- The Dry Low NOx combustion system is available, which can achieve NOx emissions of 15 ppm when burning natural gas.

MS6001FA Simple Cycle Performance		Power Generation 50 Hz	60 Hz
Output	(MW)	75.9	75.9
Heat Rate	(Btu/kWh) (kJ/kWh)	9,760 10,300	9,795 10,330
Pressure Ratio		15.6:1	15.7:1
Mass Flow	(lb/sec) (kg/sec)	447 203	449 204
Turbine Speed	(rpm)	5,231	5,254
Exhaust Temperature	(°F) (°C)	1,120 605	1,118 604
Model Designation		PG6111FA	

MS7001FA Simple Cycle Performance		60 Hz Power Generation
Output	(MW)	171.7
Heat Rate	(Btu/kWh) (kJ/kWh)	9,420 9,936
Pressure Ratio		15.5:1
Mass Flow	(lb/sec) (kg/sec)	952 432
Turbine Speed	(rpm)	3,600
Exhaust Temperature	(°F) (°C)	1,116 602
Model Designation		PG7241FA

MS9001FA Simple Cycle Performance		50 Hz Power Generation
Output	(MW)	255.6
Heat Rate	(Btu/kWh) (kJ/kWh)	9,250 9,757
Pressure Ratio		15.4:1
Mass Flow	(lb/sec) (kg/sec)	1,375 624
Turbine Speed	(rpm)	3,000
Exhaust Temperature	(°F) (°C)	1,129 609
Model Designation		PG9351FA

MS6001FA Combined Cycle Performance

		Net Plant Output (MW)	Heat Rate (Btu/kWh)	Heat Rate (kJ/kWh)	Net Plant Efficiency	GT Number & Type
50 Hz	S106FA	117.7	6,240	6,580	54.7%	1 x MS6001FA
50 Hz	S206FA	237.9	6,170	6,510	55.3%	2 x MS6001FA
60 Hz	S106FA	118.1	6,250	6,590	54.6%	1 x MS6001FA
60 Hz	S206FA	237.5	6,210	6,550	54.9%	2 x MS6001FA

MS7001FA Combined Cycle Performance

		Net Plant Output (MW)	Heat Rate (Btu/kWh)	Heat Rate (kJ/kWh)	Net Plant Efficiency	GT Number & Type
60 Hz	S107FA	262.6	6,090	6,425	56.0%	1 x MS7001FA
60 Hz	S207FA	529.9	6,040	6,375	56.5%	2 x MS7001FA

MS9001FA Combined Cycle Performance

		Net Plant Output (MW)	Heat Rate (Btu/kWh)	Heat Rate (kJ/kWh)	Net Plant Efficiency	GT Number & Type
50 Hz	S109FA	390.8	6,020	6,350	56.7%	1 x MS9001FA
50 Hz	S209FA	786.9	5,980	6,305	57.1%	2 x MS9001FA

MS7001FB/MS9001FB

- The FB is the latest evolutionary step in GE's F series.
- Using materials developed for the *H System.*
- The FB firing temp was increased more than 100 deg F over FA, resulting in combined cycle efficiency rating improvements of better than 1%. Output improvements of more than 5%.
- Use of advanced turbine materials, such as Single Crystal First-Stage Buckets, ensures that components can stand up to the higher firing temperatures of the FB without an increase in maintenance intervals.

MS7001FB/MS9001FB Combined Cycle Performance

		Net Plant Output (MW)	Heat Rate (Btu/kWh)	Heat Rate (kJ/kWh)	Net Plant Efficiency	GT Number & Type
50 Hz	S109FB*	412.9	5,880	6,205	58.0%	1 x MS9001FB
	S209FB	825.4	5,884	6,208	58.0%	2 x MS9001FB
60 Hz	S107FB	280.3	5,950	6,280	57.3%	1 x MS7001FB
	S207FB	562.5	5,940	6,260	57.5%	2 x MS7001FB

Advancement "H" technology

MS7001H/9001H

- H System™—combined cycle system, capable of breaking the 60% efficiency barrier—integrates the gas turbine, steam turbine and heat recovery steam generator into a seamless system, optimizing each component's performance.

Design Features

Closed-loop steam cooling system

- Open loop air-cooled GTs have a significant temp drop across the first stage nozzles, which reduces firing temp. H combined cycle systems are based on a unique technology platform in which the steam plant reheat process and gas turbine bucket and nozzle cooling are accomplished by the same integrated heat transfer system.

- This closed-loop steam cooling system allows the turbine to fire at a higher temperature for increased performance, yet without increased combustion temperatures or their resulting increased emissions levels.

- Closed-loop steam cooling enables the H System™ to achieve 60% fuel efficiency while maintaining low NOx standards and reducing CO2 emissions.

- Additionally, closed-loop cooling also minimizes parasitic extraction of compressor discharge air, thereby allowing more air to flow to the head-end of the combustor for fuel premixing.

Single Crystal Materials

- The use of these advanced materials, which are utilized on the first stage nozzles and buckets, and Thermal Barrier Coatings, on the first and second stage nozzles and buckets, ensures that the components stand up to high firing temperatures while meeting maintenance intervals.

Dry Low NOx Combustors

- Employs a can-annular lean pre-mix DLN-2.5 Dry Low NOx (DLN) Combustor System. Fourteen combustion chambers are used on the 9H, and 12 combustion chambers are used on the 7H.

- The H System™ offers a greater than 40% reduction in land area per installed MW compared to other combined cycle systems, once again helping to reduce the overall cost of producing electricity.

- Axial exhaust

- Firing temperature Increased over 100 °C (212 °F) to 1,430 °C (2,606 °F)

- 18-Stage Compressor, GE Aircraft Engine CF6 derivative, Higher flow 60 Higher Pr Ratio -23:1 Hz 7H - 1230 lbs airflow , 50 Hz 9 H - 1510 lbs airflow

- Increased output : 60 Hz 7H - 400 MW , 50 Hz 9H - 480 MW

- 4-Stage Turbine Section , 3-D aerodynamics

GE SPEEDTRONIC™ Mark VI control system

- Microprocessor based control system. Single platform provides focal point for all control, protection, and monitoring.

Emissions

- Equipped with DLN 2.6 combustion systems which achieve NOx emissions of 9 ppm - CO2. In addition, produces the lesser tons of CO2 per kilowatt of electricity generated per year.

7H / 9H Performance

	60 Hz - 7H	50 Hz - 9H
CC output	400	480
CC net	60%	60%
NOx emissions	9 ppm	25 ppm
Firing temp	2,600 °F 1,430	2,600 °F 1,430
Air flow	1,230 lbs/s 558 Kg/s	1,510 lbs/s 685 Kg/s
Pressure Ratio	23:1	23:1

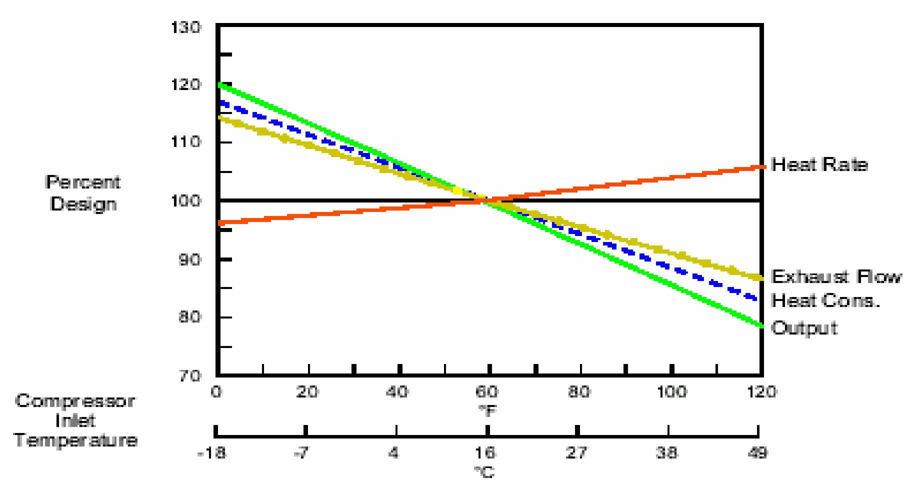
Factors Affecting Gas Turbine Performance

- Air Temp and Site Elevation
- Humidity
- Inlet and Exhaust Losses
- Fuels
- Fuel Heating
- Diluents Injection
- Air Extraction

Air Temp and Site Elevation

- GT performance is changed by anything that affects the density and/or mass flow of the air intake to the compressor.
- Ambient weather conditions are the most obvious changes from the ISO conditions of 59 F/15 C and 14.7 psia/1.013 bar.

Effect of Temperature

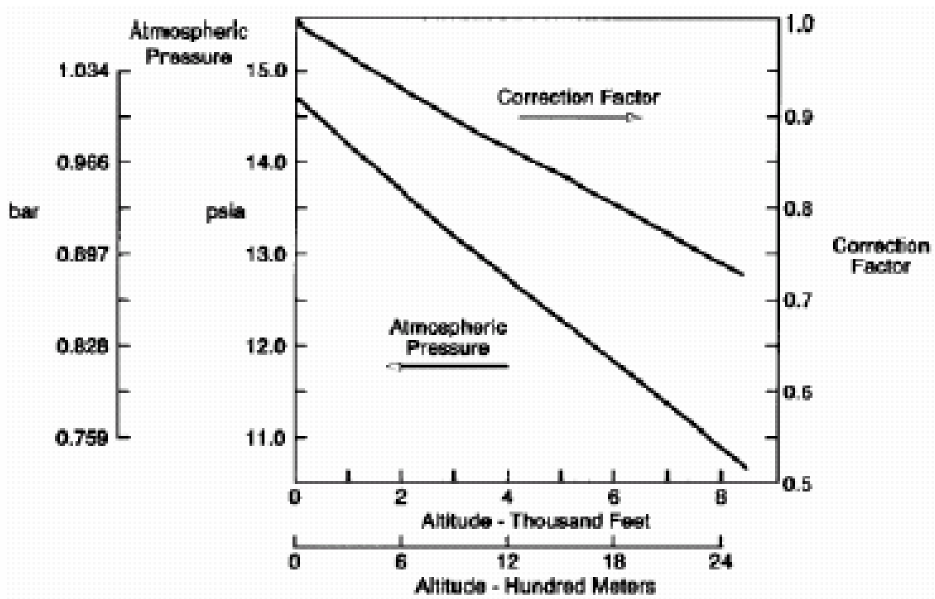


- Curve shows effect of ambient temp on Output, Heat rate, Heat consumption, and Exhaust flow for MS7001 GT.

- Each turbine model has its own temp-effect curve, as it depends on the cycle parameters and component efficiencies as well as air mass flow.

Effect of altitude

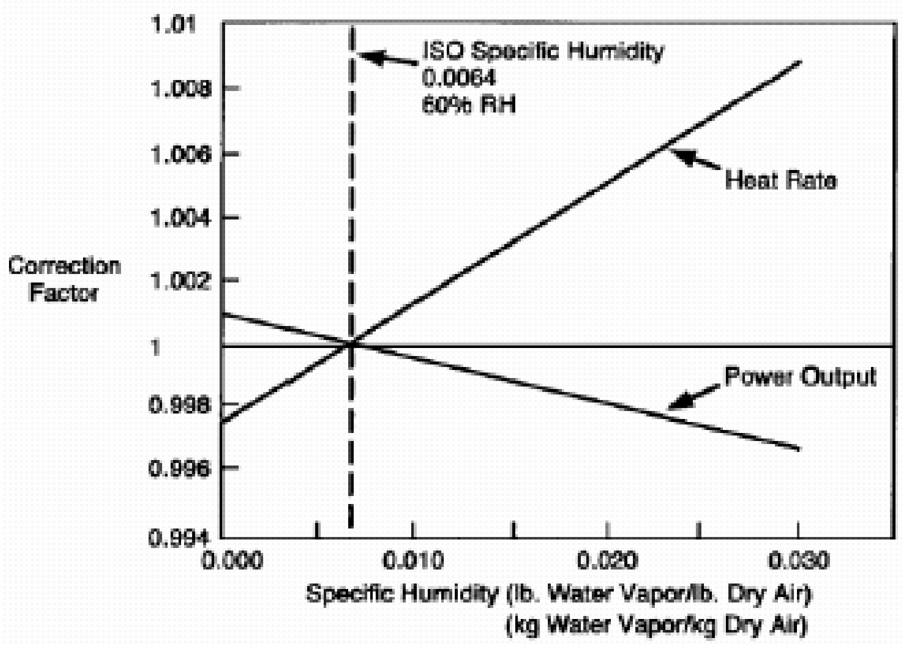
- Correction for altitude or barometric pressure is more straightforward.
- The air density reduces as the site elevation increases. While the resulting airflow and output decrease proportionately, the heat rate and other cycle parameters are not affected.



- A standard altitude correction curve is as shown above.

Humidity

- Humid air, also affects output and heat rate, as shown in curve.
- In the past, this effect was thought to be too small to be considered.
- However, with the increasing size of gas turbines and the utilization of humidity to bias water and steam injection for NOx control, this effect has greater significance.



- Humidity effect is a result of the control system approximation of firing temperature used on GE heavy-duty gas turbines.

- Single-shaft turbines that use turbine exhaust temperature biased by the compressor pressure ratio to the approximate firing temperature will reduce power as a result of increased ambient humidity.

- This occurs because the density loss to the air from humidity is less than the density loss due to temperature. The control system is set to follow the inlet air temperature function.

- By contrast, the control system on "Airoderivatives" uses unbiased gas generator discharge temperature to approximate firing temperature.

- The gas generator can operate at different speeds from the power turbine, and the power will actually increase as fuel is added to raise the moist air (due to humidity) to the allowable temperature. This fuel increase will increase the gas generator speed and compensate for the loss in air density.

Inlet & Exhaust Losses

- Inserting air filtration, silencing, evaporative coolers or chillers into the inlet or heat recovery devices in the exhaust causes pressure losses in the system.

- The effects of these pressure losses are unique to each design.
- Effects on the MS7001EA, which are typical for the E technology family of scaled machines (MS6001B, 7001EA, 9001E).

4 Inches (10 mbar) H_2O Inlet Drop Produces:
- 1.42% Power Output Loss
- 0.45% Heat Rate Increase
- 1.9 F (1.1 C) Exhaust Temperature Increase

4 Inches (10 mbar) H_2O Exhaust Drop Produces:
- 0.42% Power Output Loss
- 0.42% Heat Rate Increase
- 1.9 F (1.1 C) Exhaust Temperature Increase

Fuels

- GT output =Mass flow *Heat energy in the combusted gas (Cp) *Temp differential across the turbine.

- The mass flow in this equation is the sum of compressor airflow and fuel flow.

- The heat energy is a function of the elements in the fuel and the products of combustion.

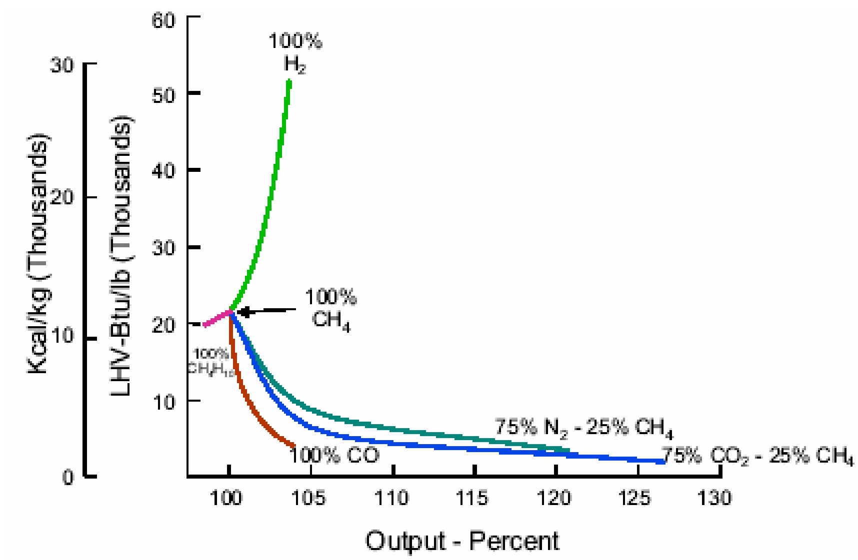
- Natural gas (methane) produces nearly 2% more output than distillate oil.

- This is due to the higher specific heat in the combustion products of natural gas, resulting from the higher water vapor content produced by the higher hydrogen/carbon ratio of methane.

- This effect is noted even though the mass flow (lb/h) of methane is lower than the mass flow of distillate fuel. Here the effects of specific heat were greater than and in opposition to the effects of mass flow.

- Curve shows the total effect of various fuels on turbine output. This curve uses methane as the base fuel.

- Although there is no clear relationship between fuel lower heating value (LHV) and output, it is possible to make some general assumptions.



- If the fuel consists only of hydrocarbons with no inert gases and no oxygen atoms, output increases as LHV increases. Here the effects of Cp are greater than the effects of mass flow.

- Also, as the amount of inert gases is increased, the decrease in LHV will provide an increase in output.

- This mass flow addition, which is not compressed by the gas turbine's compressor, increases the turbine output. Compressor power is essentially unchanged.

- Several side effects must be considered when burning this kind of lower heating value fuels:

- Increased turbine mass flow drives up compressor pressure ratio, which eventually encroaches on the compressor surge limit

- The higher turbine power may exceed fault torque limits. In many cases, a larger generator and other accessory equipment may be needed

- High fuel volumes increase fuel piping and valve sizes (and costs).

- Low- or medium-Btu coal gases are frequently supplied at high temp, which further increases their volume flow.

- Lower-Btu gases are frequently saturated with water prior to delivery to the turbine. This increases the combustion products heat transfer coefficients and raises the metal temp in the turbine section which may require lower operating firing temp to preserve parts lives
- As the Btu value drops, more air is required to burn the fuel. Machines with high firing temp may not be able to burn low Btu gases

- Most air-blown gasifiers use air supplied from the gas turbine compressor discharge. The ability to extract air must be evaluated and factored into the overall heat and material balances

- As a result of above, each turbine model will have some guidelines on flows, temp and shaft output to preserve its design life.

- In most cases with lower heating value fuels, it can be assumed that output and efficiency => than that obtained on natural gas.

- In the case of higher heating value fuels, such as refinery gases, output and efficiency may be <= than that obtained on natural gas.

Fuel Heating

- Most of the combined cycle GTs are designed for maximum efficiency. These GTs often utilize integrated fuel gas heaters. Heated fuel results in higher turbine efficiency due to the reduced fuel flow required to raise the total gas temperature to firing temperature.

- Fuel heating will result in slightly lower gas turbine output because of the incremental volume flow decrease.

- The source of heat for the fuel typically is the IP feed-water.

- Since use of this energy in the gas turbine fuel heating system is thermodynamically advantageous, the combined cycle efficiency is improved by approximately 0.6%.

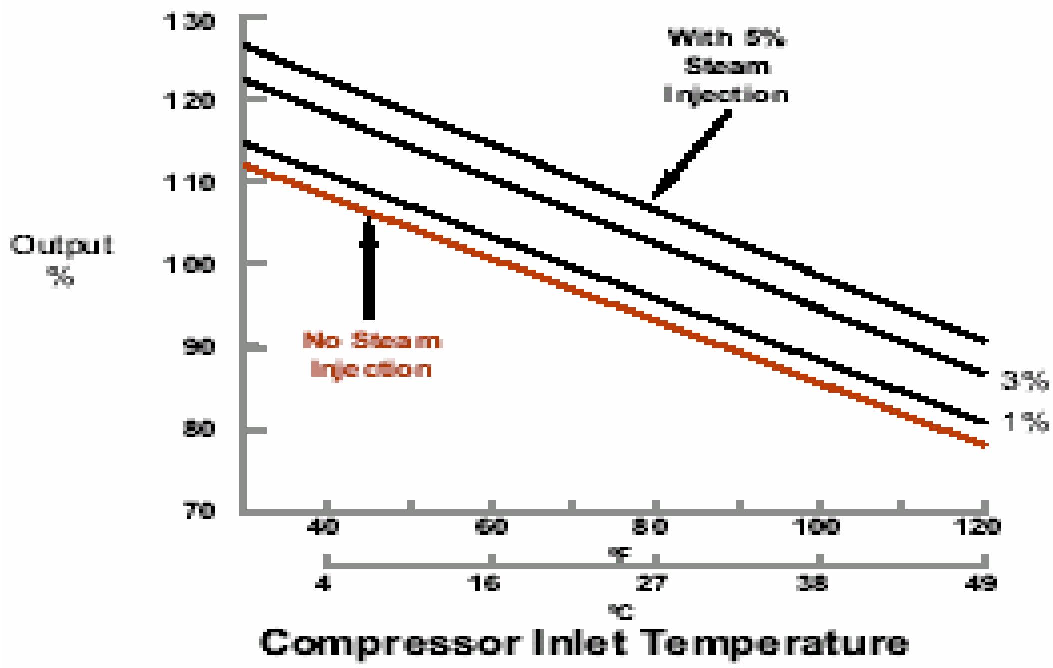
Diluent Injection

- Water or steam injection for NOx control is used to meet regulations.

- Accomplished by admitting water or steam in the cap area or "head-end" of the combustion liner.

- Each machine and combustor configuration has limits on water or steam injection levels to protect the combustion system and turbine section.

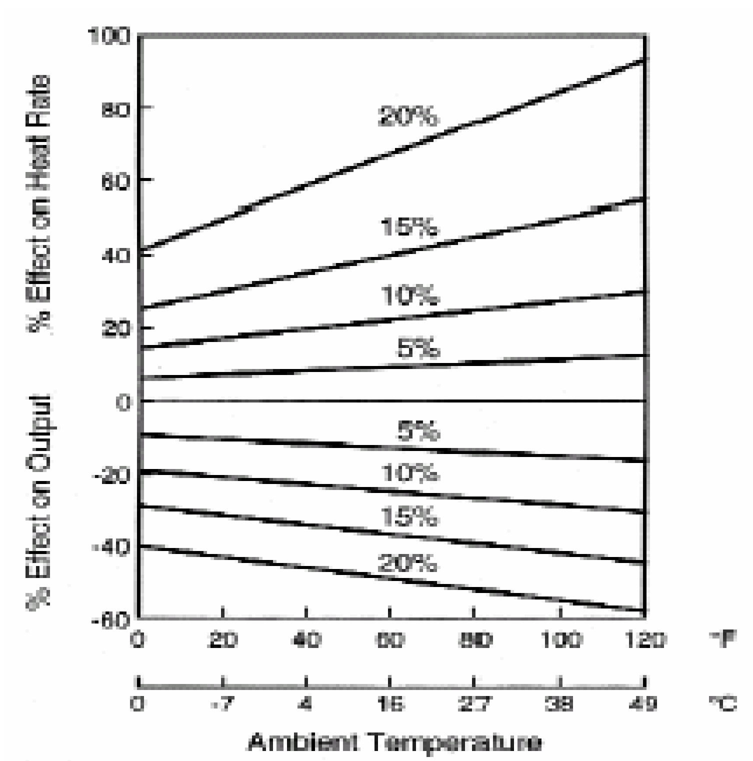
- Depending on the amount of water or steam injection needed to achieve the desired NOx level, output will increase because of the additional mass flow.



- Curve shows the effect of steam injection on output and heat rate for an MS7001EA.
- These curves assume that steam is free to the gas turbine cycle, therefore heat rate improves. Since it takes more fuel to raise water to combustor conditions than steam, water injection does not provide an improvement in heat rate.

Air Extraction

- In some GTs , it may be desirable to extract air from the compressor.
- Generally, up to 5% of the compr airflow can be extracted from the comprr discharge casing without modification to casings or on-base piping.
- Air extraction between 6% - 20% may be possible, depending on the machine and combustor configuration, with some modifications to the casings, piping and controls.
- Air extractions above 20% will require extensive modification to the turbine casing and unit configuration.



- Curve shows the effect of air extraction on output and heat rate. As a "rule of thumb," every 1% in air extraction results in a 2% loss in power.

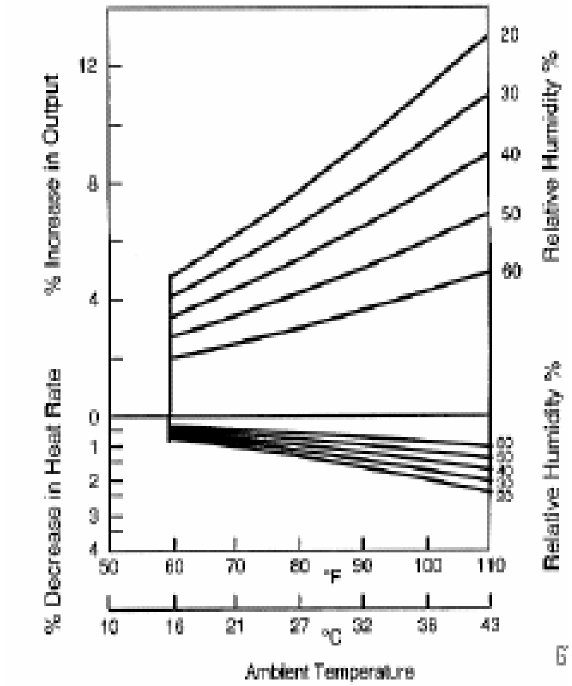
Performance Enhancements

- Generally, controlling some of the factors that affect gas turbine performance is not possible.
- The planned site location and the plant configuration (such as simple- or combined-cycle) determine most of these factors.
- In the event additional output is needed, several possibilities to enhance performance may be considered.
  - Inlet Cooling
  - Steam and Water Injection for Power Augmentation
  - Peak Rating

Inlet Cooling

- The ambient effect curve clearly shows that turbine output and heat rate is improved as compressor inlet temperature decreases.
- Lowering the compressor inlet temperature can be accomplished by installing an evaporative cooler or inlet chiller in the inlet ducting downstream of the inlet filters.
- Careful application of these systems is necessary, as condensation or carryover of water can exacerbate compressor fouling and degrade performance.
- These systems generally are followed by moisture separators or coalescing pads to reduce the possibility of moisture carryover.
- As curve shows, the biggest gains from evaporative cooling are realized in hot, low-humidity climates.
- Evaporative cooling is limited to ambient temp of 59 F/15 C and above (Compr inlet temp >45 F/7.2 C) because of the potential for icing the compressor.

- Curve is based on an 85% effective evaporative cooler. Effectiveness is a measure of how close the cooler exit temperature approaches the ambient wet bulb temperature.

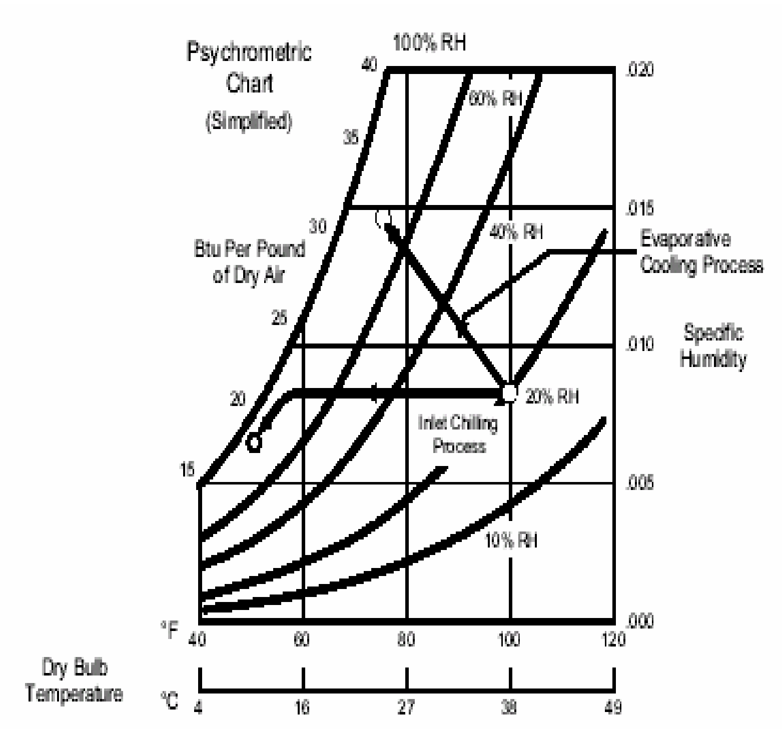


- Chillers, unlike evaporative coolers, are not limited by the ambient wet bulb temperature.

- The achievable temp is limited only by the capacity of the chilling device to produce coolant and the ability of the coils to transfer heat.

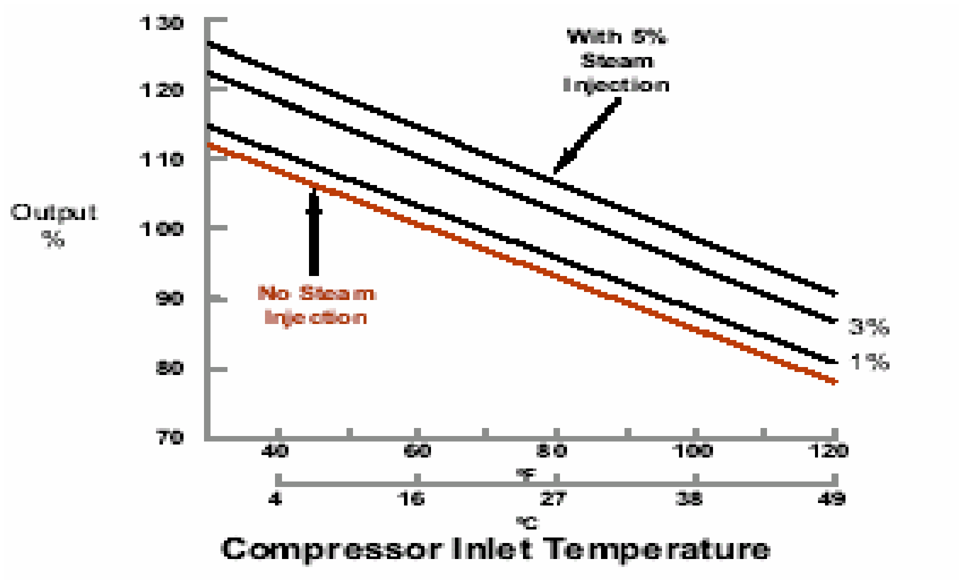
- Cooling initially follows a line of constant specific humidity, as shown in curve. As saturation is approached, water begins to condense from the air, and mist eliminators are used.

- Further heat transfer cools the condensate and air, and causes more condensation. Because of the relatively high heat of vaporization of water, most of the cooling energy in this regime goes to condensation and little to temperature reduction.



Steam & water Injection for Power Augmentation

- Injecting steam or water into the head end of the combustor for NOx abatement increases mass flow and, therefore, output.
- Generally, the amount of water is limited to the amount required to meet the NOx requirement in order to minimize operating cost and impact on inspection intervals.
- Steam injection for power augmentation has been an available option.
- When steam is injected for power augmentation, it can be introduced into the compressor discharge casing of the gas turbine as well as the combustor.
- GE gas turbines are designed to allow up to 5% of the compr airflow for steam injection to the combustor and compr discharge.
- The effect is the same as earlier shown.



- Steam must contain 50 F/28 C superheat and be at pressures comparable to fuel gas pressures.

- When either steam or water is used for power augmentation, the control system is normally designed to allow only the amount needed for NOx abatement until the machine reaches base (full) load. At that point, additional steam or water can be admitted via the governor control.

Peak Ratings

- ANSI B133.6 Ratings and Performance defines Base load as operation at 8,000 hours per year with 800 hours per start.

- It also defines Peak load as operation at 1250 hours per year with five hours per start.

- In recognition of shorter operating hours, it is possible to increase firing temperature to generate more output. The penalty for this type of operation is shorter inspection intervals.

- Despite this, running an MS5001, MS6001 or MS7001 at peak may be a cost-effective way to obtain more kilowatts without the need for additional peripheral equipment.
- Generators used with gas turbines likewise have peak ratings that are obtained by operating at higher power factors or temperature rises.

- Peak cycle ratings are ratings that are customized considering both starts and hours of operation.

- Firing temp between base and peak can be selected to maximize the power capabilities of the turbine while staying within the starts limit envelope of the turbine hot section repair interval.

- For instance, the 7EA can operate for 24,000 hours on gas fuel at base load, as defined. The starts limit to hot section repair interval is 800 starts.

- For peaking cycle of five hours per start, the hot section repair interval would occur at 4,000 hours, which corresponds to operation at peak firing temperatures.

- Turbine missions between five hours per start and 800 hours per start may allow firing temperatures to increase above base but below peak without sacrificing hours to hot section repair.

- Water injection for power augmentation may be factored into the peak cycle rating to further maximize output.

Performance Degradation

- All turbo-machinery experiences losses in performance with time.

- Gas turbine performance degradation can be classified as:

Recoverable loss

- Usually associated with compr fouling and can be partially rectified by water washing or, more thoroughly, by mechanically cleaning the compr blades and vanes after opening the unit.

Non-recoverable loss

- Due to increased turbine and compressor clearances and changes in surface finish and airfoil contour.
- Because this loss is caused by reduction in component efficiencies, it cannot be recovered by operational procedures, external maintenance or compressor cleaning, but only through replacement of affected parts at recommended inspection intervals.

- Quantifying performance degradation is difficult because consistent, valid field data is hard to obtain.
- Correlation between various sites is impacted by variables such as mode of operation, contaminants in the air, humidity, fuel and dilutent injection levels for NOx.
- Another problem is that test instruments and procedures vary widely, often with large tolerances.
- Typically, performance degradation during the first 24,000 hours of operation (the normally recommended interval for a hot gas path inspection) is 2% to 6% from the performance test measurements.
- This assumes degraded parts are not replaced. If replaced, the expected performance degradation is 1% to 1.5%.
- Frequent off-line water washing is not only effective in reducing recoverable loss, but also reduces the rate of non-recoverable loss.
- Machines located in dry, hot climates typically degrade less than those in humid climates.

Verifying Gas Turbine Performance

- Once the gas turbine is installed, a performance test is usually conducted.
- Preferably, this test should be done as soon as practical, with the unit in new and clean condition. In general, a machine is considered to be in new and clean condition if has less than 200 fired hours of operation.
- Testing procedures and calculation methods are patterned after those described in the ASME Performance Test Code PTC-22-1997, "Gas Turbine Power Plants."
- As per ASME PTC-22-1997, the methodology of correcting test results to guarantee conditions and measurement uncertainties (approximately 1% on output and heat rate when testing on gas fuel) shall be agreed upon by the parties prior to the test.

Turbine Inspections

- Broadly classified under Unit Running & Unit Shutdown.

- Running inspection is performed during start-up and while the unit is running. It indicates the general condition of the Gas Turbine & associated equipment.

- The shutdown inspection is performed while the unit is under shutdown condition. It includes:

  - Combustion Liner inspection
  - Combustion -Transition Piece inspection
  - Hot gas path inspection
  - Major inspection

- The standby inspection can be done while the unit is under shutdown. Routine preventive maintenance e.g. filter changing, checking oil, coolers, electrical & instrument system.

- Unit must be operated on load for at least 1 hr bi-monthly, and data recorded.

- Gas turbine on extended shutdown (3 weeks or more) should be operated on ratchet for 1 hr a day . To prevent the build up of corrosive deposits on turbine wheel dovetail during extended shutdown condition, turbine should be operated at full speed, no load for 1 hr per week to dry the turbine out.

Special Inspections

- Boroscopic
- Eddy current probe

Boroscopic Inspection

- Conducting Borescope inspections has become an important tool for preventive maintenance.
- With the appropriate expertise and state-of-the art imaging equipment, this technology enables inspectors to monitor conditions more comprehensively and to optimize service intervals.
- It also provides an advance look at what to fix during the next scheduled shutdown and to have the replacement parts ready in time.

- Scheduling is enhanced, leading to quicker, lower cost maintenance turnarounds.

- An added benefit of video borescope inspection is the technology's ability to show flaws better than visual inspection. Very real potential problems can be quickly identified and corrected.

- For instance, a South American utility station inadvertently lost a borescope plug and spring inside a GE Frame 6B gas turbine during a scheduled combustion outage.

- In the past they would have had to open the casings at a considerable cost. Instead, borescope equipment was used to find the plug and spring by snaking down to the bottom of the casing.

- In another recent case, a borescope inspection of blades and vanes, at an Oklahoma gas pipeline compressor station revealed early signs of two different cracks on the first stage nozzle of a GE Frame 6B turbine.

- To the inspector's trained eye, it seemed likely that the cracks would intersect. If that happened, a wedge of the nozzle would break off during operation and probably wipe out downstream blades and vanes. The operator replaced the nozzles before anything broke. Costly repairs and an emergency outage were prevented, saving millions of dollars.

- Without opening turbines, expert inspectors and miniature video borescopes can save money by pre-planning and hence shortening shutdowns.

- They can reduce maintenance costs during shutdowns, and avoid prohibitively expensive catastrophic failures.

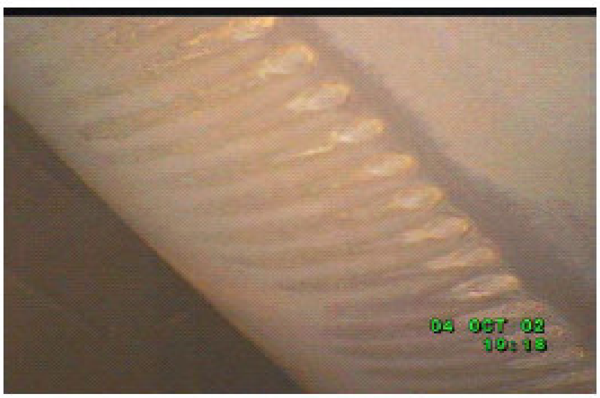
Corrosive deposits on 13th stage Compressor Rotor blades & Stator vanes.

Trailing edge tip rubs & rounding on 13 stage Stator vanes.

Corrosive deposits on 13th stage Compressor Rotor blades & Stator vanes.

Trailing edge tip rubs & rounding on 13 stage Stator vanes.

Compressor Rotor blade tip in satisfactory condition



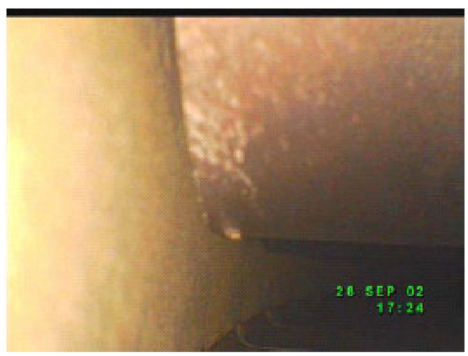
Stage # 1 Nozzle Cooling holes & light trailing edge erosion

I Stage Nozzle Leading edae & sidewall

A close view of I Stage Nozzle sidewall

A view of stage # 2 variable Nozzle root,leading edge & Pr side.

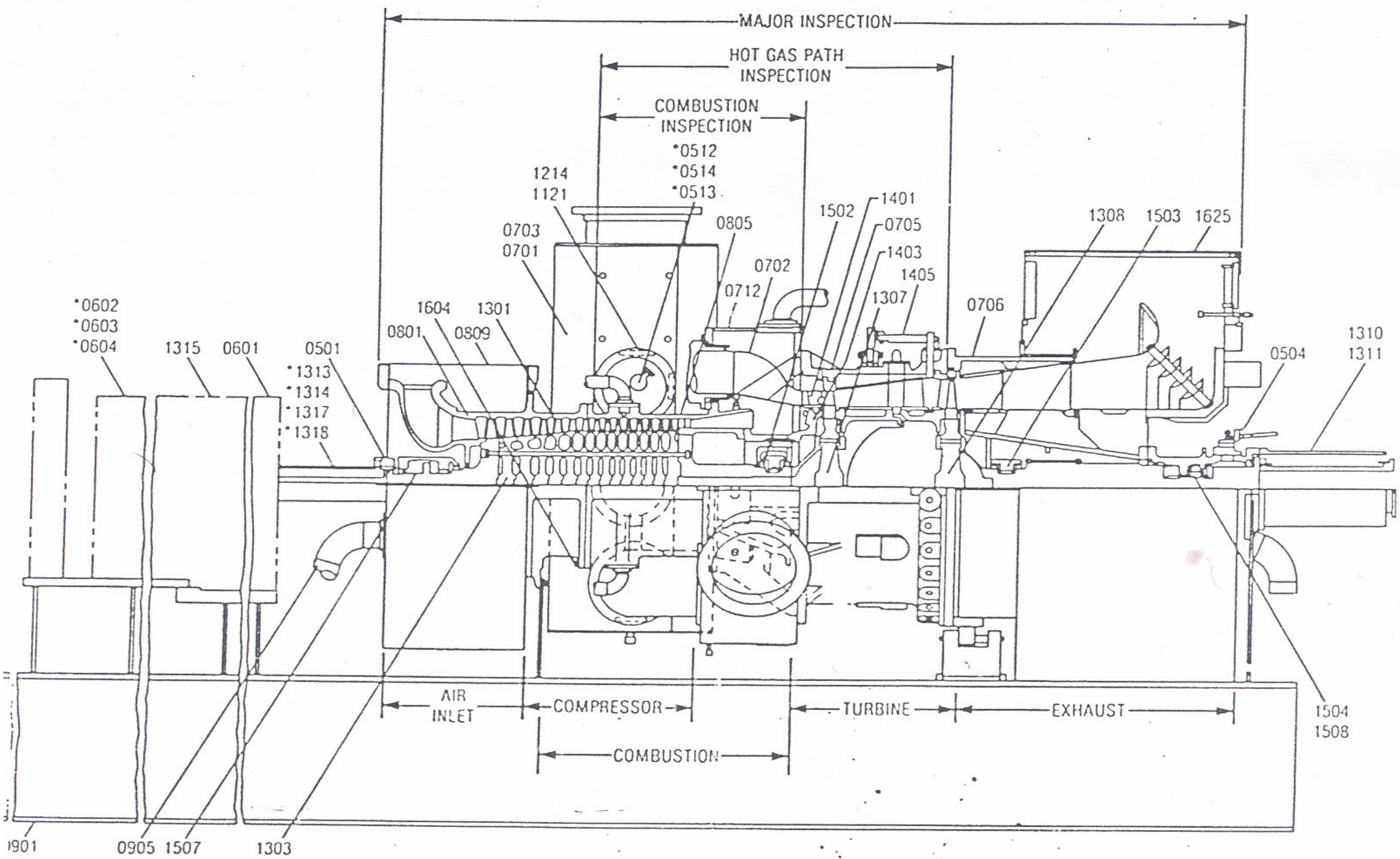
Corrosive deposits on Suction side of Rotor blade & Pressure side of Stator vanes.



Trailing edge thinning & rounding noticed on Rotor Blades.

Trailing edge thinning noticed on Stator vanes.

The shutdown inspections require disassembly of turbine in varying degrees.



Ref. No.	Part Name
501	Control Arrangement
504	Low Pressure Overspeed Trip Assembly
512	Fuel Nozzle. Dual Fuel
513	Fuel Nozzle. Gas
514	Fuel Nozzle. Oil
601	Accessory Drive
602	Diesel Starting Engine
503	Electric Starting Motor
604	Expansion Starting Turbine
701	Combustion Chamber Arrangement

Ref. No.	Part Name
0702	Combustion Chamber Transition Piece Asm.
0703	Combustion Chamber Cap & Liner Asm.
0705	Turbine Shell Arrangement
0706	Exhaust Frame Assembly
0712	Combustion Wrapper
0801	Inlet Casing & No. 1 Bearing Asm.
0805	Compressor Discharge Casing Assembly
0809	Inlet Skin Assembly
0901	Unit Base
0905	Lube Oil Feed & Drain Piping Arrangement Base

Ref. No.	Part Name
1121	Flame Detector
1214	Spark Plug
1301	Compressor Stator Blade Arrangement
1303	Compressor Rotor Assembly
1307	First-Stage Turbine Rotor Assembly
1308	Second-Stage Turbine Rotor Assembly
1310	Output Coupling
1311	Output Coupling Guard
*1313	Accessory Gear Coupling
*1314	Accessory Gear Coupling Guard
1315	Starting Means to Accessory Gear Cplg.

Ref. No.	Part Name
*1317	Starting Turbine Coupling
*1318	Starting Turbine Coupling Guard
1401	First-Stage Nozzle Arrangement
1403	First-Stage Nozzle Support Ring
1405	Second-Stage Nozzle Partition & Lever Assembly
1502	No. 2 Bearing Assembly
1503	No. 3 Bearing Assembly
1504	No. 4 Bearing Assembly
1507	H.P. Thrust Bearing
1508	L.P. Thrust Bearing

NOTES: The reference numbers, listed above, are used for identification purposes only. They are derived from the turbine "Model List" which is a Medium Gas Turbine Department master listing of all gas turbine components. For those items which carry an asterisk (*), the reader should refer to the Equipment Data Summary or the Service Manual text to determine if this optional type of component has been supplied.

FIGURE 1-6 TYPES OF SHUTDOWN INSPECTIONS

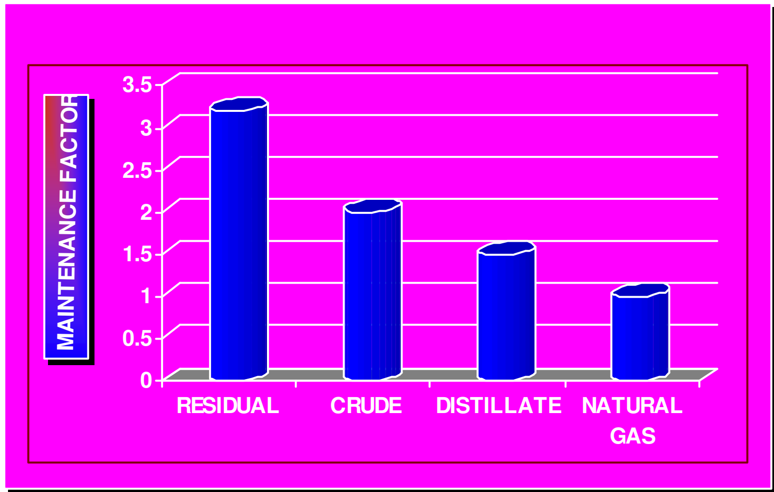
Maintenance Inspection Intervals

Inspection	Fuel	Inspection Intervals
Combustion Liners	Gas and Distillate Heavy	16,000 Hrs. 4,000 Hrs.
Transition Pieces Floating Seal	Gas and Distillate Heavy	16,000 Hrs. 4,000 Hrs.
Transition Pieces Fixed Seal	Gas and Distillate Heavy	4,000 Hrs. 4,000 Hrs.
Hot Gas Path	Gas and Distillate Heavy	16,000-24,000 Hrs. 8,000-12,000 Hrs.
Major	Gas and Distillate Heavy	32,000-48,000 Hrs. 16,000-24,000 Hrs.
Boroscope	Gas and Distillate	At Combustion Inspection or Annually whichever occurs first
	Heavy	At Combustion Inspection or Semi-Annually whichever occurs first

- The inspection interval shown are for MS 3002 machine.
- For Simple and Regenerated Cycle
- Base firing temperature
- One start per 200-100 hrs.
- Inspection intervals are for GE components.

Factors determining inspection interval

Type of Fuel.



Starting Frequency

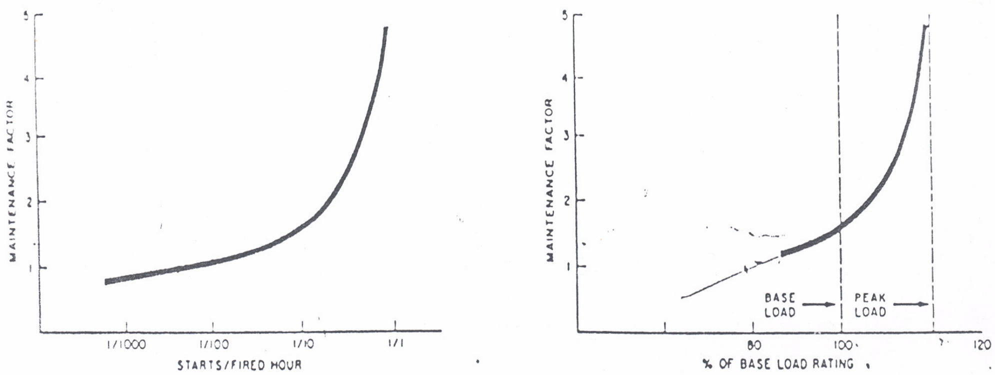
- Each start & stop of GT subjects the hot gas path to significant thermal cycles. The control systems are designed to minimize this. However the GT with frequent starting & stopping requirement will demonstrate parts life that are shorter than for a similar unit in continuous duty service.

Load cycle

- The load cycle of Gas turbine, up to its continuous rating, will have little effect on parts life, provided it does not require frequent and rapid load changes.

Environment

- Significant effect. If abrasives are in inlet air, careful attention should be paid to inlet air filtering in order to minimize the effect.
- If GT is to be operated n corrosive atmosphere (e.g. salty) , careful attention should be paid to the location of inlet air arrangement and the application of correct materials and protective coatings.



Effect of Starting Frequency & Load cycle on part's life

Heavy Oil Vapors From Turbine Exhaust Plenum

Problem

- Problem occurred in frame#3 GT at LPG phase-I Vijaipur during commissioning.
- Initially oil leakage was suspected from no.3 & no.4 bearing housing.
- Through checking was performed for identification and arresting of oil leakage.
- However heavy oil fumes persisted.

Analysis & solution

- In bearing housing, labyrinth seals, with sealing air injection, are installed to prevent oil from leaking out.
- It was found out that orifice was not provided in the sealing air line to #3 & #4 bearings.
- Due to high flow of sealing air, oil was thrown out of bearing housings, causing heavy oil fumes.
- Proper orifice as per drawing was provided.
- This solved the problem.
- However some vapors continued to come out.
- On further checking a blind sheet gasket was found in the 6" lube oil vent line.
- Problem got completely solved on its removal.

Oil leakage from acc gear box shaft (clutch side)

Problem

- Occurred at fr#3 GT at LPG Vijaipur.
- Suspected for failure of oil seal.

Analysis & solution

- Air ejector is installed in gear box for removal of oil vapors by pulling vacuum.
- Ejector was not creating enough velocity for pulling sufficient vacuum.
- Accessory gear box got pressurized, leading to oil leakage through seals.
- Ejector tubing was taken out & rectified.
- The problem got solved, without machine outage.

High Vibration Of Brg#1 During Startup

Problem

- Occurred at fr - 1 GT at PRU-I Vijaipur.
- Usually during startup, brg.#1 vibration was touching up to alarm level.
- The vibration comes to normal level after complete sequence.
- During one startup, vibration was persisting at very high level, just below trip value.

Analysis & solution

- Suspected the malfunctioning/looseness of probes etc.
- While thorough checking was going on, suddenly oil leakage was observed from torque converter shaft.
- The machine was stopped.
- Failure of the oil seals was a consequence.
- The root cause was the failure of torque converter bearings.
- As the torque converter is required only during startup, the deteriorated condition of torque converter bearings, reflected in high vibration of hp shaft, only during startup.
- The torque converter assembly was taken out, bearings and seals were replaced.
- The problem got solved.

Heavy Vibration & Hunting Of LP Shaft Speed (TNL).

Problem

- Occurred at fr-1 GT at PRU-II Vijaipur during commissioning.
- On loading the turbine, vibration of LP shaft was going high, with heavy abnormal sound and hunting of LP shaft speed.
- Initially the problem was considered on load side, as vibration at no load condition was ok.
- The Compr. Suction strainers were repeatedly cleaned, but without any result.

Analysis & solution

- Turbine was de-coupled from Compr. & alignment was checked.
- Alignment was found in out condition with incorrect coupling distance. A mark was also found on the coupling spacer.
- The alignment was properly carried out, with & without piping.
- Recommended coupling distance was maintained.
- The unit was put in operation.
- The severity of vibration reduced, however it still existed.
- The fluctuation of LP shaft speed and abnormal sound still remained.
- The rotor system seemed to be mechanically ok.
- Thought for checking the flue gas leakage at turbine loaded condition.
- On checking during extended cranking, heavy leakage of flue gas was observed from exhaust diffuser bottom casing.

- It was found that gasket was not provided at the bottom diffuser casing during assembly at BHEL, Hyd.
- In front of diffuser casing, LVDT (Linear Variable Differential Transducer) of 2nd stage nozzle control assembly was installed.
- LVDT sends the positional feed back of 2nd stage nozzle to control system, for governing the speed of LP shaft.
- Due to direct impingement of the high temp. Flue gases on LVDT, it started malfunctioning.
- That resulted in LP shaft speed fluctuation & abnormal sound due to abrupt compressor flow variations.
- The problem got solved, after insertion of exhaust diffuser gasket with the help of BHEL shop floor team.

Fall In Hydraulic Oil Pressure

Problem

- Occurred at fr.#3 GT at LPG Vijaipur.
- Turbine was getting started after a major inspection.
- The auxiliary hydraulic oil pump (AHP) was not getting cut off on auto.
- As soon as AHP was stopped on manual, the hydraulic oil pressure came to zero.

Analysis & solution

- The regulator of main Hyd Oil Pump (MHP) at hyd. Oil manifold was checked.
- Insignificant amount of oil was observed getting drained.
- Pressure compensator installed at MHP was adjusted, without any improvement.
- Finally MHP was taken out.
- The coupling between MHP & Accessory gear box found in dislocated condition.
- Resulting in non transmission of torque from accessory gear box to MHP.
- Similar problem occurred at fr. 5 GT # 1 at UPPC, where coupling was replaced.

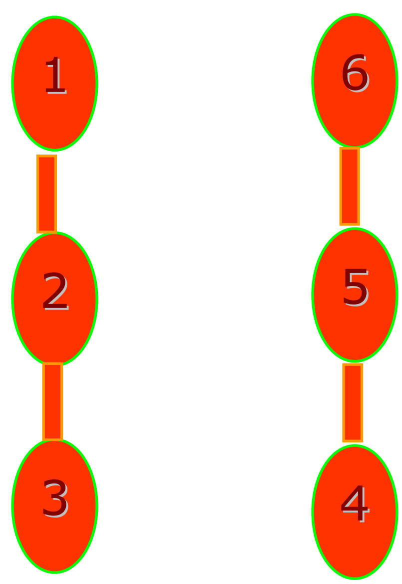
Flame-out condition at combustion chamber no. 2 & 3

Problem

- Occurred at fr. # 3 GT at LPG Lakwa.
- During commissioning of the machine, flame was not observed at combustion chamber (CC) no. 2 & 3.
- As in frame # 3 machines, the flame detection problems were earlier encountered. It was also considered similar scanner problem.
- But the exhaust temperature profile revealed a dangerous situation.
- No temperature in CC #1,2 & 3.

Analysis & solution

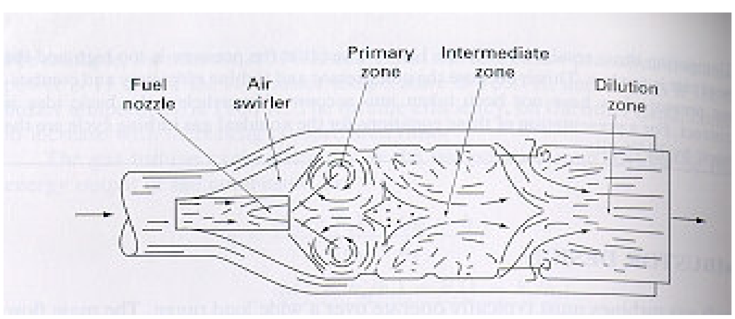
- The 13 thermocouples are installed at exhaust plenum circumferentially, which approximately gives the temp profile in individual combustion chambers & exhaust segment.



- In fr # 3 GT the combustion chamber arrangement is as above
    - The CC 1, 2 & 3 and CC 4, 5 & 6 are connected with crossfire tubes.
    - Spark plugs are installed at CC # 1 & 6.

- Sparking takes place in CC#1. Flame spreads to CC# 2 & 3.
- Sparking takes place in CC#6, flame spreads to CC# 5 & 4.
- Flame detectors are installed at CC # 2,3 & 4,5.

- The temp in the CC # 1,2,3 was found ~ 90°c, as against ~ 350°c in other zones.
- On touching the combustion casings # 1,2,3 it was evident that combustion was not actually taking place.
- The problem was suspected with ignition transformer & spark plugs.
- After thorough checking of spark plugs & ignition transformer the turbine was restarted, but without success.
- Suspected the problem with combustion liners / fuel nozzles.
- However first concentrated in fuel nozzles.
- The combustion takes place at right fuel / air ratio.
- If mixture is too lean ==> no combustion.
- Also if mixture is too rich ==> no combustion.



- Due to erosion, average dia of the gas passage holes at fuel nozzle tip got increased.
- It resulted in reduction in velocity. Leading to fuel / air mixture becoming too lean locally.
- The fuel nozzle of CC#1 was replaced for solving the problem.

Turbine going to temp. Control as load is increased to 90 – 95%

Problem

- Occurred at fr # 3 GT at LPG Ph #2 Vijaipur.
- Loss, as causing limitation of load.
- Under similar ambient condition other GT could be loaded up to 110-115%.
- Frequent rice cleaning of compressor blades was carried out.

Analysis & solution

- The turbine was running for 3 years under above condition with frequent rice cleaning.
- During hot gas path inspection, when the turbine casing was lifted, rubbing on 1st stage turbine buckets was observed.
- 1mm to 2mm of material was found chopped off on all 80 nos. of Turbine buckets.
- The coating on 1st stage shrouds was also found damaged.
- As the machine was running under load limitation since commissioning, probably this was caused by Foreign Object Damage (FOD) at initial stages.
- Replacement of 1st stage buckets & 1st stage shrouds was carried out.
- Problem got solved, turbine could be loaded up to 110 – 115%.

Regenerative-Cycle Gas Turbine

Introduction

The regenerative-cycle gas turbine is similar to the simple-cycle gas turbine except that in the former, the low-pressure hot exhaust gases are used to heat the high-pressure compressor discharge air in a heat exchanger (regenerator). This heated high-pressure air then enters the combustion chamber where it is mixed with fuel and burns. Recovery and transfer of heat from the hot exhaust gas to the compressor discharge air may be accomplished through the use of either a fixed-boundary heat exchanger or a moving-element heat exchanger.

In the ***fixed-boundary heat exchanger*** (**regenerator**) the hot exhaust gas passes on one side of a thermally conductive barrier while the cooler compressor discharge air travels on the other side. The heat is transferred from the hot stream to the cooler stream through the barrier. The basic principle of the fixed-boundary heat exchanger is shown schematically in Fig. 1. This type of heat exchanger (regenerator) normally is used with large gas turbines (regenerative-cycle) for industrial applications and power-generating systems

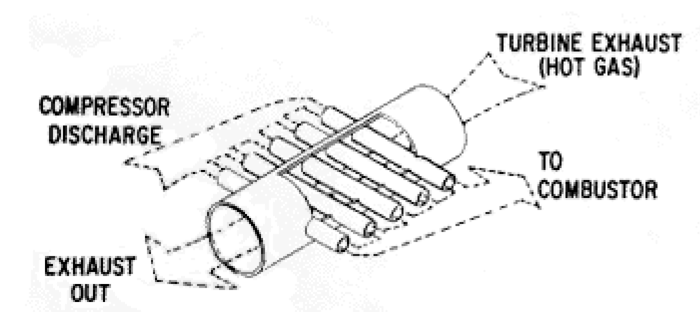


Fig. 1 Fixed Boundary Heat Exchanger

In the ***moving element heat exchanger***, heat transfer is accomplished by a moving element that passes through the hot exhaust gas, absorbs heat, and then releases the heat energy to cooler compressor discharged air. The schematic representation of a moving-element heat exchanger is shown in Fig. 2. This type of heat exchanger is smaller and is used with smaller gas turbines for vehicular applications. –

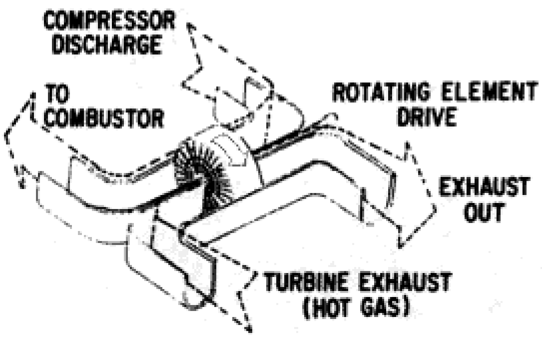


Fig. 2 Moving Element Heat Exchanger

Large Regenerative-Cycle Gas Turbines

Description

An understanding of regenerator design will aid in the understanding of performance characteristics, operation, and economics of regenerative-cycle gas turbines used for Integrated Community Energy Systems (ICES) applications. The next few sections provide basic design details of presently available commercial regenerators.

The basic flow pattern in a fixed-boundary regenerator normally is cross-flow, counter-flow, or cross-counter-flow. Modern high-performance regenerators have counter-flow or cross-counter-flow patterns.

The regenerators used in a regenerative gas turbine cycle can be classified according to their physical configuration as U-tube type and plate-fin type. The former is manufactured by Foster Wheeler Energy Corporation, and the latter by Harrison Radiator Division and Garrett/Air Research Manufacturing Company. The plate-fin design can be further classified into external strong back and internal pressure support according to its respective structural design.

• ***U-tube designs.*** The U-tube regenerator is a self-supporting box type structure, supported on structural steel columns, and containing a heat-transfer surface in the form of U-tubes as shown in Fig. 3. The U-tubes are supported at each end by tube sheets which, in turn, are incorporated into headers. They are also laterally supported at appropriate intervals with special stainless-steel support grids. Each regenerator unit is fully shop-assembled and is shipped as a single, finished component. Field work consists of construction of the base at the site and connection of gas ducts and/or pipes to the unit.

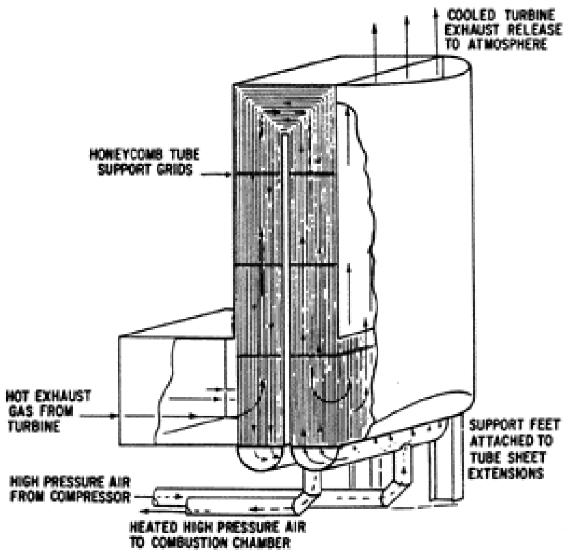


Fig 3 Typical Arrg. of a U-Tube Regenerator

Plate-fin design (strong back design). The basic regenerator is of bar and plate construction as shown in Fig. 4. The exhaust gas tube consists of two plates, separated by a corrugated heat-transfer surface. The corrugated surface is copper-brazed to the plates. Each tube (gas passage) generally is 150 in. long, 28 in. wide, and approximately 1 in. high.

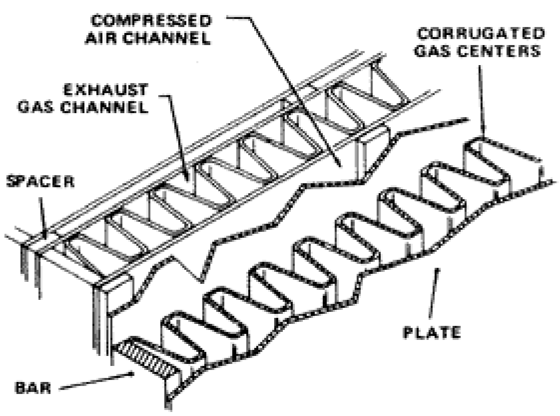


Fig. 4 Tube Construction (Strong Back Design)

A tube bank is fabricated from several of these tubes, separated by spacers, and welded together to form an integral unit. The gap, formed by the spacers between the exhaust gas tubes, is the passage for compressed air. The number of tubes used depends on the particular flow conditions.

A regenerator assembly is constructed by welding together two tube banks separated by inlet and exhaust manifolds. The regenerator assembly is completed by adding strong bank structures, tie straps, and mounting legs. Figure 5 shows a vertically-mounted regenerator.

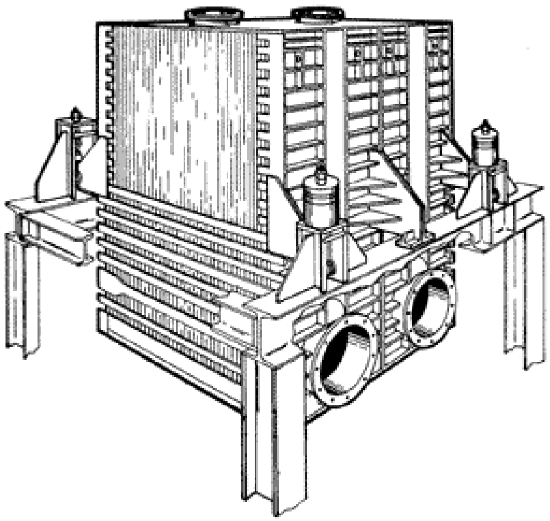


Fig 5 Support Structures of a Vertically Mounted Regenerator (Strong Back Design)

Plate-Fin design (tension braze design). Figure 6 shows the basic core structure of *tension braze concept*. The corrugated fin surfaces are assembled in alternating exhaust gas and compressor discharge air passages, with passages separated by plates. The air passage corrugated fins are brazed with high-temperature, nickel braze alloy.

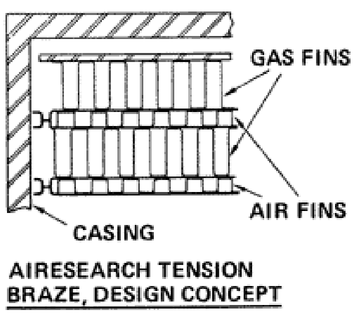


Fig 6 Schematic of Core Structure(Tension Braze, Design Concept)

This type of brazing is both strong and oxidation-resistant at operating temperatures.

Figure 7 shows a single, completed block of a regenerator core. Because the internal forces, produced by high-pressure compressor discharge air in each air passage, are balanced by tensile forces in the fins inside the passage, the need for strong-back has been eliminated. Several (3 to 6, depending on the application) of these individual core assemblies are connected to make up a regenerator sub-module.

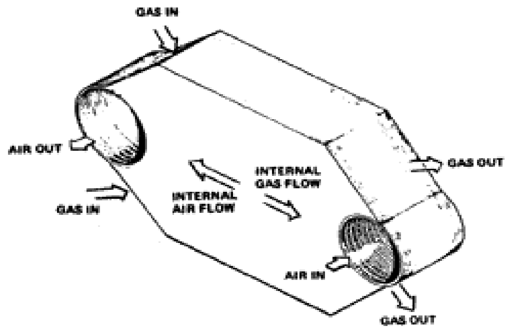


Fig. 7 General Configuration of a Single Core Assembly

Figure 8 shows two regenerator sub-modules arranged in parallel in a casing.

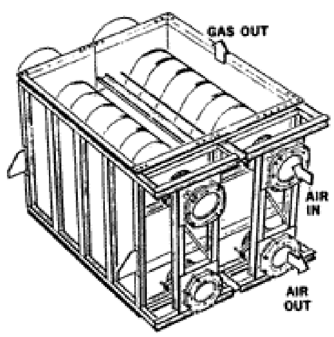


Fig. 8 Regenerator Installation with Vertical Gas Flow (Tension Braze Design)

The casing, which acts as support for the core sub-modules, also contains the low-pressure exhaust gas. The regenerator, shipped in two halves is bolted together at the installation site.

Available Size Range

The regenerative cycle gas turbines are available from approximately 12,000 to 50,000 SHP. The gas turbine and regenerators are transported separately to the site. Large regenerators are manufactured in sub-modules and are assembled at the site. The assembled regenerator then is connected to the gas turbine.

Dimensions and Shipping Weights

Dimensions and weights of regenerators vary considerably according to design configuration. Because plate-fin regenerators offer more heat-transfer area per unit volume than do tubular regenerators, they are smaller and weigh less. The size and weight of the regenerator increase in applications that demand higher effectiveness.

Usually it is difficult to generalize dimensions of regenerators with respect to any particular parameter, unless specific information is known about several parameters, such as air flow rate, compressor pressure, and type of application. Table 1 shows the approximate dimensions for a typical plate-fin (tension braze design), a plate-fin (strong-back) and a tubular regenerator.

Table 1 Typical Dimensions and Weights of Regenerators						
Regenerator Type	*Width (ft)*	*Length (ft)*	*Height (ft)*	*Weight (lb)*	*Gas Flow(lb/sec)*	*Effectiveness %*
U-Tube	14	9	35	187,400	95	80
Plate-Fin(tension	12	18	15	110,000	115	82
Plate-Fin(strong back)	8.5	11	12	-	115	80
Plate-Fin(strong back)	10	50	30	-	115	86

Many regenerators are of modular design, and the increase in turbine capacity is handled by the addition of one or more modules to the gas turbine. Table 2 shows the number of modules used for various General Electric gas turbines.

Table 2 Typical Number of Regenerators Used for Various Turbine Capacities		
Model	*Approx. HP Range*	*No. of Regenerators[(a]*
MS 3002R	12,000 - 15,000	1
MS 5002R	20,000 - 30,000	2
MS 7001R	50,000 - 65,000	4
[(a)] *Dimensions of the each module are approximately 8.5 x 11 x 12 ft (plate-fin generator)*		

Material Balance

A regenerative-cycle gas turbine has two primary inputs: air and fuel. Air functions as the working fluid and is admitted to the system at the compressor. Fuel is admitted to the system at the burner and generally is either oil or natural gas. Most regenerative-cycle gas turbines are purchased for pipeline applications and burn natural gas. However, with increased fuel cost, more regenerators are being used for other industrial applications with fuels other than natural gas.

Energy Balance and Performance

Fuel is the primary energy input in a regenerative cycle gas turbine. The rate of fuel consumption is related to the system's efficiency. Regenerator effectiveness and regenerator total pressure drop are among the parameters that influence thermal efficiency of the regenerative cycle. Fig.9 defines these two parameters.

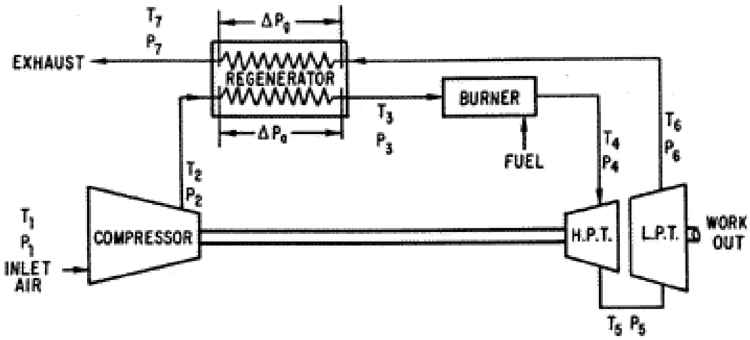


Fig. 9 Typical Gas Turbine Regenerative Cycle

Regenerator effectiveness is defined by the ratio of the temperature rise of compressor discharge air through the regenerator to the difference between the turbine exhaust temperature and the compressor discharge air, and is given by the following equation:

$$e = \frac{T_{3'}^{*} - T_{2}}{T_{6'} - T_{2'}}$$

……………………………………………………………… ………………………… Eq. 1

The regenerator total pressure drop is the sum of the air-side pressure drop divided by the air inlet pressure plus the gas-side pressure drop divided by the gas inlet pressure and is given by:

$$\%\Delta P_{total} = \%\ \Delta P_{air} + \%\ \Delta P_{gas}$$

$$= \left[\frac{P_{2'} - P_{2'}}{P_{2'}} + \frac{P_{6'} - P_{7}}{P_{6'}}\right] \times 100$$

…………………………………………………………………………Eq. 2

*The prime (') variable indicates actual temperature on T-S diagram .

Figures 10 and 11 show the effect on the overall thermal efficiency of the system of regenerator effectiveness and total pressure drop, respectively. It can be seen from Fig. 10 that, with increased regenerator effectiveness, the overall thermal efficiency increases. Fig. 11 shows that an increase in total pressure drop results in a decrease of overall thermal efficiency. Fig 10 shows that peak efficiency increases at lower pressure ratios. This indicates that a gas turbine with lower pressure is more suitable for conversion to a regenerative cycle, because at high pressure ratios the compressor discharge air is at much higher temperatures, and the heat gain through the regenerator is smaller; thus, regenerator effectiveness is lowered.

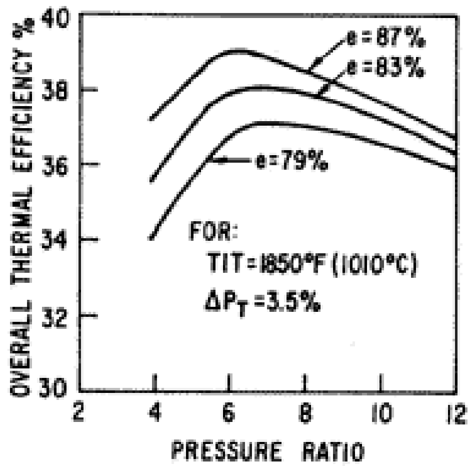


Fig 10 Overall Thermal Efficiency Vs Pressure Ratio for Different Regenerator Effectiveness

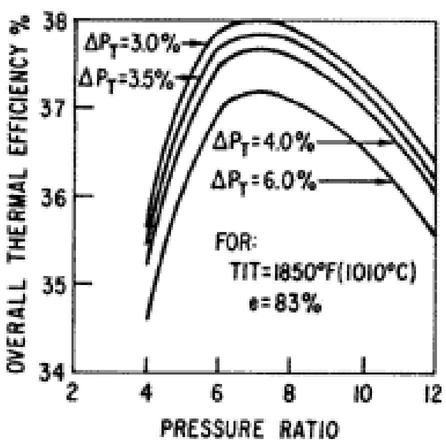


Fig 11: Overall Thermal Efficiency Vs Pressure Ratio for Different Regenerator Total Pressure Losses

One way to increase the effectiveness of a regenerator is to allocate more surface area for heat transfer. The increased surface area, in turn, increases the total pressure drop and thereby imposes a limit as to what extent effectiveness could be increased. Moreover, increased surface area rapidly increases regenerator costs. The actual design values of regenerator effectiveness and total pressure drop normally are fixed by the economics of fuel cost vs overall regenerator costs. Today's regenerators have a regenerator effectiveness of about 80% and total pressure drops of approximately 3 to 4%.

The full-load thermal efficiency of a regenerative-cycle gas turbine is defined as the ratio of net work output to fuel input and is expressed by the following equation:

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}}$$ ………Eq. 3

Equation 3 can be further expanded into a form containing parameters related to the regenerator, such as regenerator effectiveness and pressure drop which facilitate an investigation of the system's overall thermal efficiency.

Full-Load Performance

The thermal efficiency of presently manufactured regenerative cycle gas turbines that have base-load ratings of 10,000 to 32,000 horsepower at full-load capacity is about 34%. Table 3 shows full-load thermal efficiency of a set of regenerative cycle gas turbines. Although the data in Table 3 belong to a single manufacturer, they can be considered as typical full-load efficiencies of today's regenerative-cycle gas turbines.

Table 3 Typical Full-Load Efficiencies of Regenerative-Cycle Gas Turbine

Base-Load Rating HP	*Thermal Efficiency*[a] *%*	*Type*[b]
12,000	34.1	MD
13,000	32.9	TG
13,750	34.3	MD
20,000	33.8	MD
25,000	34.1	MD
25,200	34.4	MD
32,000	35.4	MD

[a] All the units burn natural gas (LHV)
[b] MD = Mechanical drive, TG, Turbine generator set

Part-Load Performance

Part-load performance data generally are derived empirically from test data for each gas turbine. Fig 12 shows the part-load thermal efficiency of a 13,300 HP simple-and regenerative-cycle gas turbine using nearly identical components. The thermal efficiency of regenerative units can be expressed by the following relation:

$$\eta_{th} = 8.69 + (0.576)X - (3.23 \times 10^{-3})X^2 \quad \text{......... Eq. 4}$$

Where X= percent of rated load.

As shown by the lower curve on Fig. 12, fuel savings resulting from the addition of a regenerator, amount to 1/4 at full load and to about 1/3 at half load.

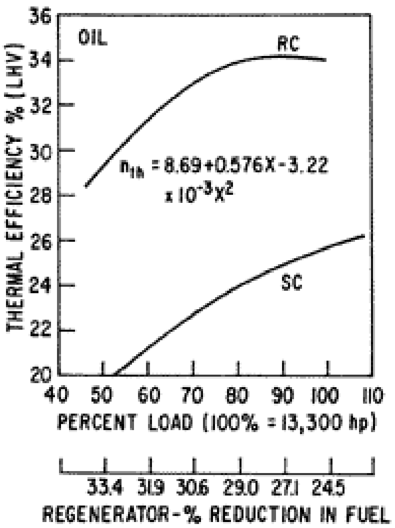


Fig.12 Part-Load Performance of a Simple-and Regenerative Cycle Gas Turbine(for regenerative unit, A = 8.689, B = 0.5759, C = -3.23213 x 10⁻)

Environmental Effects

Thermal Discharge

The only significant thermal discharge from regenerative-cycle gas turbines is hot exhaust gas at a typical exhaust temperature of about 650°F.

Noise Attenuation

Basically there is no noise level difference between a simple-cycle unit or regenerative-cycle unit provided no sound-absorbing material is used on either unit. Lower sound level can be achieved by the use of sound-absorbing material around the regenerator casing, air inlets, and gee discharges.

Effluent Discharge

Among the exhaust emissions only, NO_X emissions (Fig. 13) are of major concern in any combustion process. The solid lines in Fig. 13 indicate that regenerative cycle becomes a low emitter of NO_X at higher thermal efficiencies. This is in contrast with the simple cycle at a high pressure ratio, which benefits from high thermal efficiencies but suffers from high emissions of NO_X.

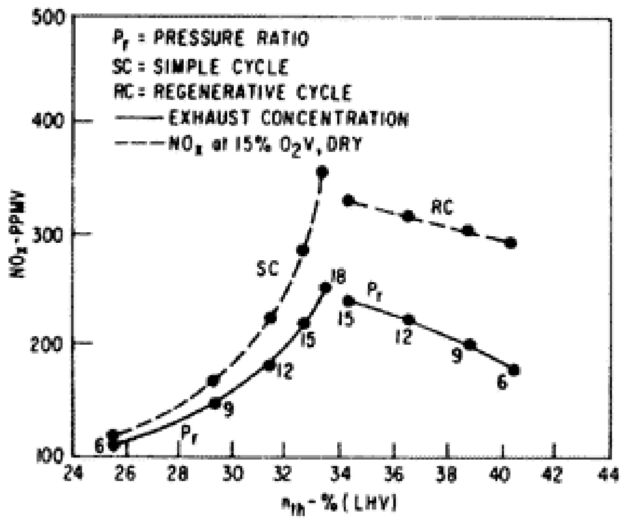


Fig. 13 Nominal NO_X Emission (Dry) Vs Thermal Efficiency

Figure 13 shows the NO_X emissions for simple and regenerative cycles. Tentative EPA rules require that the NO_X concentration be corrected to what it would have been had the exhaust contained only 15% oxygen. In Fig. 13, the broken lines indicate the larger concentrations of NO_X that would occur if fuel were increased to obtain 15% oxygen exhaust concentration.

Operating Requirements

A regenerative-cycle unit retains most of the advantage of a simple-cycle unit such as automated, remote operation. If the regenerators are cold, the turbine operated at synchronous speed for about 30 min and full load is achieved in about 90 min. This loading procedure normally is performed in regenerative-cycle gas turbines used in mid-range utility applications to minimize thermal loadings. In cyclic applications, electric strip heaters are mounted on the regenerator structure, and the stack closure damper is closed to reduce heat loss from the regenerator during the short shutdowns. Modern regenerators can be used as fast as the gas turbine can be started. With modern regenerators, the operating procedure is virtually the same as for simple-cycle units.

Maintenance And Reliability

Inspection and Cleaning

The extent of usage, operational environment, and field experience will determine the required inspection interval. Generally, the regenerator is inspected at engine inspection periods. At each inspection, the air and gas sides should be examined for evidence of mechanical damage or unusual deformation.

Most regenerators are equipped with air side passage ways for access to the air manifold for inspection. The air side generally does not require cleaning. However, if cleaning becomes necessary, the method and procedure should be discussed with the manufacturer. The gas side cleaning becomes necessary when the operator's log indicates a drop in thermal efficiency or increased AP in the gas side because of deposits on the fins. Methods of cleaning usually are suggested by the manufacturer. Among the methods used are injection of walnut shells or flushing with water and detergent.

Leak Detection and Repair

If, during a routine inspection, evidence of leakage is found, or if operational monitoring of the system indicates leakage, a pressure decay check of the regenerator may be required. This check is made by removing the air inlet and outlet ducts and then closing them, so that the regenerator air side can be pressurized. If the rate of decay exceeds leakage limits, the leakage must be located and repaired.

Leakage locations often are isolated by audible examination or soap bubble testing of the gas side when air side is pressurized.

Some leaks in the core manifold and gas inlet and outlet can be repaired by welding. The type of welding generally is specified by the manufacturer and is usually tungsten inert gas welding. The leaks that are in interior regions of the core are not accessible. The common procedure is to seal off an air passage as shown in Fig. 14. The man-hour estimates for leak detection and repair are directly dependent on the type of installation, extent of damage, and type of regenerator.

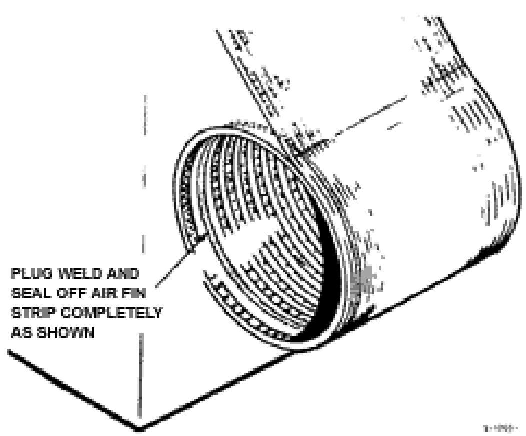


Fig. 14 Leakage Repair in the Core of a Plate-Fin Design Regenerator

Corrosion Protection

Regenerators are made of carbon steel or stainless steel. Moisture condensation on the regenerator core can cause corrosion. This problem is intensified by the presence in a marine or salt environment. Condensation is prevented during normal operation because both the regenerator core and the casing are hot. The regenerator will remain hot enough to prevent condensation for a shutdown of up to 24 hours. For a shutdown period of about 10 days, however, all the openings (inlets and exhausts) must be closed to prevent circulation of moist atmospheric air through the regenerator. For extended shutdowns, all the openings to the system should be closed, and an inhibitor material should be blown into air and gas sides of the regenerator. The type of inhibitor usually is specified by the manufacturer of the regenerator.

Expected Equipment Life

The expected life of a regenerator depends on the type of material used in the core structure (carbon steel or stainless steel) of the regenerator and the type of application. One manufacturer estimates that its regenerator (stainless core) is designed for 1,200,000 hours and 5,000 cycles without scheduled repair, with a life expectancy of 15 to 20 years.

Availability and Reliability

The availability and reliability are very high for regenerative-cycle gas turbines. Table 4 shows reliability and availability of several simple-cycle (SC) and regenerative-cycle (RC) gas turbines. All the gas turbines studied were made by a single manufacturer and used natural gas.

Table 4 Reliability and Availability of Simple and Regenerative-Cycle Gas Turbines

Based on 40 SC & 84 RC Units	Total Plant		Basic Gas Turbine	
	SC	RC	SC	RC
Availability	95.90	95.36	97.10	96.70
Reliability	98.47	98.84	99.06	99.45

The gas turbines were mostly operated in domestic pipelines or petrochemical installations. As Table 4 indicates, reliability and availability were evaluated, based on total station data and then on basic turbine data, excluding controls, accessories, station controls, and load equipment.

Cost Considerations

Regenerative-Cycle Gas Turbine Capital Cost

The cost of a regenerative-cycle gas turbine can vary widely with the type of gas turbine and regenerator. Generally, the following factors greatly influence the costs:

(1) type of turbine,
(2) type of regenerator (U-Tube, plate-fin),

(3) regenerator material (carbon steel, stainless steel),
(4) supporting structure requirement (horizontal, vertical),
(5) exhaust flow rate,
(6) pressure drop required, and
(7) number of modules involved -- with larger gas turbines the number of regenerator modules will increase, which accordingly lowers the unit price.

Fig 15 shows the approximate cost of factory-assembled regenerative-cycle gas turbines.

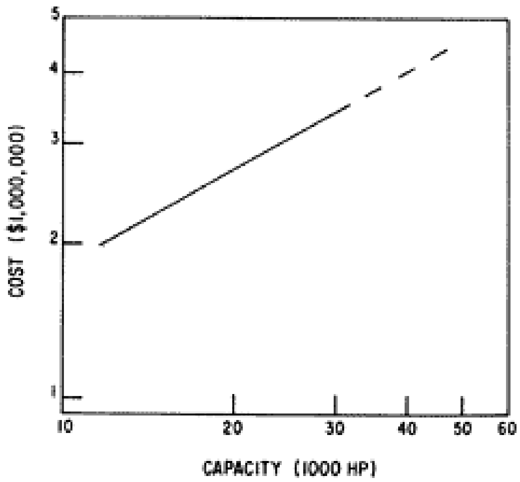


Fig. 15 Approximate Cost of Turbine and Regenerator (1976$)

Figure 16 shows the approximate cost of simple and regenerative cycle turbine generator sets of a single manufacturer. The data shown in

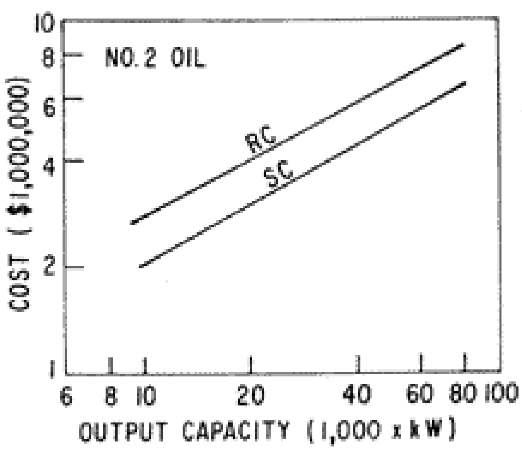


Fig. 16 Comparative Cost of Simple- and Regenerative-Cycle Turbine Generator Sets (1976$)

<u>Regenerator Costs</u>

The present approach to design of the regenerators has been based on the modular concept. Existing industrial gas turbines in the 5,000 to 7,000 hp range have a flow rate of 45 to 60 lb/sec. Based on this flow rate, at least one manufacturer has designed modular regenerators with each basic core handling 45--60 lb/see of the gas. For each engine manufactured in the power levels to 7,000 HP, from 15,000 HP to 30,000 HP; or from 60,000 HP to 120,000 HP, modules are combined to obtain the necessary performance characteristics. For example, a 30,000-HP engine will use a four-core module, and a 100,000-HP engine would use a twelve-core module. Although costs are greatly influenced by several factors, a rough order of magnitude price for plate-fin regenerators (tension braze design) is given in Table 5.

Table 5 Approximate Cost of Plate-Fin Regenerators (Tension Braze

Turbine Capacity (HP)	Regenerator Cost (1977 $)
5 - 7,000	215,000
15,000	300,000
30,000	600,000
60,000	1,200,000
120,000	2,400,000

Another commercially available modular regenerator is the U-tube design. The approximate price for discussion purposes only is given in Table 6.

Table 6 Approximate Cost of U-tube Design Regenerators

Material	Cost[a] ($/lb/sec flow)[b]
Carbon steel	2700
Stainless steel	3700

[a]1977$
[b]The units manufactured so far have been in the range of 50 to 150 lb gas/sec.

Cost of Conversion from Simple to Regenerative Cycle

Many simple-cycle gas turbines presently in operation were designed to facilitate conversion to the regenerative cycle. What distinguished these turbines from typical simple-cycle gas turbines is the addition of combustion wrappers to the combustion system during the manufacturing process. The conversion of simple-cycle gas turbines, not designed for changeover to the regenerative cycle, is generally more involved. This type of conversion requires rebuilding the combustion system to accommodate combustion air piping to and from the regenerator. Moreover, regenerators, piping, new headers, outer and inner elbows, caps and liners, fuel nozzle gas tips, and flame detector bodies would be required in this conversion. The conversion cost is totally dependent on each individual case and is affected by various factors, such as type of regenerator and support structure.

Table 7 shows the estimated cost of conversion for several existing simple-cycle gas turbines manufactured by General Electric Company. These prices also include the combustion wrapper and the generator. From Table 7 the estimated cost to add a regenerator to an existing simple-cycle FS-3002 would be $1,039,970. However, the cost of converting a simple cycle FS-3002 unit which already has factory provisions (combustion wrapper) for future conversion to a regenerative-cycle unit would be only $989,970.

Table 7 Estimated Cost of Conversion to Regenerative Cycle

Model	Approximate Range (HP)	Conversion Cost* (1976 $)
FS-3002	10,000 - 14,000	1,039,970
FS-5002	20,000 - 25,000	1,489,970
FS-7000	50,000 - 65,000	2,289,970

*Costs include combustion wrapper and regenerator (plate-fin design).

SOME OTHER GE GAS TURBINES

		Output (MWs)	
Frame Size	Hz	Simple Cycle	Combined Cycle
MS6001B	50/60 Hz	42.1 MW	64.3 MW
MS6001FA	50/60 Hz	70.14 MW	107.1 MW
MS7001EA	60 Hz	85.4 MW	130.2 MW
MS9001E	50 Hz	123.4 MW	189.2 MW
MS9001EC	50 Hz	169.2 MW	259.3 MW
MS7001FA	60 Hz	171.7 MW	262.6 MW
MS7001FB	60 Hz	184.5 MW	280.3 MW
MS9001FA	50 Hz	255.6 MW	390.8 MW
MS7001H	60 Hz	Not Applicable	400 MW
MS9001H	50 Hz	Not Applicable	480 MW

GE5

The GE5 is a 6 MW range heavy duty gas turbine designed in two configurations: single shaft for power generation and two shaft for mechanical drive applications. The completely new design of the GE5 combines the technology of aircraft engine design with the ruggedness of the heavy duty PGT class of turbines. The flexibility, simplicity, and compactness of the GE5 makes it ideal for industrial power generation (including steam production), oil and gas applications in remote areas, and offshore installations. The control system is configured for fully automatic operation and provides for connection to remote monitoring and diagnostics. The GE5 is ideally suited for applications that require a continuous supply of electrical power with high availability and reliability. The exhaust energy is enough to provide a substantial quantity of steam at various pressures and temperatures when coupled to a heat recovery steam generator.

Design Information

- 11-stage axial flow compressor; first three stages with variable geometry; pressure ratio 15:1
- Annular combustion chamber with 18 fuel nozzles

- Single-shaft turbine with two reaction stages; first stage cooled
- The gas turbine module on a single base plate includes the engine, starting system, load gear, auxiliaries, and acoustic enclosure
- The off-base equipment is limited to the lubricating oil coolers and electric generator
- The inlet filtration module is designed for mounting on top of the gas turbine enclosure
- The enclosure has wide double-hinged doors for ease of access to all turbine components and auxiliaries or engine removal
- The package design is standardized for quick delivery; custom applications can be provided
- The standard configuration, including the filters on top of the enclosure, is 19 by 8 by 19 ft (5.9 by 2.5 by 5.7 m) and weighs 30 t
- The standard unit is equipped with a dry low emissions combustion system

Performance Information

Natural gas fuel

Output	: 5,500 kWe
Heat rate	: 11,740 kJ/kWh
Exhaust flow	: 19.6 kg/s
Exhaust temperature	: 1,065 °F (574 °C)

GE10

The GE10 is a high efficiency and environmentally-friendly heavy duty gas turbine designed and developed by GE Oil & Gas for power generation (including industrial cogeneration) and mechanical drive applications. Since its introduction in 1988, the PGT10A model has provided high performance, reliability, and availability, while retaining features for ease of maintenance.

In 1998, GE launched the high-performance version of this model with two configurations: two shaft for mechanical drive, and single shaft for power generation and cogeneration applications. Because of its ability to burn a variety of fuels, including natural gas, distillate oil, and low BTU fuel, the GE10 can operate in temperate, tropical, offshore, and desert environmental conditions. For continuously improving the GE10's performance and emissions reduction capability, particular emphasis has been placed on the design of a DLN system for nitrogen oxide reduction to meet present and future standards for pollutant emissions.

Design Information

- 11-stage axial flow compressor; first three stages with variable geometry; pressure ratio 15.5:1
- Single combustion chamber

- Single-shaft GE10/1 has three reaction stages, the first two of which are cooled; the two-shaft GE10/2 has two reaction stages
- The gas turbine module on a single base plate includes the engine and the load gear; the auxiliaries are installed on a separate base plate bolted to that of the gas turbine to form a single lift on which the sound-insulated enclosure is mounted
- The electric generator is installed on a concrete foundation to limit overall shipping dimension
- The package design is standardized for quick delivery, but custom applications can be provided
- The standard configuration, excluding the generator and filters, is 30 by 8 by 10 ft (9 by 2.5 by 3 m) and weighs 40 t
- The combustion system is available in conventional and dry low NOx configuration to satisfy the most stringent environmental regulations
- Steam and water injection systems are available for nitrous oxide reduction and power augmentation

Performance Information	
Generator drive, single-shaft version, natural gas fuel	**Mechanical drive, two-shaft version, natural gas fuel**
Output : 11,250 kWe Heat rate : 11,481 kJ/kWh Exhaust flow : 46.9 kg/s Exhaust temp : 903 °F (484 °C)	Output : 15,675 shp (11,690 kW) Heat rate : 7,817 btu/shp-h (11,060 kJ/kWh) Exhaust flow: 103.4 lb/s (46.9 kg/s) Exhaust temp: 903 °F (484 °C)

PGT10

The PGT10 is a high efficiency gas turbine for shaft outputs ranging between 9,500 and 15,000 HP at ISO conditions. Since its introduction in 1988, the PGT10 has provided high performance, reliability, and availability in a design that is simple and easy to maintain. To achieve high efficiencies over an extended power range an uncommon combination of features have been incorporated into the design: high pressure ratio, firing temperature level in line with second generation gas turbines, and variable axial compressor stator vanes and power turbine nozzles.

The PGT10 combustion system consists of a single combustion chamber designed for low nitrous oxide emissions, and is suitable for a large variety of gaseous and liquid fuels. Typical applications for PGT10 two-shaft gas turbines are natural gas compression, centrifugal pump drive, process applications, and power generation (including cogeneration) and offshore applications.

Design Information

- 17-stage axial flow compressor; pressure ratio 14.1:1
- Single combustion chamber
- Two-shaft turbine with two reaction stages
- The gas turbine module on a single base plate includes the engine and the load gear; the auxiliaries are installed on a separate base plate bolted to that of the gas turbine to form a single lift on which the sound-insulated enclosure is mounted
- The electric generator is installed on a concrete foundation to limit overall shipping dimension
- The package design is standardized for quick delivery, but custom applications can be provided
- The standard configuration, including the filters on top of the enclosure, is 30 by 8 by 13 ft (9.1 by 2.5 by 4 m) and weighs 32 t
- The combustion system is available in conventional and dry low emissions configuration to satisfy the most stringent environmental regulations
- Steam and water injection systems are available for nitrous oxide reduction and power augmentation

Performance Information

Generator drive, two-shaft version, natural gas fuel

- Output : 10,220 kWe
- Heat rate : 11,536 kJ/kWh
- Exhaust flow : 42.3 kg/s
- Exhaust temp : 910 °F (488 °C)

Mechanical drive, two-shaft version, natural gas fuel

- Output : 14,295 shp (10,660 kW)
- Heat rate : 7,817 btu/shp-h (11,060 kJ/kWh)
- Exhaust flow: 93.3 lb/s (42.3 kg/s)
- Exhaust temp: 910 °F (488 °C)

PGT16

The PGT16 gas turbine consists of a twin spool LM1600 GE aeroderivative gas generator coupled with a rugged, industrial power turbine designed by GE Oil & Gas. The LM1600's gas generator is derived from the F404 turbofan aircraft engine, while the power turbine of the PGT16 gas turbine is identical to that of the PGT10. The power turbine shaft speed (7,900 RPM) is optimized for direct coupling to pipeline, injection, and process centrifugal compressors with speed ranges that suit all operating conditions. For generator drive applications, the LM1600, coupled to its synchronous generator with speed reduction gear, is a highly flexible turbo generator that can also cover combined cycle and cogeneration applications with an electrical efficiency approaching 50%.

Design Information

- Twin spool axial compressor (three stages LP compressor, seven stages HP compressor); pressure ratio 20.1:1
- Annular combustion chamber (18 fuel nozzles)
- Twin spool gas generator turbine (one stage HP turbine, one stage LP turbine)
- Two stages power turbine (7,900 RPM) with variable first stage nozzles
- The complete gas turbine module is mounted on a single base plate
- The enclosure is integrated with the base plate providing maximum accessibility for gas turbine and auxiliaries maintenance
- The standard configuration, excluding the inlet and exhaust ducts, is 27 by 8 by 12 ft (8.1 by 2.5 by 3.8 m) and weighs 19 t
- Dry low emission (DLE) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information	
Generator drive, natural gas fuel	**Mechanical drive, natural gas fuel**
Output : 13,735 kWe	Output : 19,120 shp (14,252 kW)
Heat rate : 10,314 kJ/kWh	Heat rate : 7,020 btu/shp-h (9,939 kJ/kWh)
Exhaust flow : 47.4 kg/s	Exhaust flow: 104.5 lb/s (47.4 kg/s)
Exhaust temp : 919 °F (493 °C)	Exhaust temp: 919 °F (493 °C)

PGT25

The PGT25 gas turbine consists of an LM2500 GE aeroderivative gas generator coupled with a rugged, industrial power turbine. The LM2500 gas generator and the PGT25 power turbine has one of the best overall performance in the 17,000 to 31,000 HP range, with maximum efficiency above 37 percent. The speed of the output shaft, 6,500 rpm, as well as its high capacity and simplicity of maintenance have made the PGT25 highly suitable for driving direct coupled centrifugal compressors for pipeline service or natural gas re-injection plants. It's light weight and high efficiency makes it well-suited to offshore and industrial power generation. The modular design, extended to all accessory equipment, takes into account the special requirements of platform applications (minimum weight and overall dimensions), and drastically reduces erection time and costs. The gas generator can be removed easily with a simple translation within the enclosure, reducing the time required for maintenance. Simplicity of construction and the high quality of the components allow for long intervals between overhauls and reduced maintenance costs.

Design Information

- 16-stage axial compressor; pressure ratio 17.9:1
- Annular combustion chamber (30 fuel nozzles)
- Two stage gas generator turbine
- Two stage power turbine (6,500 RPM)
- The complete gas turbine module is mounted on a single base plate
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance.
- The standard configuration, excluding the inlet and exhaust ducts, is 30 by 11 by 12 ft (9.1 by 3.5 by 3.7 m) and weighs 38 t
- Dry low emission (DLE) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information			
Generator drive, natural gas fuel		**Mechanical drive, natural gas fuel**	
Output	: 22,417 kWe	Output	: 31,200 shp (23,261 kW)
Heat rate	: 9,919 kJ/kWh	Heat rate	: 6,750 btu/shp-h (9,560 kJ/kWh)
Exhaust flow	: 68.9 kg/s	Exhaust flow	: 151.9 lb/s (68.9 kg/s)
Exhaust temp	: 976 °F (525 °C)	Exhaust temp	: 977 °F (525 °C)

PGT25+

The PGT25+ gas turbine has been developed for 30 MW ISO shaft power service, and has one of the highest thermal efficiency level (approximately 40 percent) in this power range. The PGT25+ gas turbine consists of an LM2500+ GE aeroderivative gas generator (updated version of the LM2500 gas generator with the addition of a zero stage to the axial compressor) coupled with a 6,100 RPM power turbine. Built on the LM2500 heritage and with demonstrated 99.6 percent reliability, the PGT25+ features proven technology improvements and a large percentage of parts in common with LM2500 to deliver the same outstanding level of reliability. Designed for ease of maintenance, the PGT25+ provides a high level of availability. High efficiency and reliability are just two of several benefits contributing to PGT25+ customer value. Application flexibility makes the PGT25+ ideal for a range of mechanical drive, power generation, industrial cogeneration, and offshore platform applications in any environment.

Design Information

- 17-stage axial compressor; pressure ratio 21.5:1
- Annular combustion chamber (30 fuel nozzles)
- Two stage gas generator turbine
- Two stage power turbine (6,100 RPM)
- The gas generator, power turbine, and auxiliary system are mounted on a single base plate
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance.
- The standard configuration, excluding the inlet and exhaust ducts, is 21 by 12 by 13 ft (6.5 by 3.6 by 3.9 m) and weighs 38 t
- Dry low emission (DLE) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information	
Generator drive, natural gas fuel	**Mechanical drive, natural gas fuel**
Output : 30,226 kWe	Output : 42,060 shp (31,364 kW)
Heat rate : 9,084 kJ/kWh	Heat rate : 6,180 btu/shp-h (8,754 kJ/kWh)
Exhaust flow : 84.3 kg/s	Exhaust flow: 185.8 lb/s (84.3 kg/s)
Exhaust temp : 931 °F (500 °C)	Exhaust temp: 931 °F (500 °C)

LM6000

LM6000 delivers more than 44.8 MW of power at greater than 42.7 percent thermal efficiency. LM6000 is the one of the most fuel efficient simple-cycle gas turbine. High efficiency, low cost, and easy installation make it the perfect modular building block for electrical power applications such as industrial cogeneration or utility peaking, in both mid range and base-load operation. As an aircraft engine aboard the Boeing 747, the LM6000 has logged more than ten million flight hours, with the lowest shop visit rate of any jet engine. Continuing the tradition of GE's LM6000 established record, the LM6000 is an ideal source of drive-power for pipeline compression, offshore platforms, gas re-injection, and liquefied natural gas compressors. The LM6000 was GE's first aeroderivative gas turbine to employ the dry low emission premixed combustion system; this system can be retrofitted on LM6000s already in operation. Water or steam injection can also be used to achieve low nitrous oxide emissions.

Design Information

- Five-stage low pressure compressor; 14-stage high pressure compressor; pressure ratio 30:1
- Annular combustion chamber
- Two-stage high pressure turbine; five-stage low pressure turbine
- Two-stage power turbine (6,100 RPM)
- The gas generator, power turbine, and auxiliary system are mounted on a single base plate
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance
- The standard configuration, excluding the inlet and exhaust ducts, is 31 by 14 by 14 ft (9.3 by 4.2 by 4.4 m) and weighs 31 t
- Dry low emission (DLE) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information

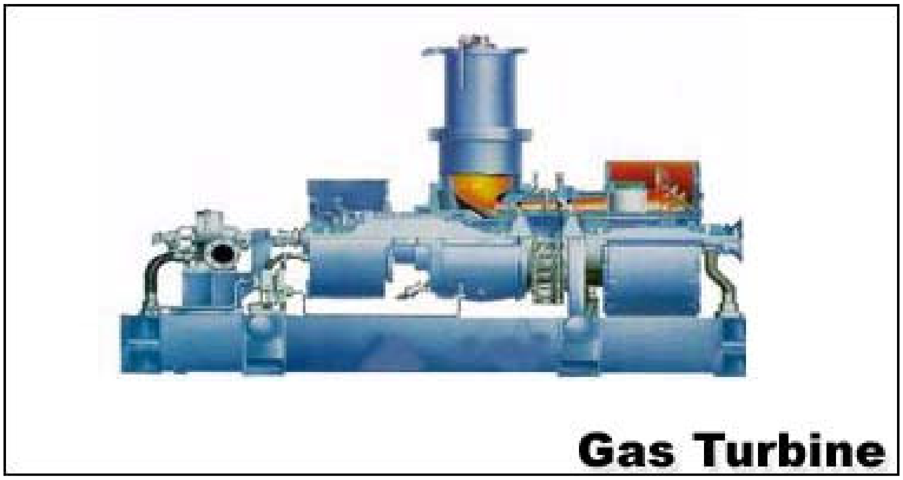
Generator drive, natural gas fuel

- Output : 43,076 kWe
- Heat rate : 8,707 kJ/kWh
- Exhaust flow : 131 kg/s
- Exhaust temp : 840 °F (449 °C)

Mechanical drive, natural gas fuel

- Output : 60,000 shp (44,740 kW)
- Heat rate : 5,980 btu/shp-h (8,455 kJ/kWh)
- Exhaust flow: 280 lb/s (127 kg/s)
- Exhaust temp: 853 °F (456 °C)

MS 1002



Construction Features

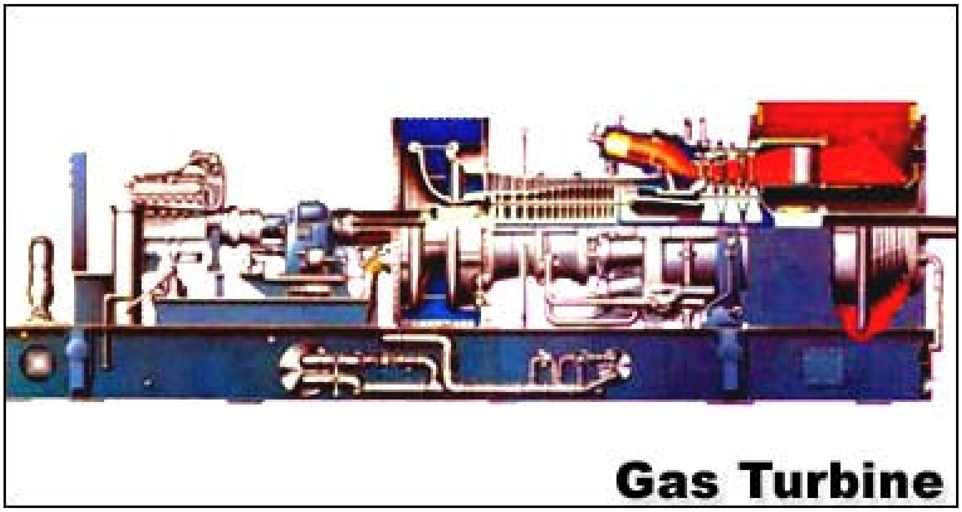
Compressor Stages	15
Turbine Stages	2
Number of Shafts	2
Number of Combustors	1
Pressure Ratio	8.2
Load Gear Box Design Horizontal offset, single stage, single helical gears Dimensions L x W x H mtrs	5.8 x 2.5 x 3.4
Package Weight, Tons	18

Design Features

- Turbine is skid mounted. Lube oil tank and accessories are housed in separate skid
- Two shaft machine, can be used for compressor drive or power generation
- Diesel Engine/Electric motor with torque converter and Gas Expander or Steam Turbine are offered as starting systems. Generator is at exhaust end
- Side or top hot gas exhaust arrangement

- Speedtronic Mark-V control system for control, operation protection of gas turbine package with triple redundant microprocessor controllers and windows based interface station

MS6001



MS6001 is a high efficiency, compact, single shaft heavy-duty gas turbine. Its design was based on the well-proven mechanical features of the MS5001. MS6001 is widely applied in power generation for base, mid-range, and peak load service. Other typical applications include driving process machines such as compressors in liquefied natural gas plants. Combined cycle plants based on the MS6001 achieve very high efficiencies with higher availability and reliability than conventional thermal plants.

Design Information

- 17-stage axial compressor; pressure ratio 11.9:1
- Can-annular combustion, 10 chambers; dual fuel capability
- Three stage turbine; cooled buckets on first two stages; first two stage nozzles cooled
- Complete turbine package mounted on a single base plate
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance
- The standard configuration, excluding the inlet and exhaust ducts, is 52 by 10 by 12 ft (15.9 by 3.2 by 3.8 m) and weighs 96 t
- Dry low NOx (DLN) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information	
Generator Drive, Fuel - Natural Gas ➢ Output : 42100 kW ➢ Heat rate : 11230 kJ/kWh ➢ Exhaust flow : 145.8 kg/s ➢ Exhaust temp : 552 °C	**Mechanical Drive, Fuel - Natural Gas** ➢ Output : 58380 shp (43530 kW) ➢ Heat rate : 7650 btu/shp-h (10825 kJ/kWh) ➢ Exhaust flow: 319.7 lb/s (145 kg/s) ➢ Exhaust temp: 1011 °F (544 °C)

MS7001EA

MS7001EA is a single shaft heavy-duty gas turbine for power generation and industrial applications requiring the maximum reliability and availability. With design emphasis on energy efficiency, availability, performance, and maintainability, MS7001EA is a proven technology machine with more than 500 units of its class in service.In addition to 60Hz power generation, typical applications include large compressor train drives for liquefied natural gas plants.

Design Information

- 17-stage axial compressor; pressure ratio 12.5:1
- Reverse flow, multi chamber (can-annular) combustion system (10 chambers)
- Three stages turbine (3,600 RPM)
- Two base plate configuration (gas turbine flange to flange unit and auxiliary system)
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance
- The standard configuration, excluding the inlet and exhaust ducts, is 38 by 10 by 12 ft (11.6 by 3.3 by 3.8 m) and weighs 121 t
- Dry low NOx (DLN) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information	
Generator Drive, Fuel - Natural Gas ➢ Output : 85100 kW ➢ Heat rate : 11000 kJ/kWh ➢ Exhaust flow : 300 kg/s ➢ Exhaust temp : 537 °C	**Mechanical Drive, Fuel - Natural Gas** ➢ Output : 115330 shp (86000 kW) ➢ Heat rate : 7700 btu/shp-h(10900 kJ/kWh) ➢ Exhaust flow: 661.4 lb/s (300.0 kg/s) ➢ Exhaust temp: 1000 °F (538 °C)

MS9001E

MS9001E is a single shaft, heavy-duty gas turbine. It was developed for generator drive service in the 50 Hz market. MS9001E is widely applied in power generation for base, mid-range, and peak load service. Combined cycle plants based on MS9001E achieve very high efficiencies with higher availability and reliability than conventional thermal plants.

Design Information

- 17-stage axial flow compressor; pressure ratio 12.6:1
- Can-annular combustion, 14 chambers; dual fuel capability
- Three stages turbine; cooled buckets on first two stages
- Two base plate configurations (gas turbine flange to flange unit and auxiliary system)
- The enclosure is integrated with the base plate, providing maximum accessibility for gas turbine and auxiliaries maintenance
- The standard configuration, excluding the inlet and exhaust ducts, is 73 by 15 by 21 ft (22.1 by 4.5 by 6.3 m) and weighs 217.5 t
- Dry low NOx (DLN) combustion system
- Steam or water injection systems for nitrous oxide abatement

Performance Information

Generator Drive, Fuel - Natural Gas

Output	: 123400 kWe
Heat rate	: 10650 kJ/kWh
Exhaust flow	: 412.8 kg/s
Exhaust temperature	: 543 °C

MS7001H/9001H

MS7001H / 90001H Gas Turbine Development

Milestones

- 1991 - H System™ technology conceptualization May 1995 - H System™ development program announced August 1997 - Subscale compressor test completed October 1997 - First set of large single crystal airfoils produced May 1998 - 9H full speed, no load test completed
- November 1999 - 9H pre-shipment testing completed
- February 2000 - 7H full speed, no load test completed
- December 2000 - 9H gas turbine shipped to U.K.
- 2002 - 9H startup at launch site
- 2002 - 9H series of characterization and reliability tests
- 2002 - 7H pre-shipment testing scheduled

Testing

It has undergone extensive design validation and component testing. Full speed no load testing was completed in May 1998, and pre-shipment tests were completed in November 1999. The 7H Gas Turbine unit underwent similar full speed no load testing through February 2000. Both gas turbines will also undergo approximately half a year of extensive demonstration and characterization testing at the launch sites.

Technology Validation Tests	
DFSS and Design Tools ➢ Robust design ➢ Transfer of aircraft engine ➢ Design tools **Materials** ➢ Design data ➢ Process development ➢ Alternate materials ➢ High gradient castings ➢ Oxidation/corrosion	**Turbine Buckets** ➢ Rotational heat transfer ➢ Static heat transfer ➢ Casting trial support ➢ NDE **Steam Cooling** ➢ Purity tests ➢ Materials compatibility ➢ Spoolie wear tests ➢ Protection of steam cooled parts

Combustor
- DLN
- Flashback resistant fuel nozzles
- Component tests

TBC Development
- High gradient tests
- Bond coats
- Air plasma spray process development

Seals
- Cloth seals
- Brush seals

Turbine Nozzles
- Heat transfer tests
- Casting trail support
- NDE coatings

Exhaust Diffuser
- Aerodynamic tests
- Flow analysis

Component Testing
- Inlet aerodynamic test
- Compressor rig test
- Combustor tests
- Reduced pressure
- Full pressure
- Nozzle cascade
- Stage 1 nozzle
- LCF "Small Sample" Tests
- Heat Transfer Aero Tests
- Casting Trial
- Cascade LCF Test
- Exhaust aero tests
- Compressor rotor cooling
- 9H compressor rig test
- Stage 1 bucket
- Rotational heat transfer
- Casting trials
- Materials design data
- Thermal barrier coating
- Steam purity tests
- Rotating steam delivery rig test – 2000

9H Full Speed No Load Test - Completed May 1998	
Objectives: Validate	**Results**
Rotor dynamics and vibration levels	Gas turbine shaft run outs well within limits
Compressor airfoil aeromechanics	Low break-away torque to rotate shaft
Compressor airflow and efficiency	Bearing/Lube oil temperatures okay
Scale-up effects from compressor rig test	Clearance control system operational
Compressor and turbine running clearances	Mark VI control operational
Mark VI control of gas turbine	
Key system characteristics	
Bearings ,Rotor cooling	
Clearance control systems	

9H Pre-Shipment Test, Completed November 1999	
Objectives: Validate	**Results**
Rotor dynamics with turbine airfoil cooling Secondary airflow systems Turbine airfoil aeromechanics Turbine rotor purge circuit	Demonstrated repeatable rotor dynamics Compressor and turbine aeromechanics data up to 108% speed Demonstrated integrity of rotor structure

7H Full Speed No Load Test, Completed February 2000	
Objectives: Validate	**Results**
Rotor dynamics and vibration levels Compressor airfoil aeromechanics Compressor airflow and efficiency Scale-up effects from compressor rig test Compressor and turbine running clearances Mark VI control of gas turbine	Excellent rotor dynamics characteristics No aeromechanics issues Compressor airflow and efficiency exceeded predictions Successful automatic Data obtained for optimal clearances

In 1995, GE introduced its new generation of gas turbines, the 60 Hz MS7001H and the 50 Hz MS9001H. Called the H System™, this technology offers higher efficiency and greater power output in combined cycle power plant operation. The H System™ achieves 60% fuel efficiency, the first gas turbine to reach this major milestone. Because fuel represents the largest single cost of running a power plant, an increase of even a single percentage point of efficiency can reduce operating costs by $15-20 million USD over the life of a typical gas-field combined cycle plant in the 400-500 MW range..

Application

Base load power generation

Combined cycle configuration

The first 9H gas turbine was built at GE's Greenville, South Carolina manufacturing facility.

MS7001H / 90001H Gas Turbine Combined Cycle System

The H System™ is not just an advanced gas turbine; it is an advanced, integrated combined cycle system with every component optimized for the highest level of performance.

H combined cycle systems are based on a unique technology platform in which the steam plant reheat process and gas turbine bucket and nozzle cooling are accomplished by the same integrated heat transfer system. This enables higher firing temperature operation and improvement in efficiency, providing power generators with the most competitive cost of electricity. Despite higher firing temperature, combustion temperature is kept at levels that minimize emission production.

Gas Turbine

- MS9001H - 50 Hz
- MS7001H - 60 Hz

Steam turbine

- 3 pressure reheat
- 3-D aerodynamics
- Multiple configurations available

Control

- Integrated control system

HRSG

- Forced or natural circulation

Generator

- Hydrogen cooled rotor/stator
- Static start

Accessories

- Common lube oil system
- Common hydraulic power unit

MS7001H / 90001H Gas Turbine Design Features

Proven Features

Proven features of previous gas turbine models that have been incorporated into the H System™ include:

- GE aircraft engine CF6 compressor aerodynamics
- DLN combustion system
- Forward end thrust bearings
- Steel wheels
- IN 718 wheels

Technology Advances

In addition to incorporating proven technology from existing gas turbines, GE made several significant technology advances in the development of the H System™ which enables it to achieve a record-breaking 60% efficiency level.

Significant technology advances include:

- Increase in firing temperature of more than 100 °C (212 °F) which results in

- Aft bearing
- Front end drive
- Through-bolt rotor construction
- Axial exhaust

increased efficiency.

- Increased Compressor airflow and pressure ratio
- Single crystal airfoil material
- Thermal barrier coatings
- Advanced analysis tools