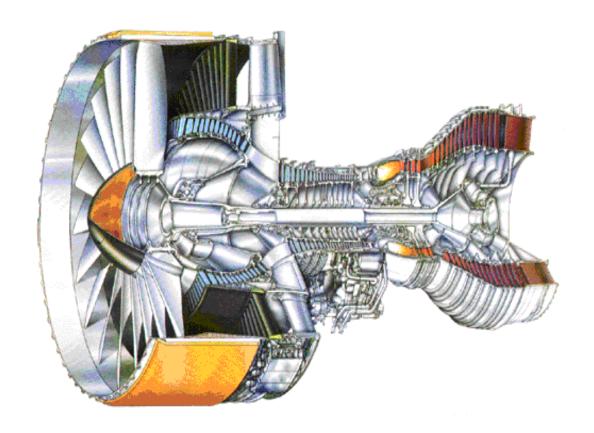
NACT 272



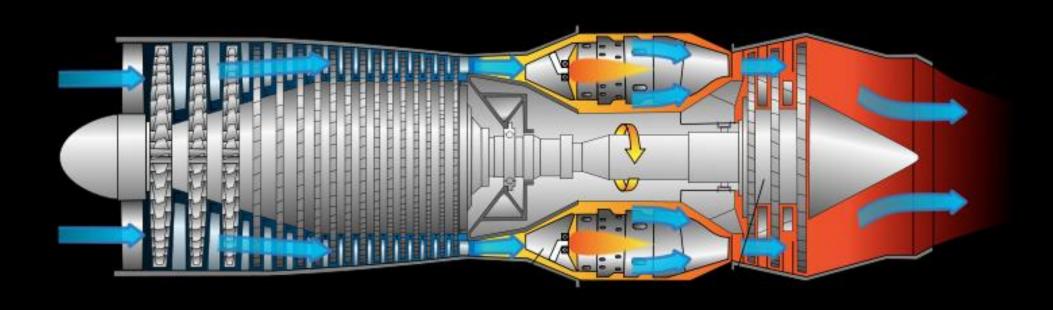
Stationary Gas Turbines

Course Overview

- Gas turbine theory and operation
- Gas turbine uses
- Air pollution control devices
- Gas turbine regulations
- Typical permit conditions
- Inspection procedures
- Continuous emission monitoring
- Source testing requirements



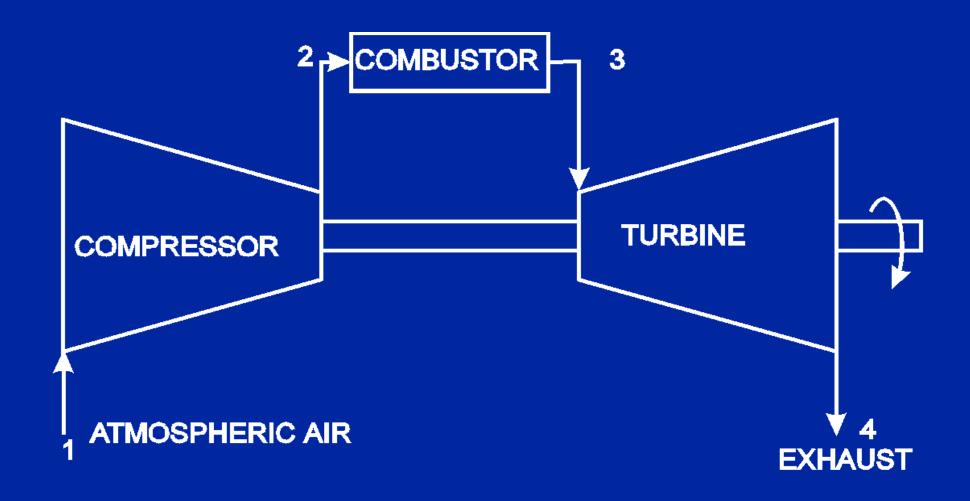
What is a Gas Turbine

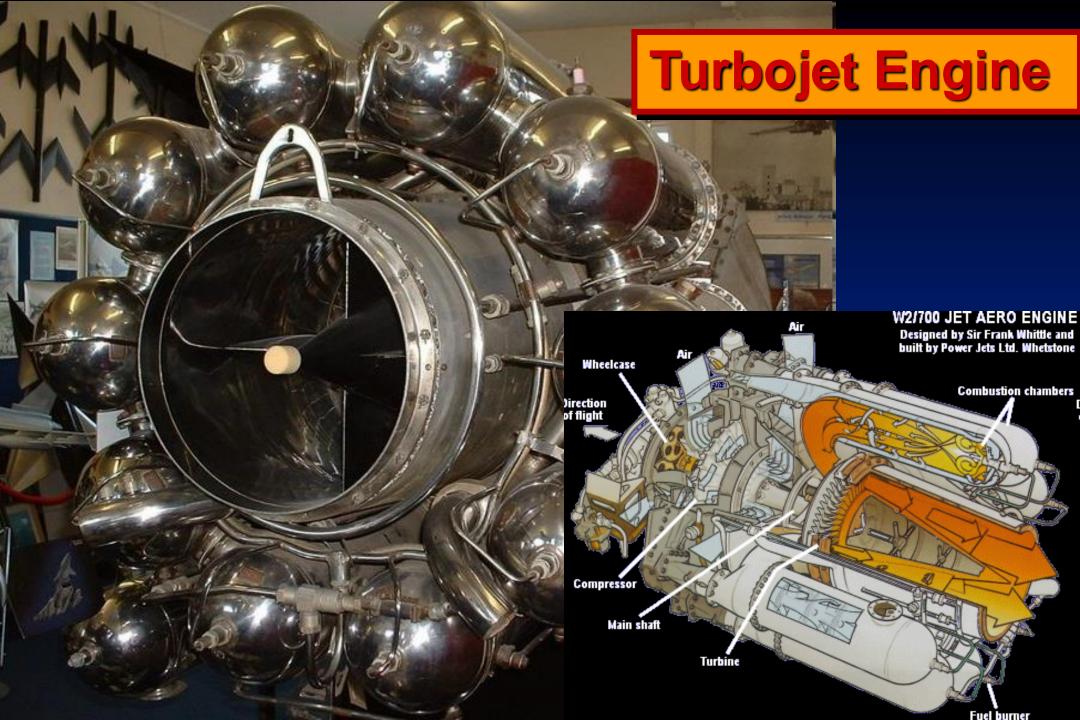


How does a Turbine Work?

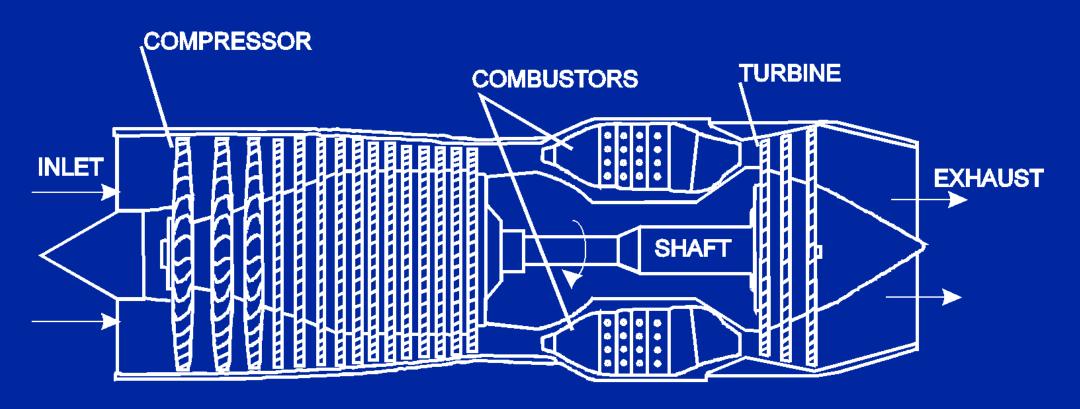


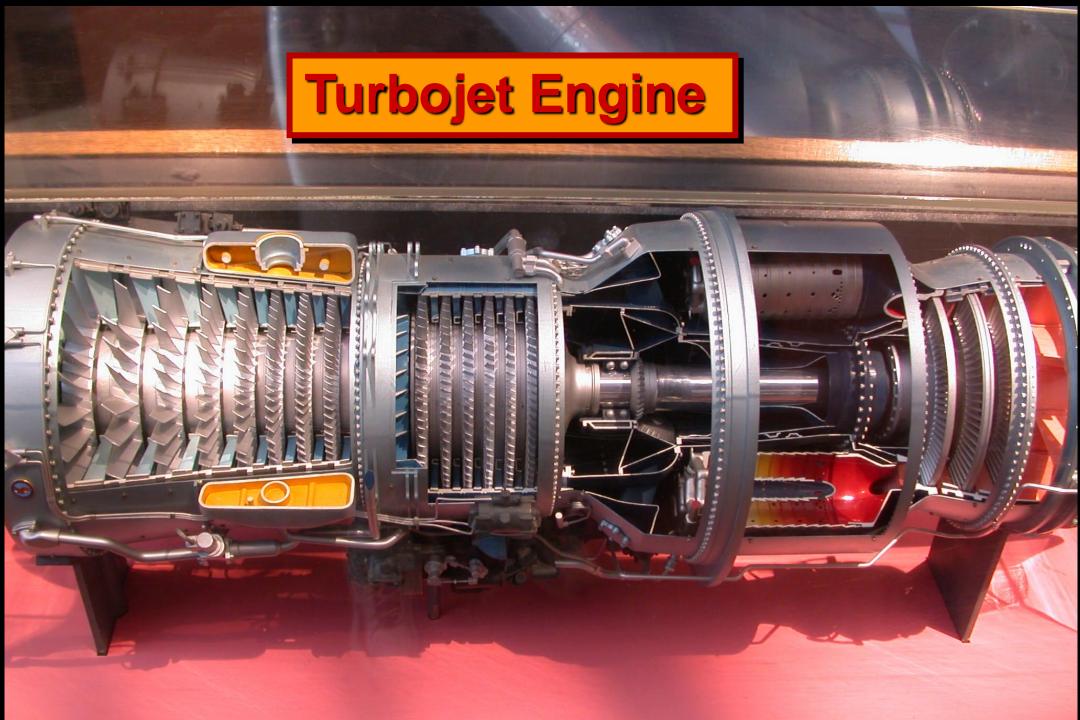
Simple Open Cycle Gas Turbine



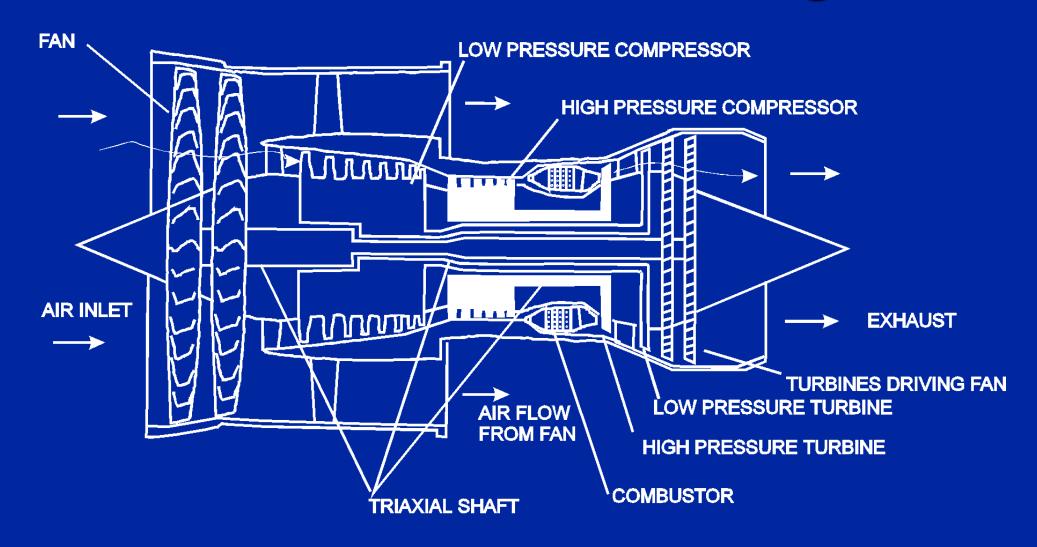


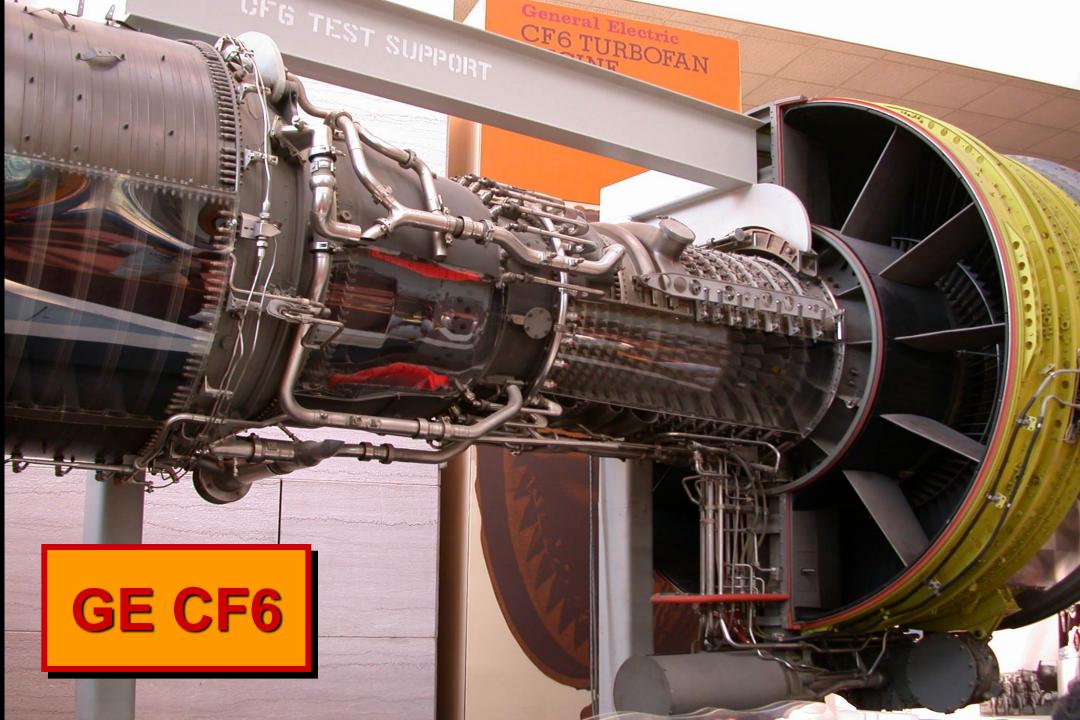
Single Spool Turbojet Engine

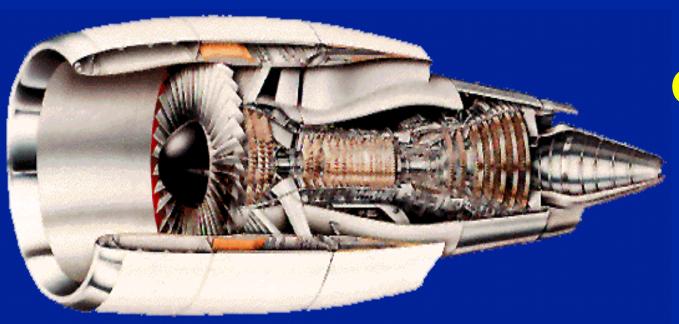




Turbofan Gas Turbine Engine





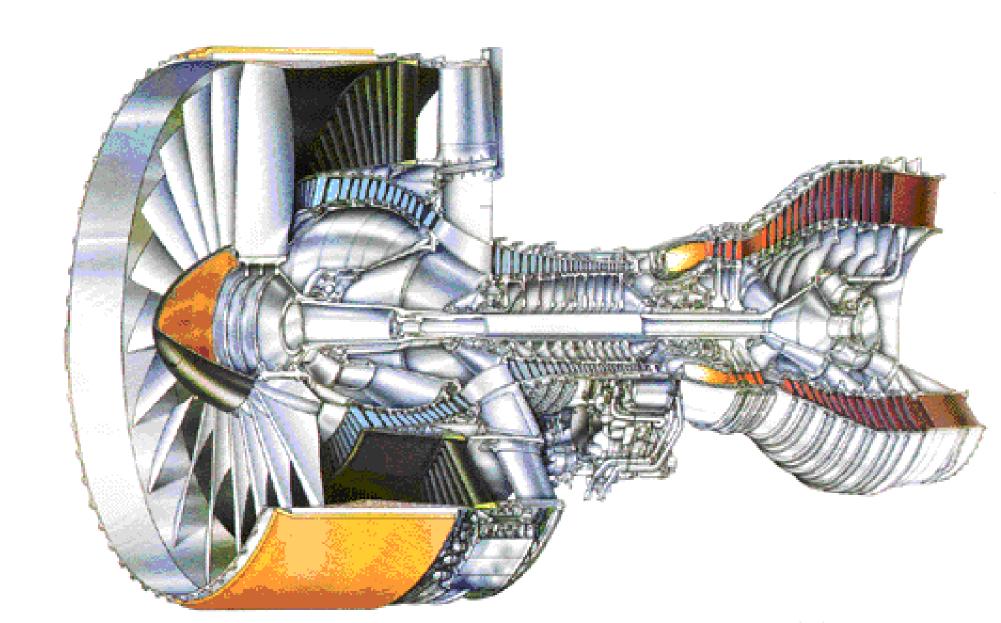


GE High Bypass Turbofan

Presidential Boeing 747



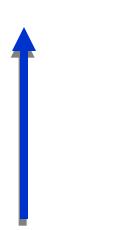
PW4000 112-INCH FAN ENGINE







Jet Aircraft



Gas Turbine Uses



Stationary Sources



Marine Power

Uses of Gas Turbines

- ◆ Aircraft Turbojet, turbofan & turboprop
- Ships
- Electrical Generation -- Base load, peaking, cogeneration and backup
- Natural gas compression and transport
- Water pumping



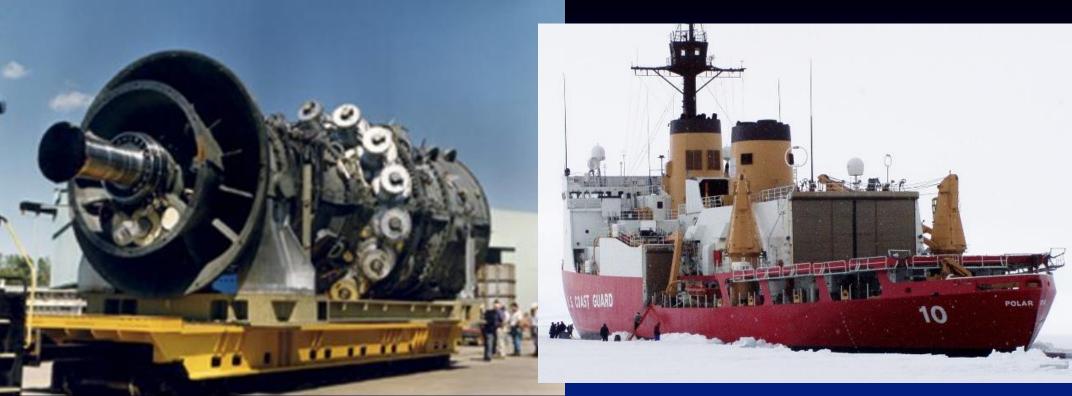
Advantages

- ◆ Relatively small size (power to size ratio)
- Light weight for output (power to weight ratio)
- Requires modest foundation
- Requires no cooling water
- Rapid startup and loading
- Good thermal efficiency
- Low maintenance
- Runs unattended
- Long life

Disadvantages

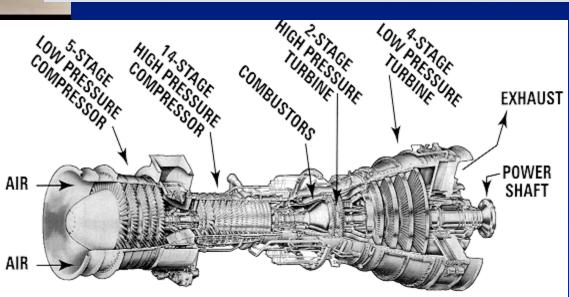
- ◆ Expensive
- ◆ Require clean fuel
- ◆ Require clean water
- ◆ Natural Gas supply
- ◆ Transmission Grid
- Use more fuel than IC Engines
- Not efficient at part load





400MW (MEGAWATT) GAS TURBINE

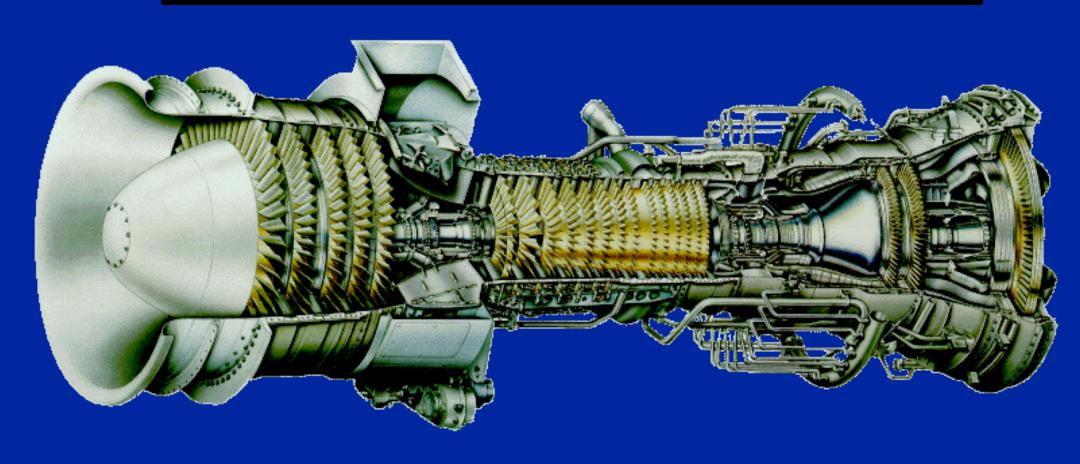
Marine Engines



Aeroderivative Turbines

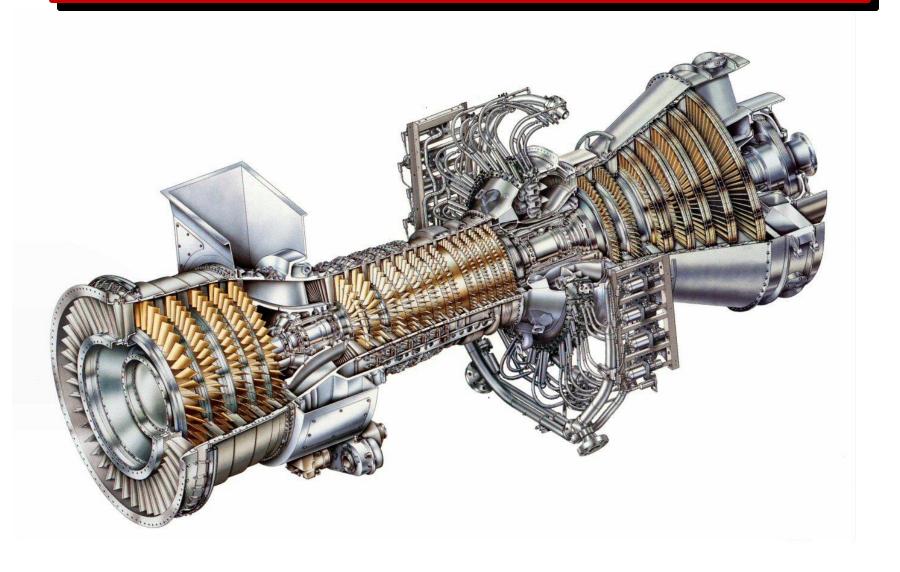
- Based on established product
- High simple cycle efficiency
- High power to weight ratio
- Direct generator drive capability
- ◆ Ease and speed of maintenance
- Parts availability

GE LM5000 Gas Turbine

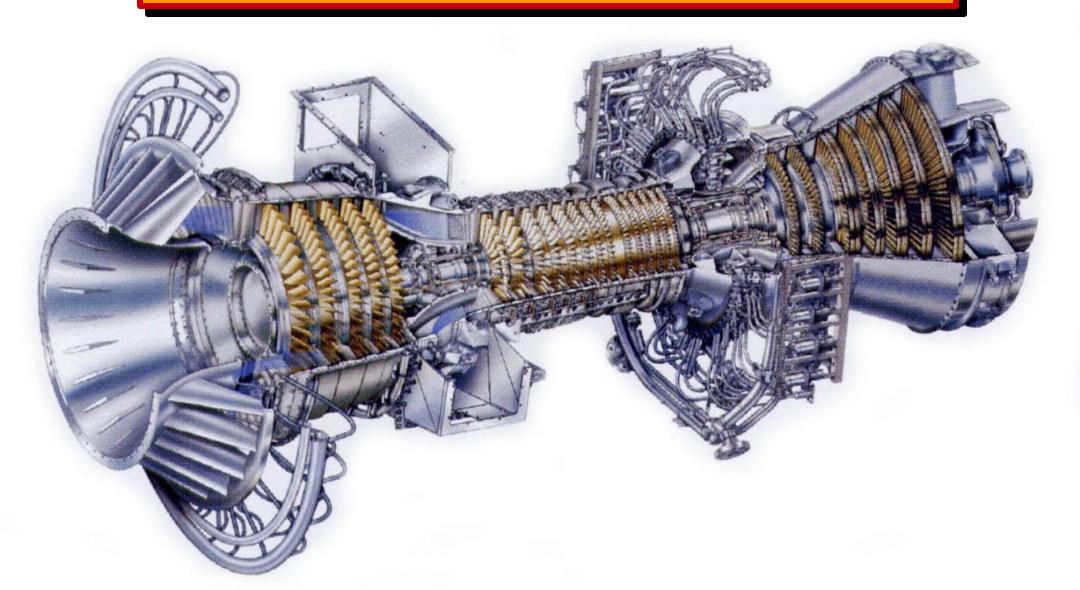


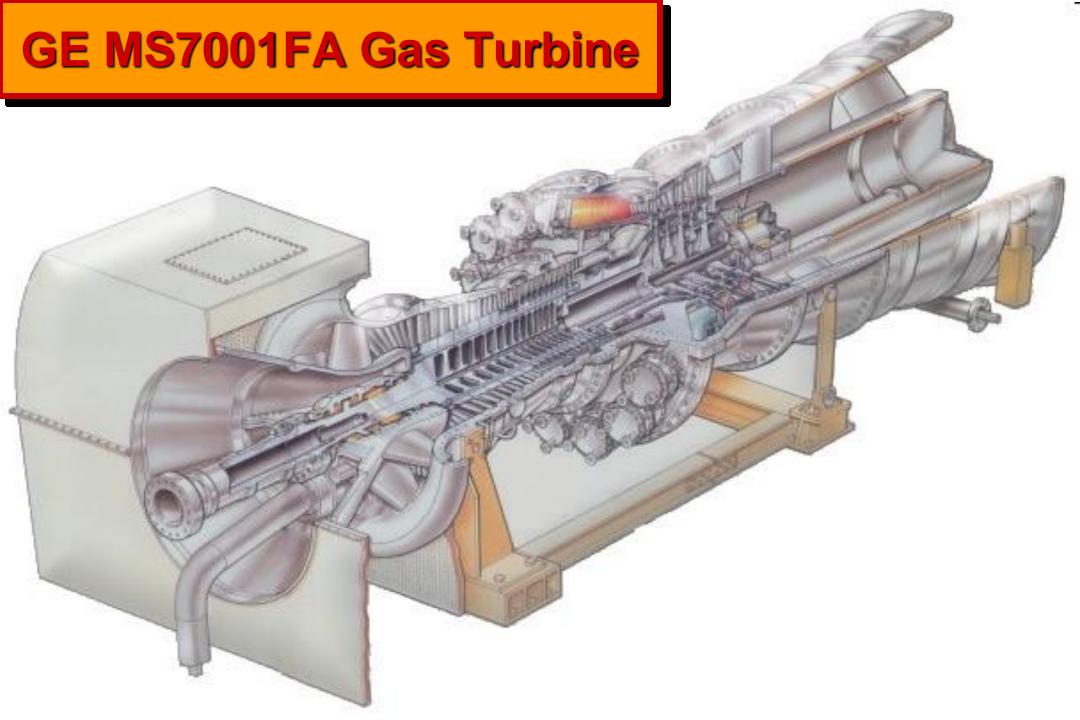
Graphic Courtesy of General Electric

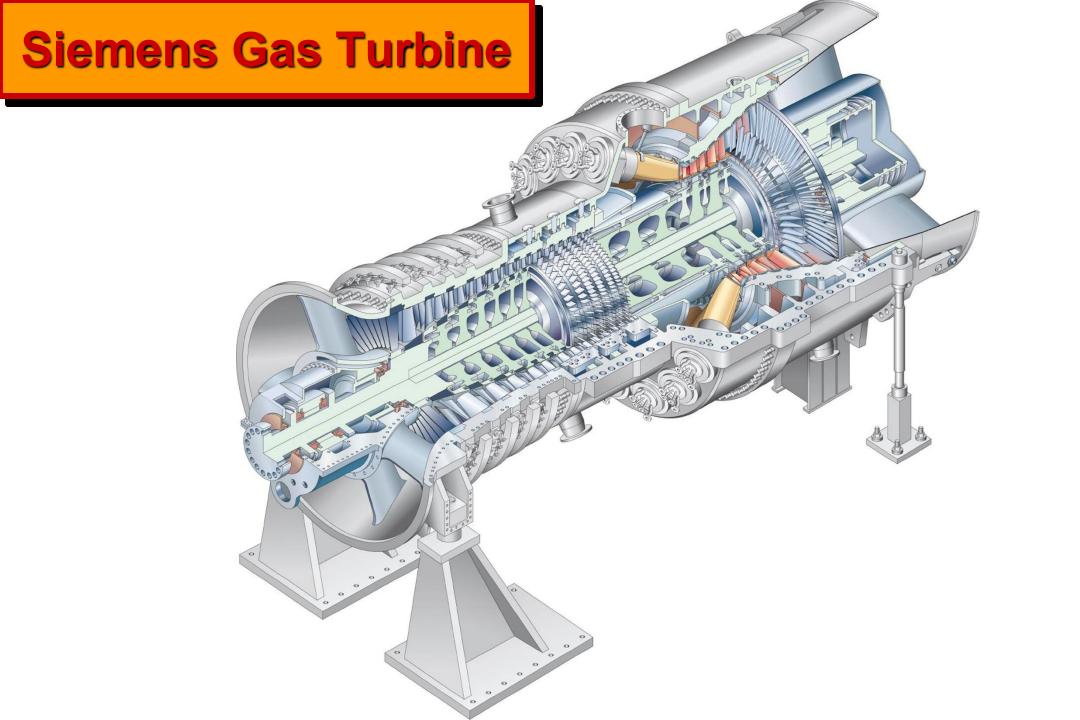
GE LM6000 Gas Turbine

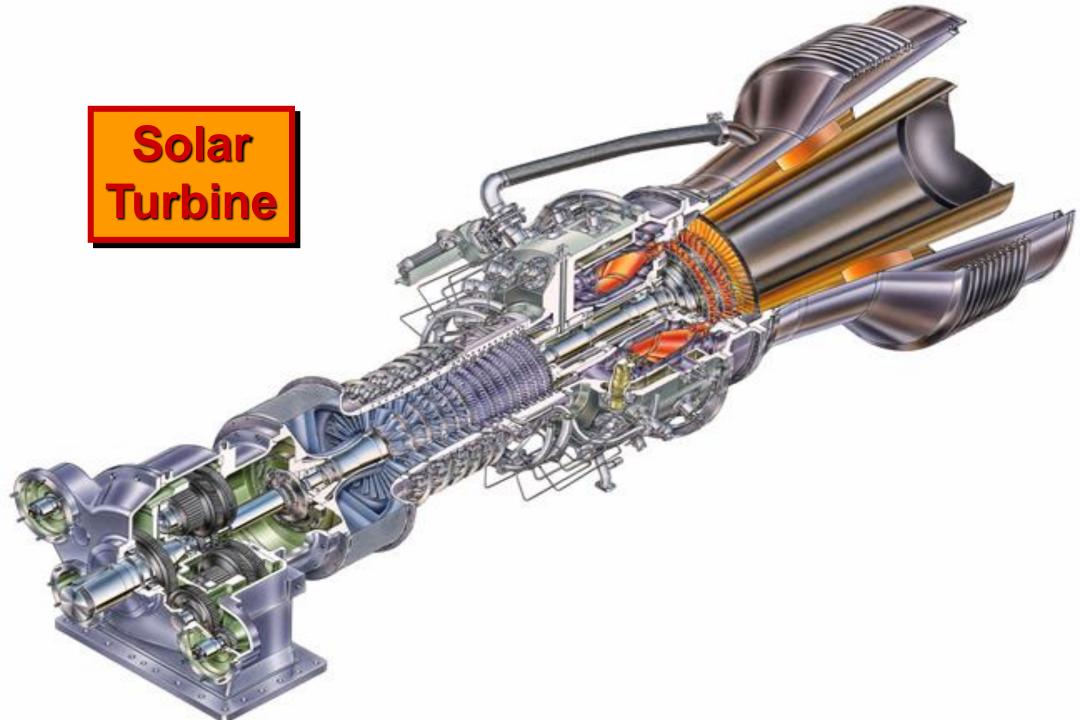


GE LM6000 with Sprint











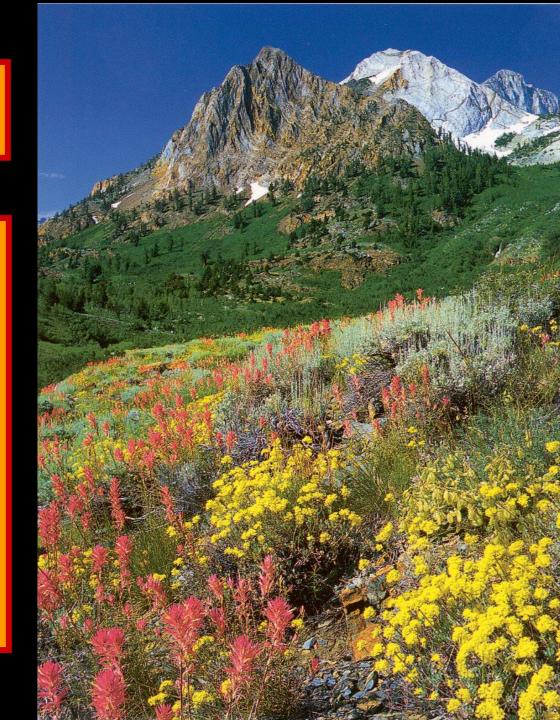
Aeroderivative Turbine

LM 6000: 50 MW



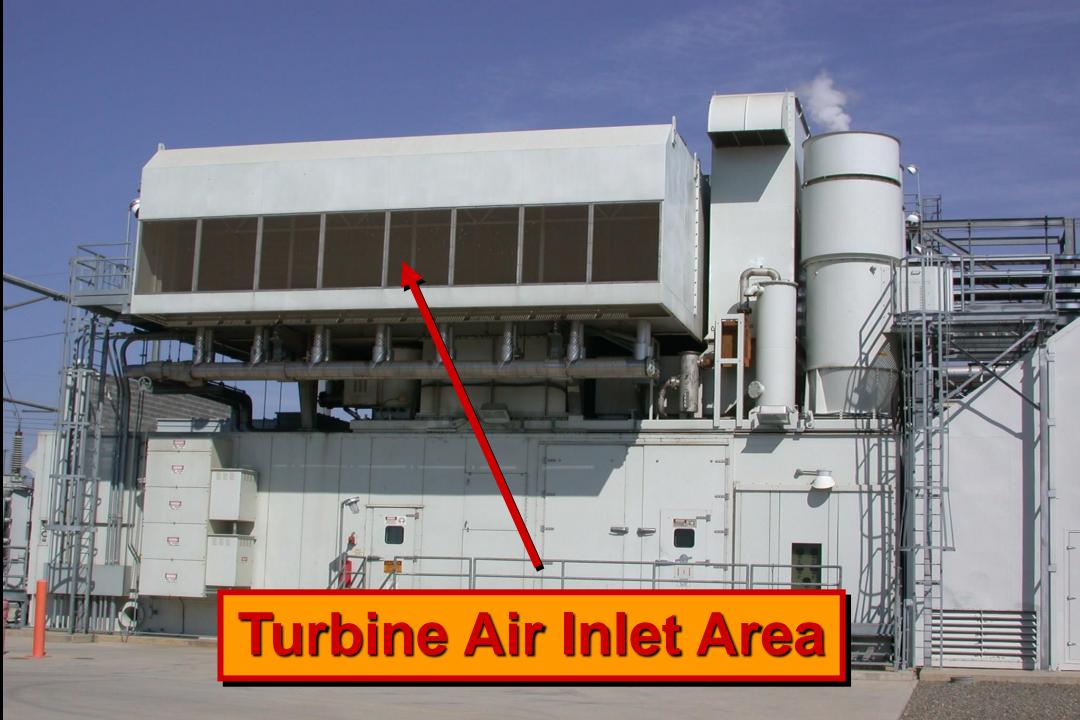
Important Terms

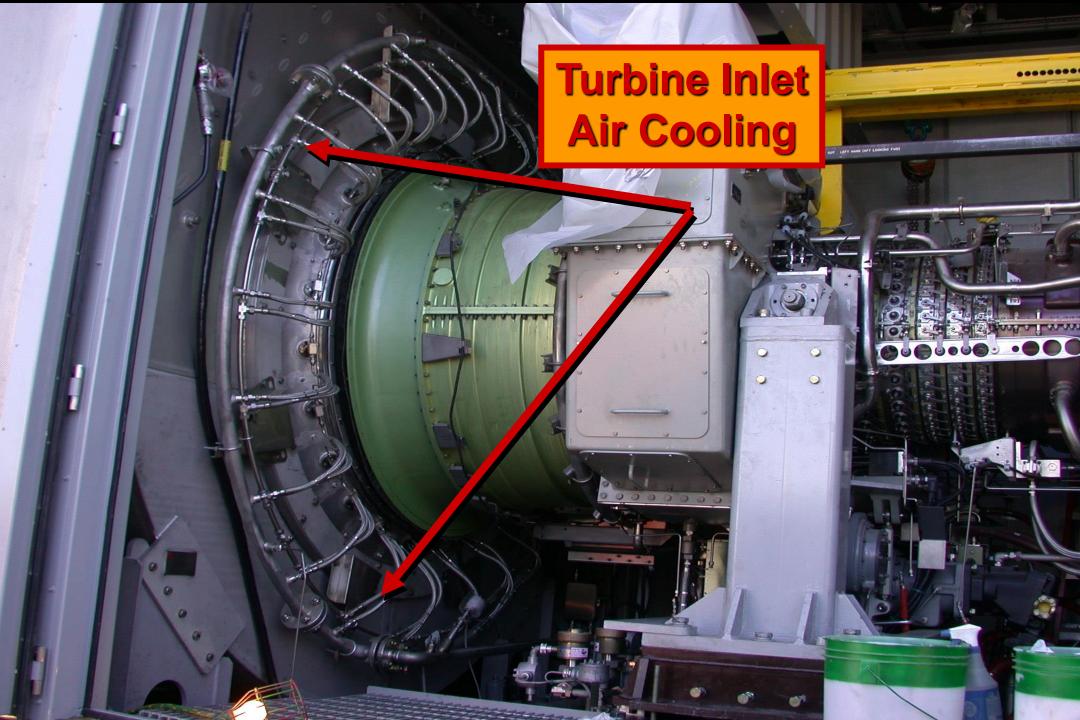
- ◆ Power
- ◆ Horsepower
- ◆ Shaft horsepower
- ◆ Megawatt
- **◆ Thrust**
- **◆ Thermal efficiency**

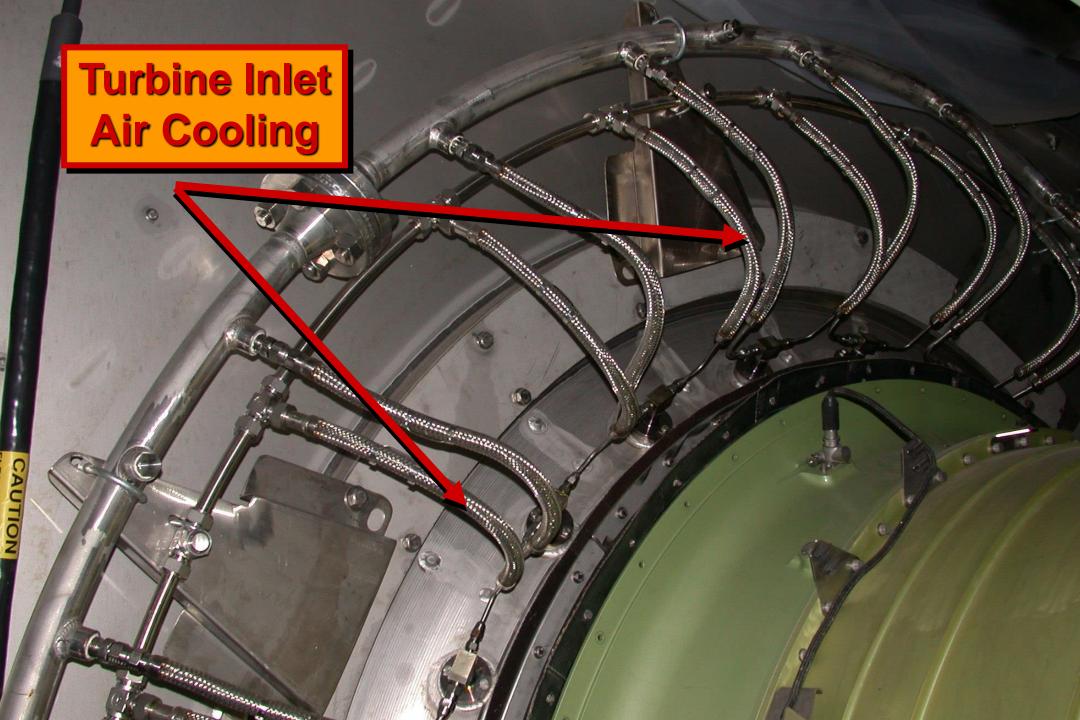


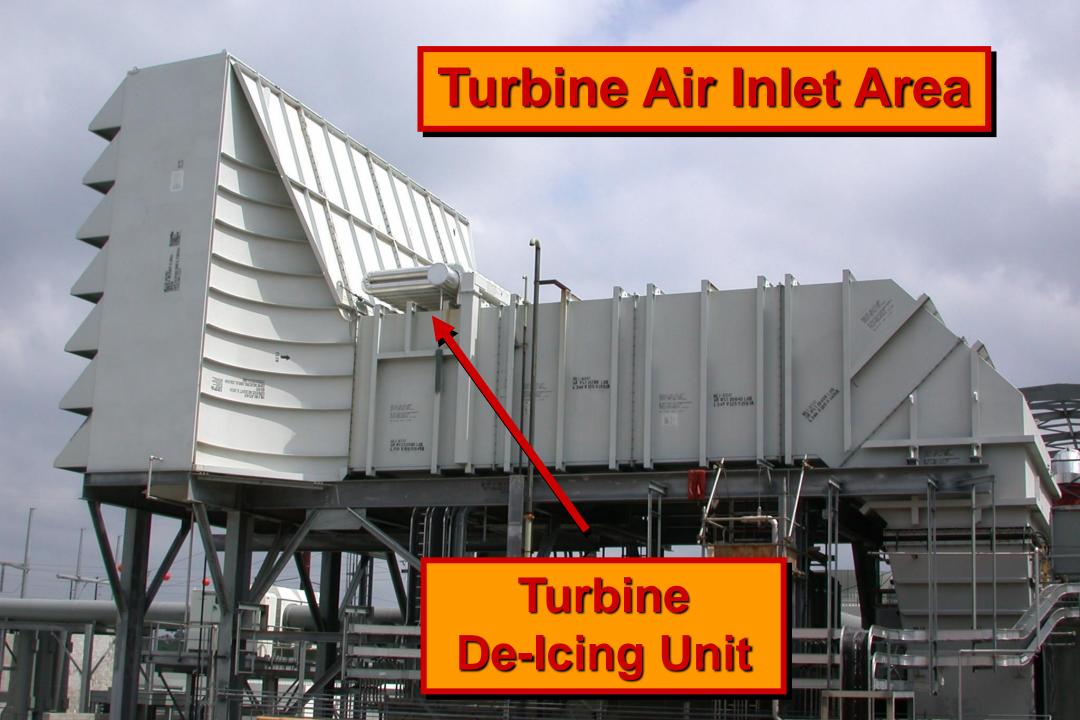








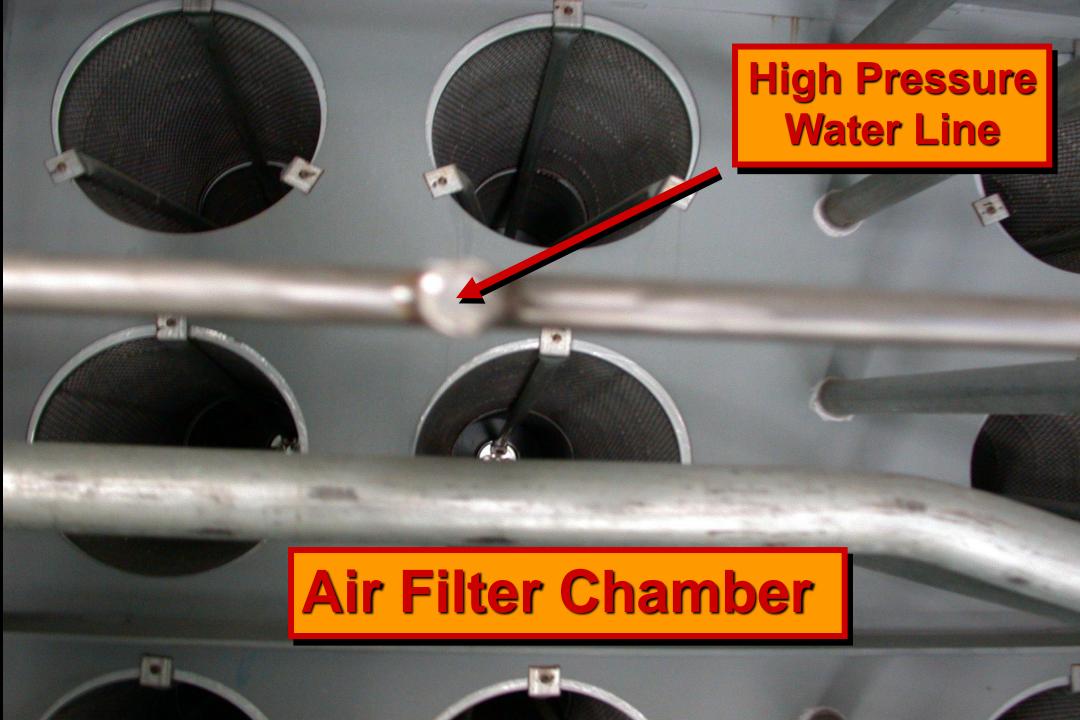








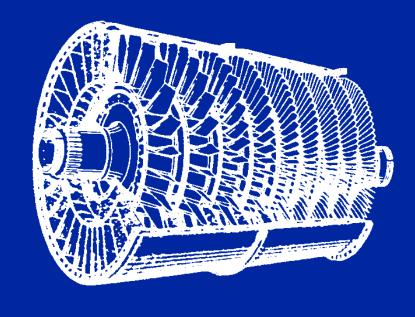


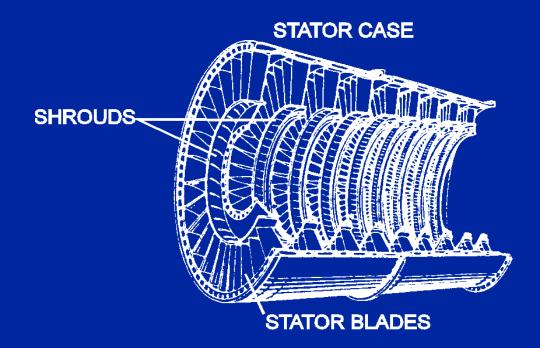




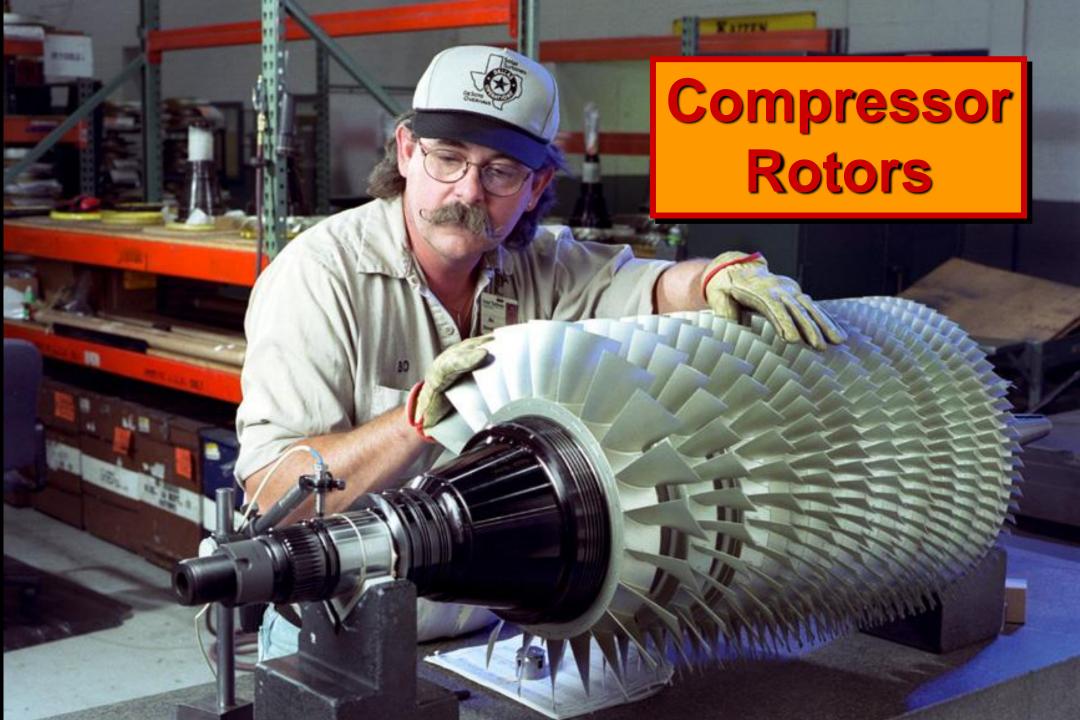
ROTOR BLADES

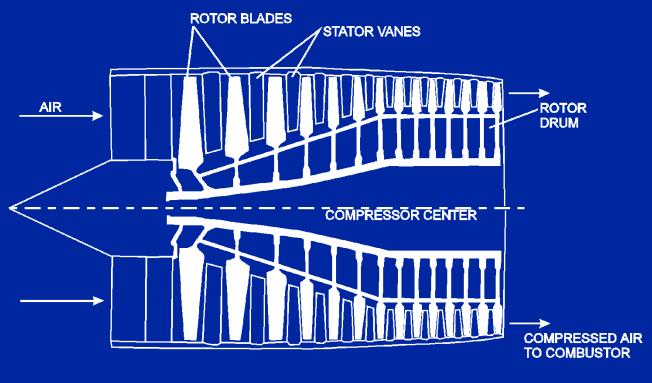
Axial Compressor

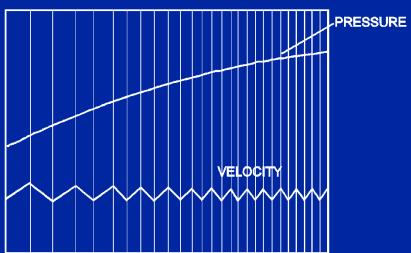




Graphic Courtesy of General Electric







Velocity Pressure in an **Axial** Compressor



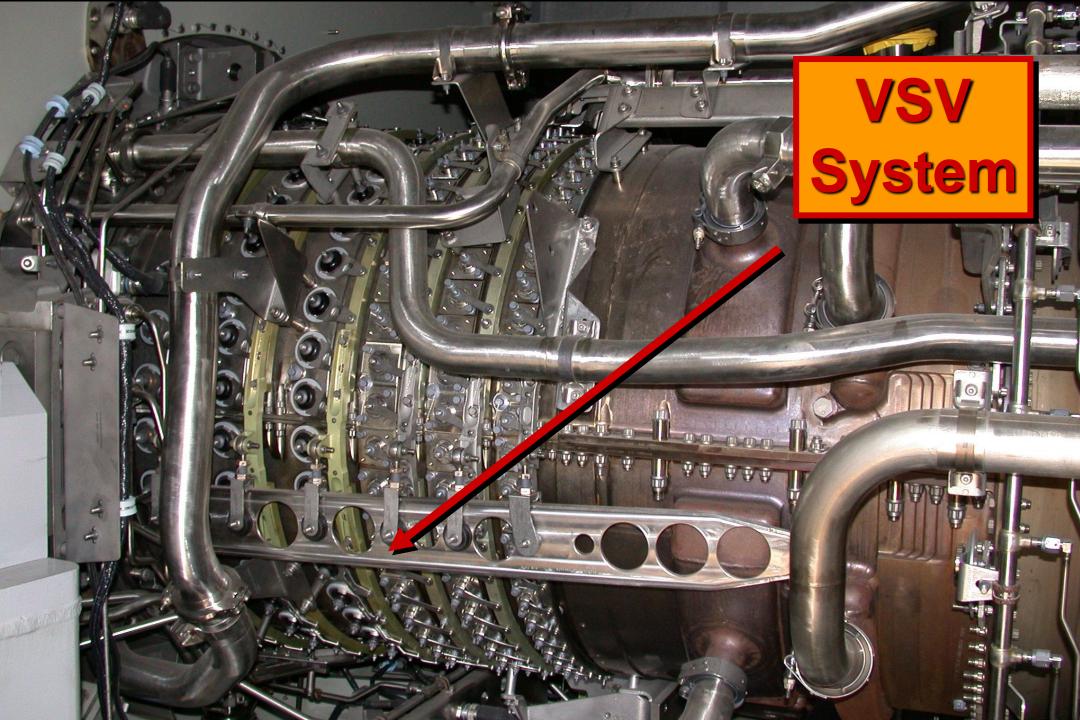
General Electric 9HA

(397 MW - 532KHP)

Compressor **Front Stators** FLANGED BUSHING IGV & VARIABLE VANE **Graphic Courtesy of General Electric**



Front Stators





Can Combustor

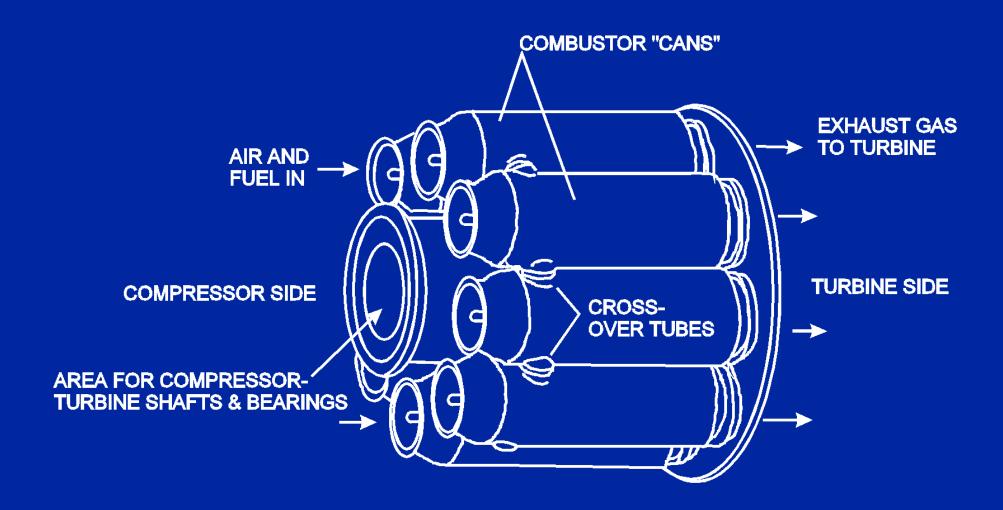
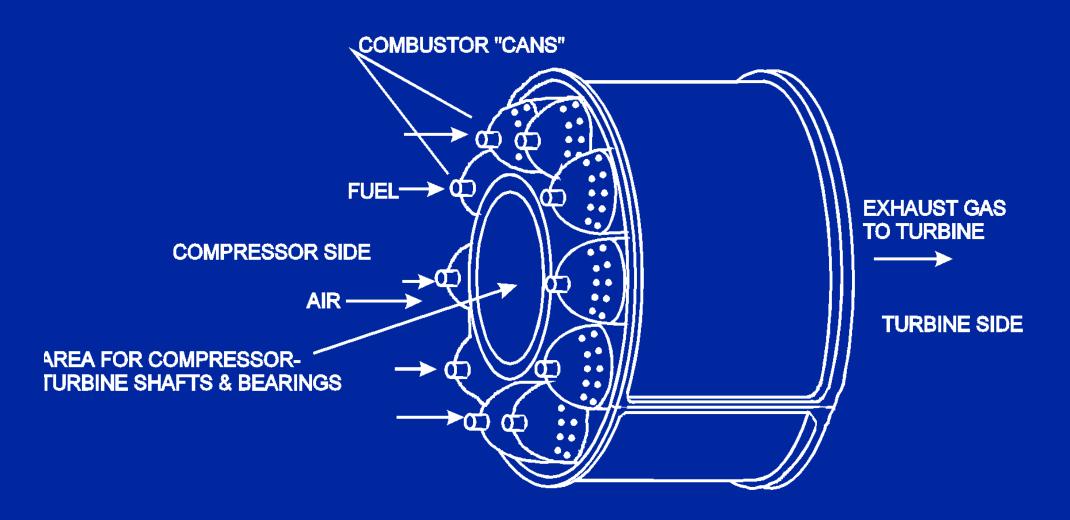


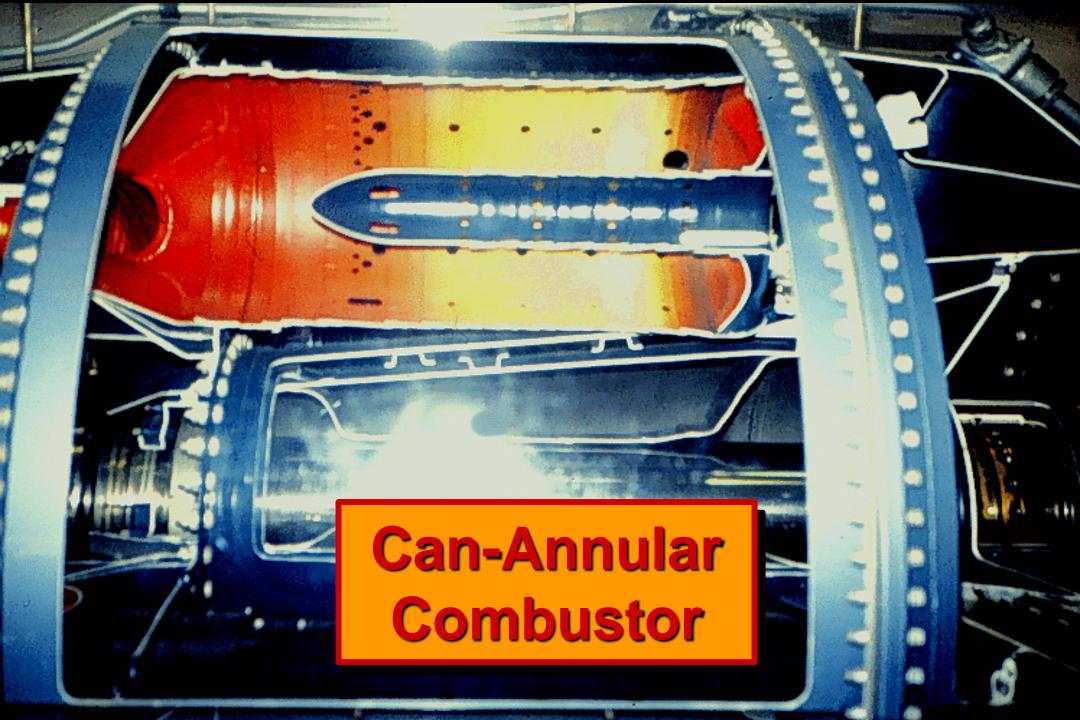
Figure 206.9





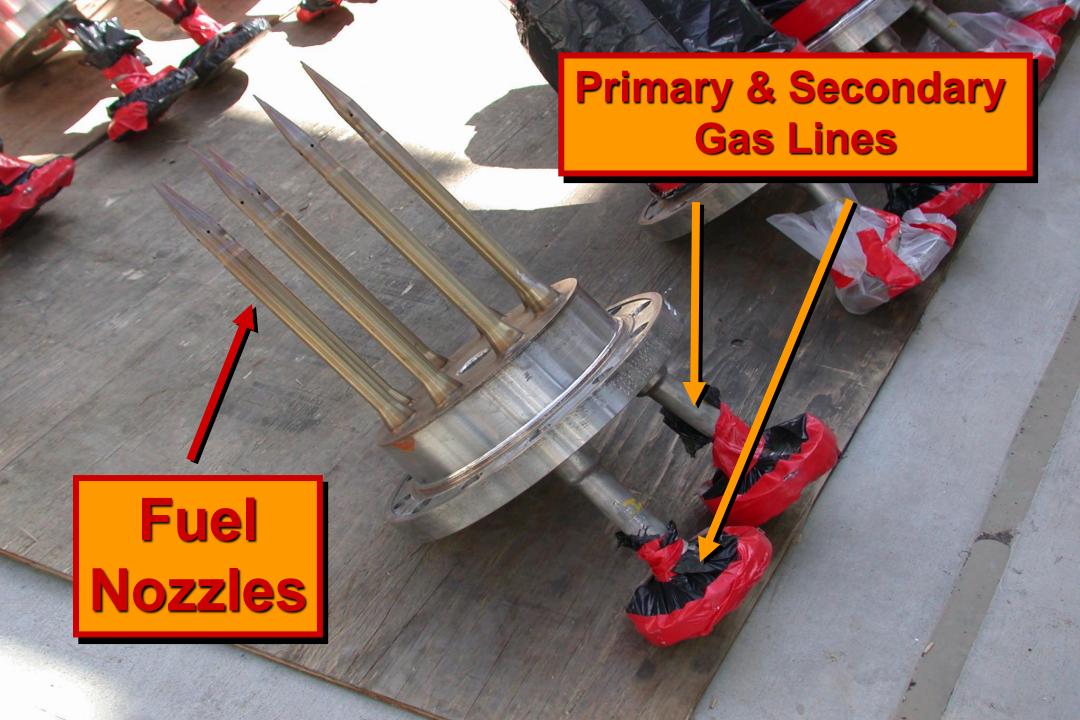
Can-Annular Combustor

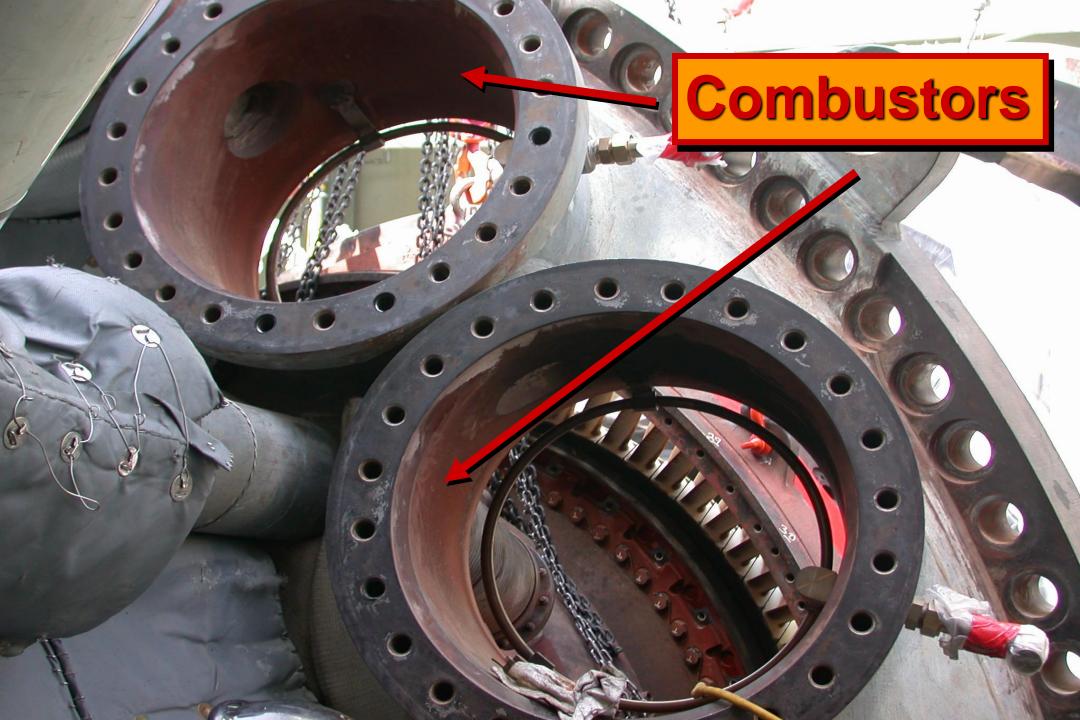


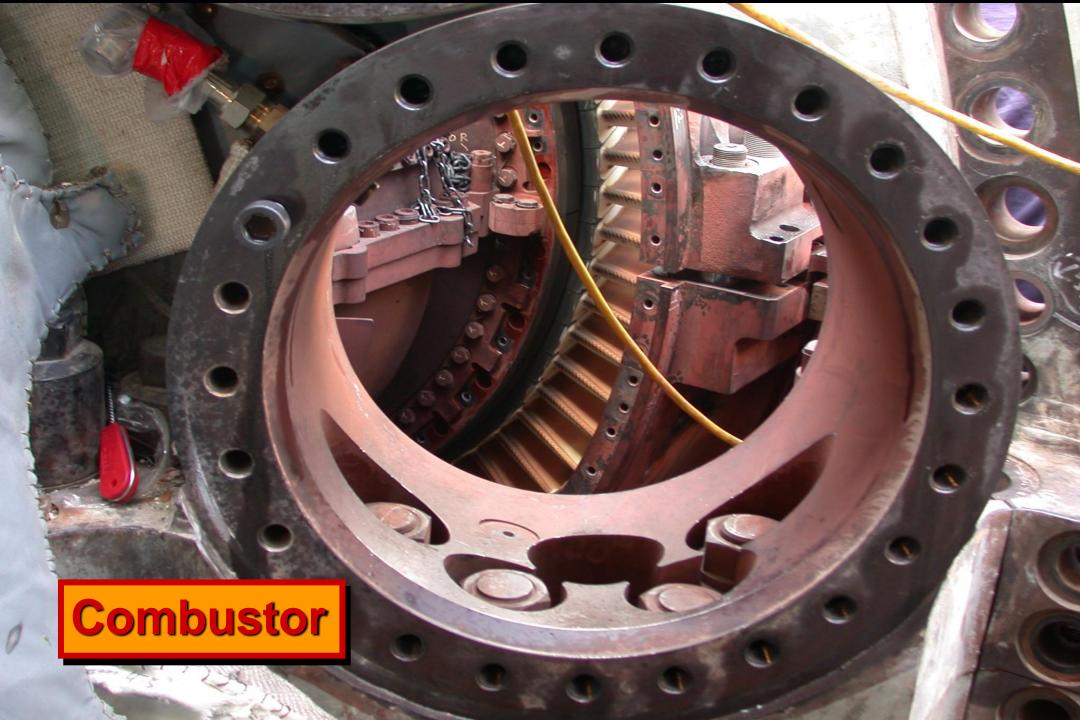


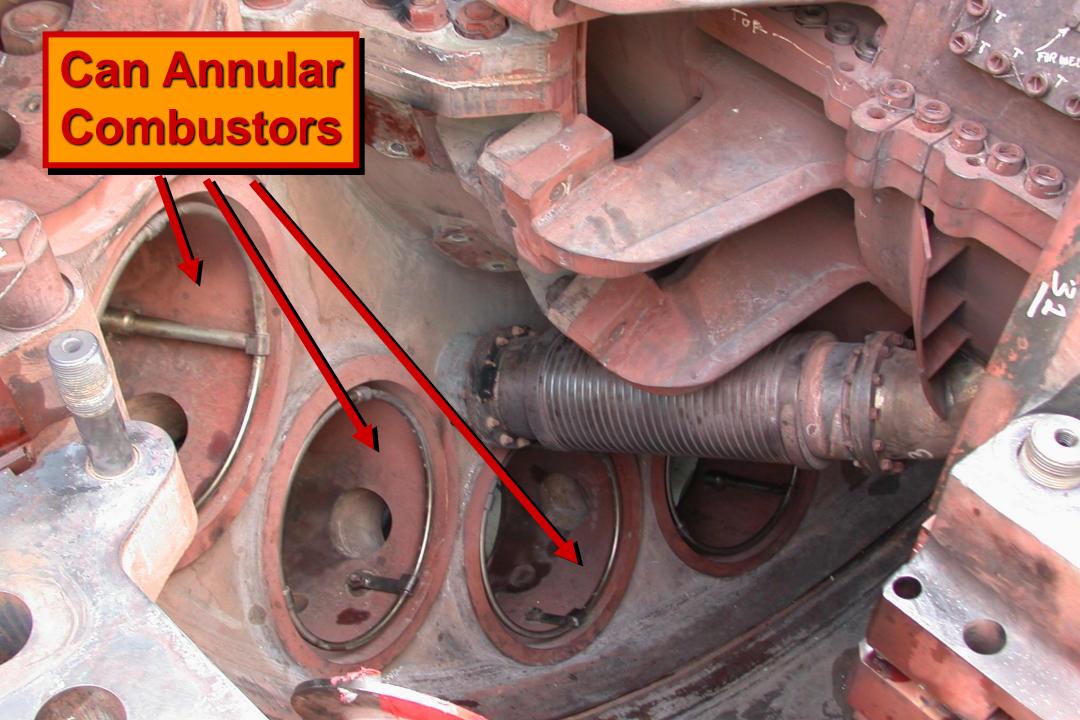


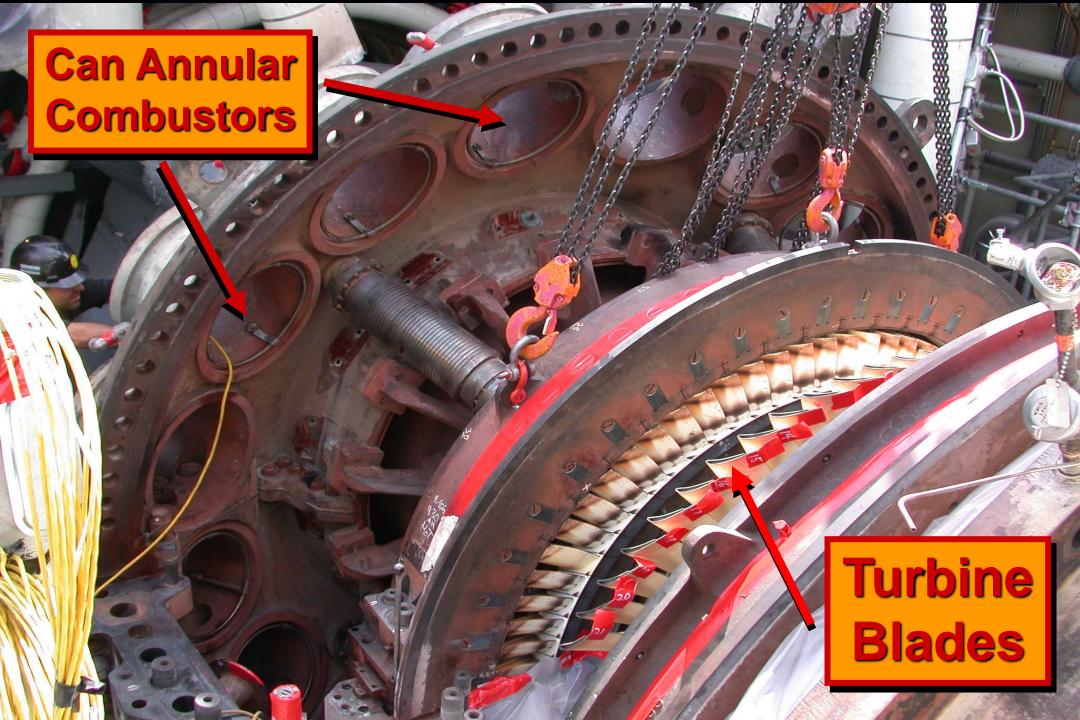


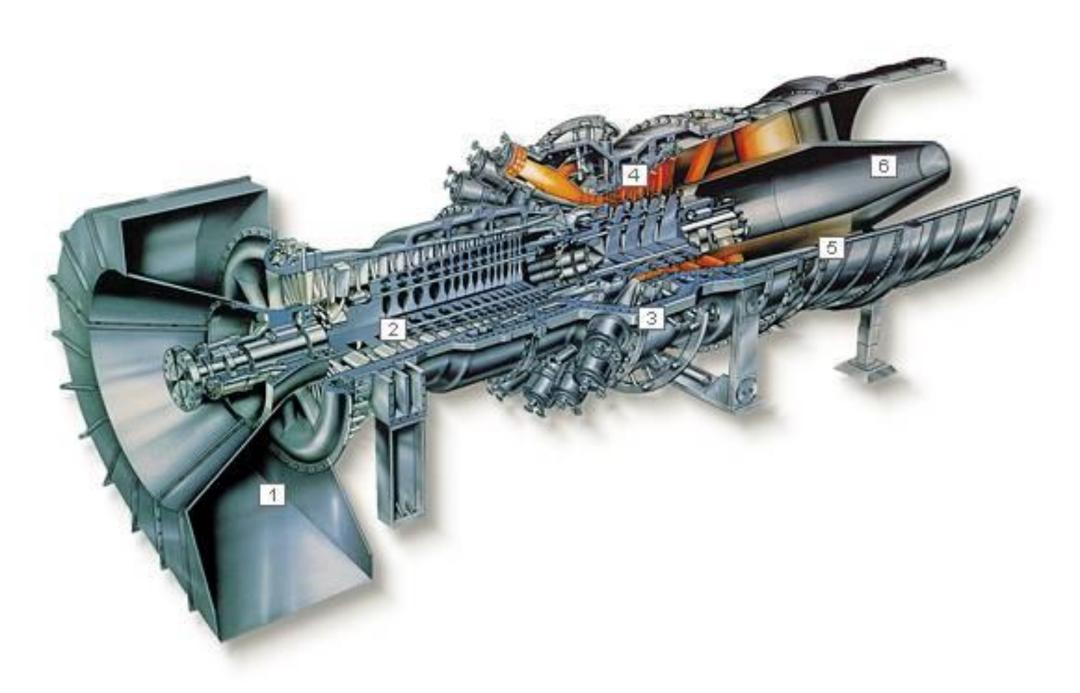


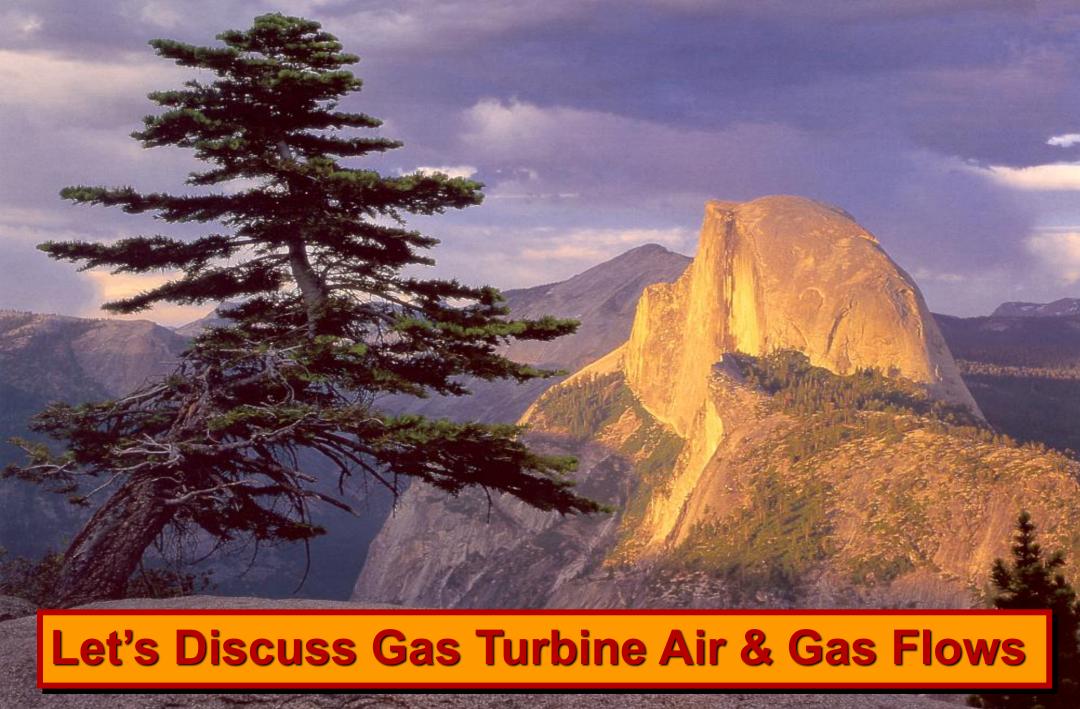




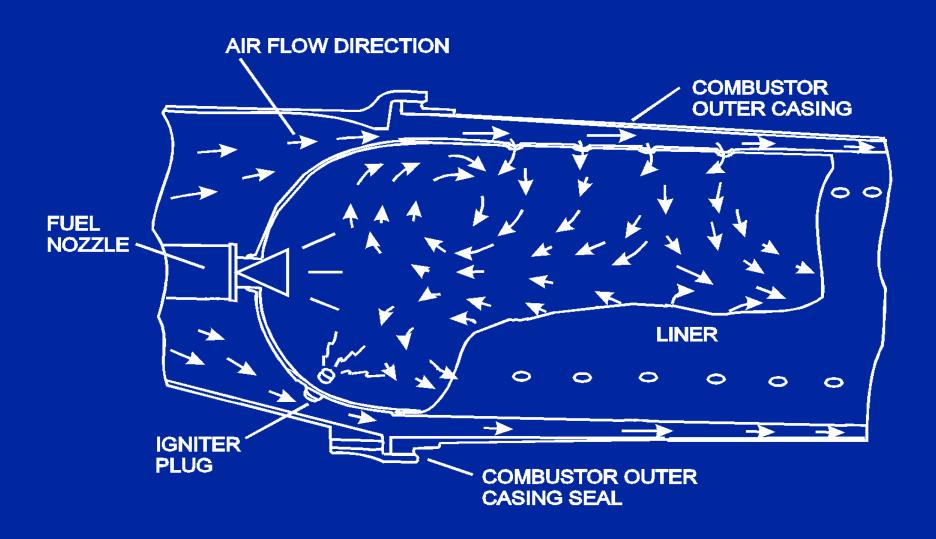


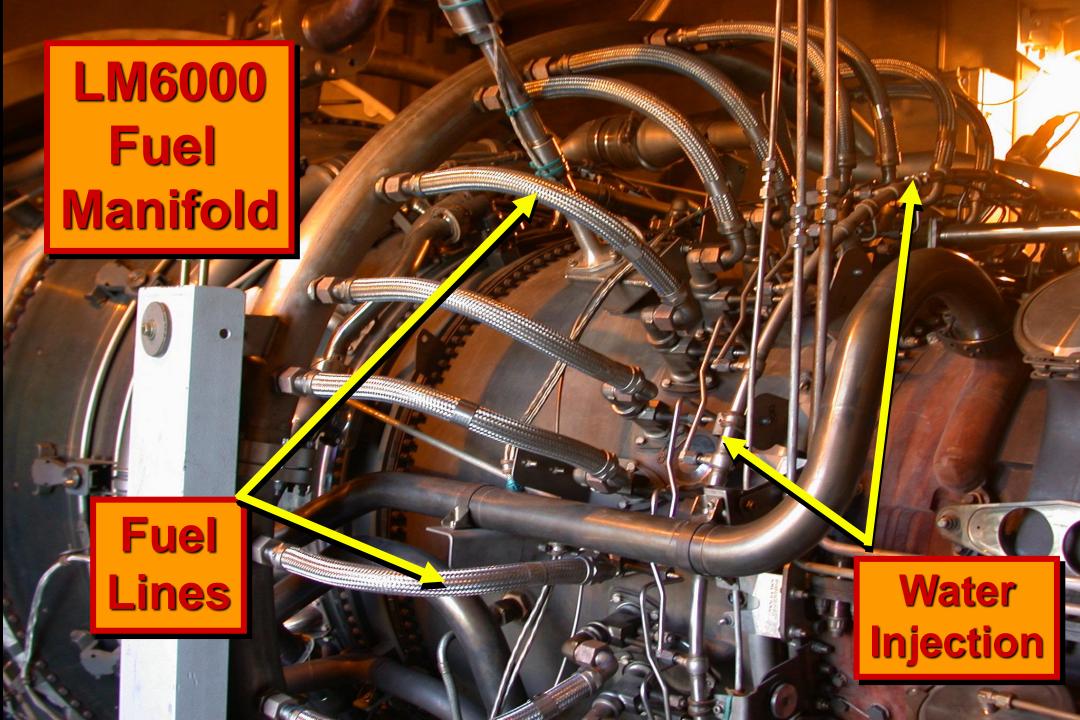






Combustor Liner and Air Flow

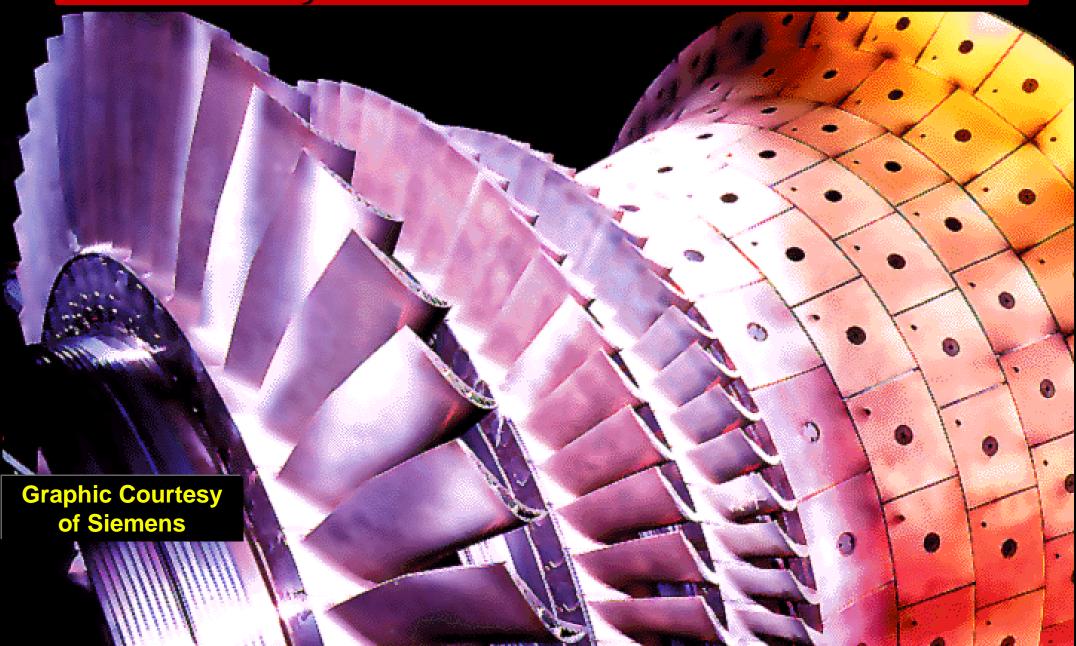


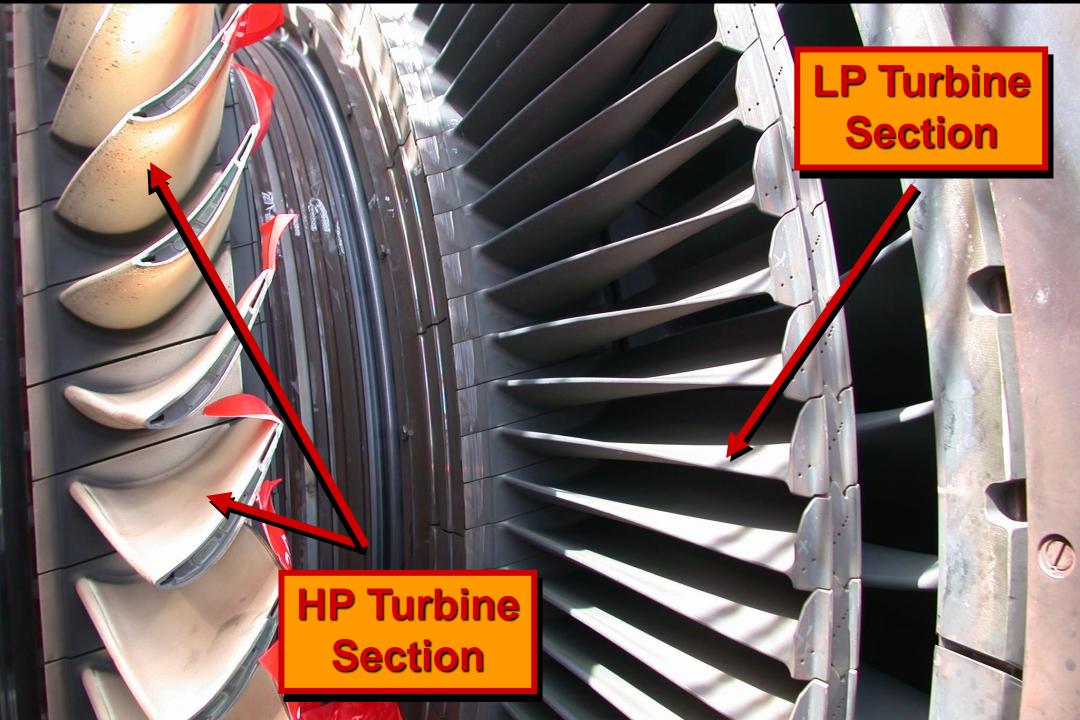






Siemens Hybrid Combustor & Turbine Blades

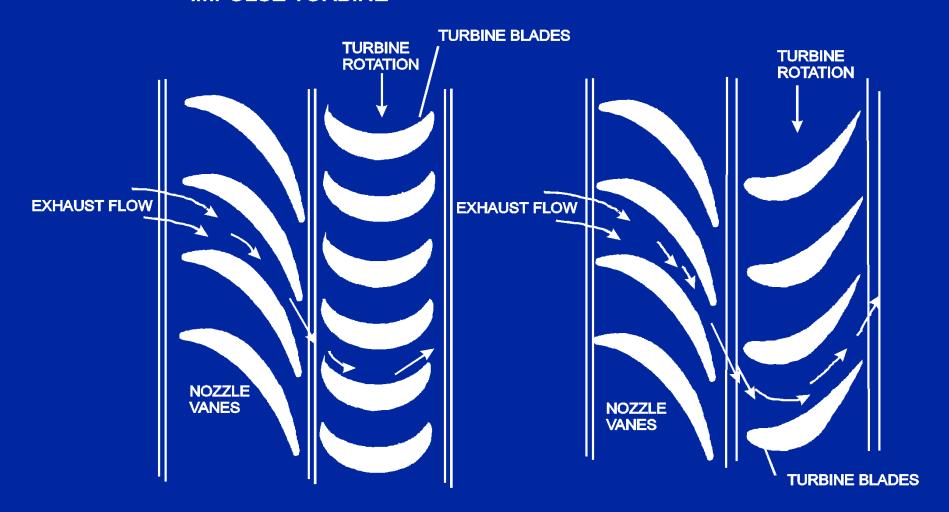


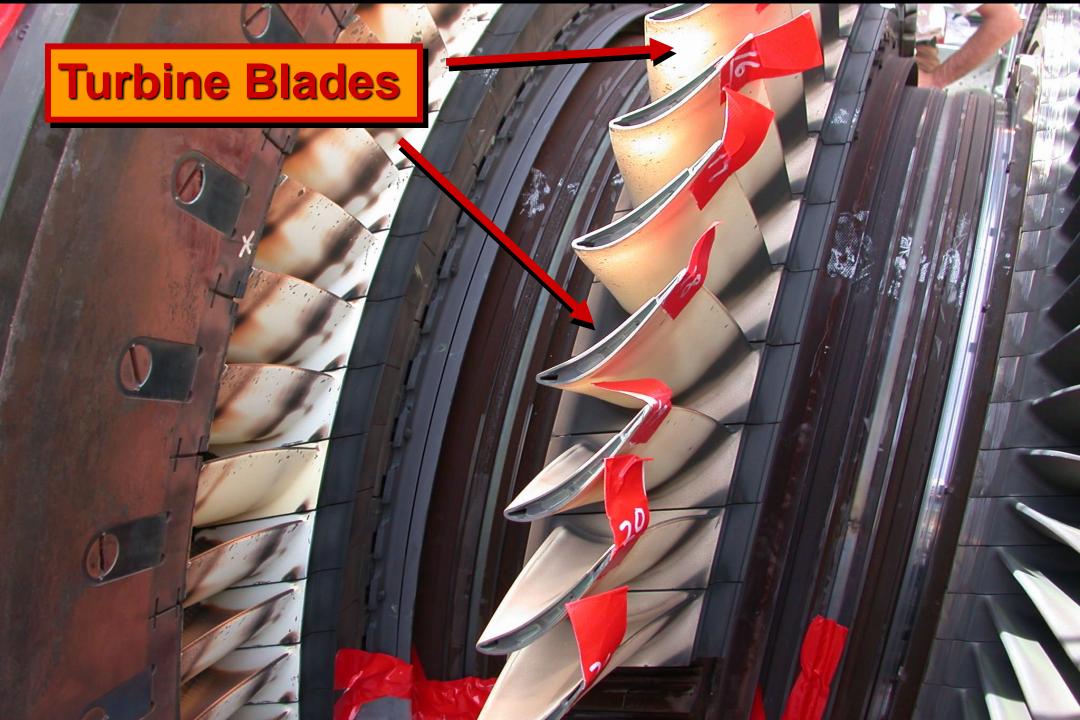


Turbine Blades

IMPULSE TURBINE

REACTION TURBINE



















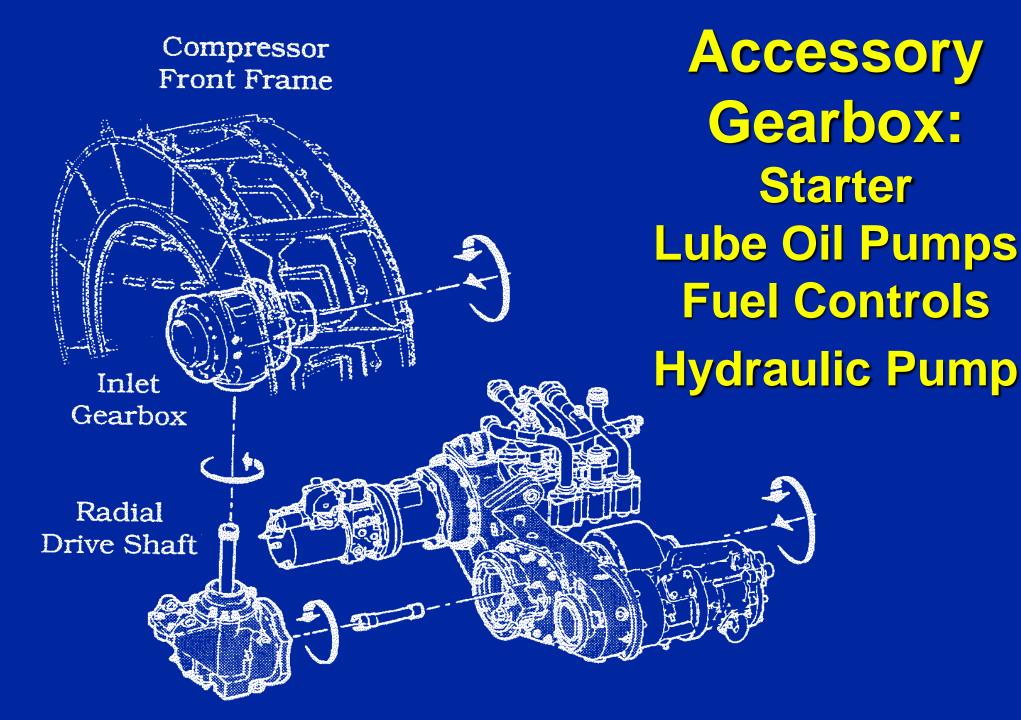








Air-Oil Separator Exhaust

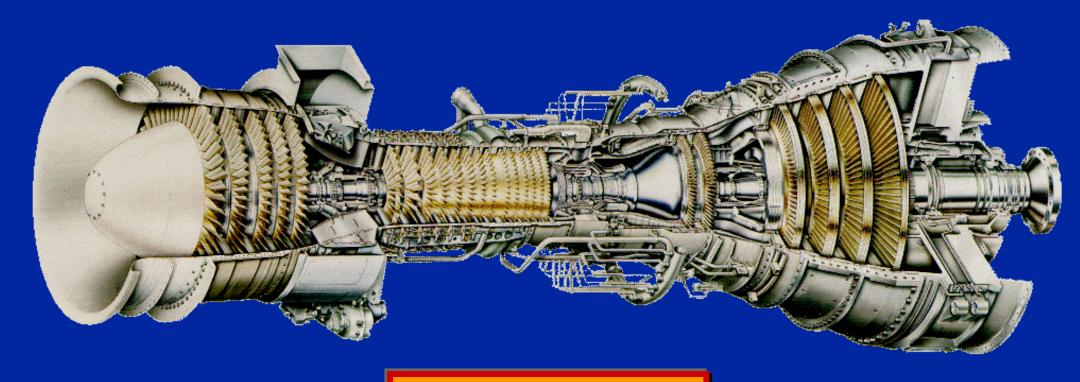






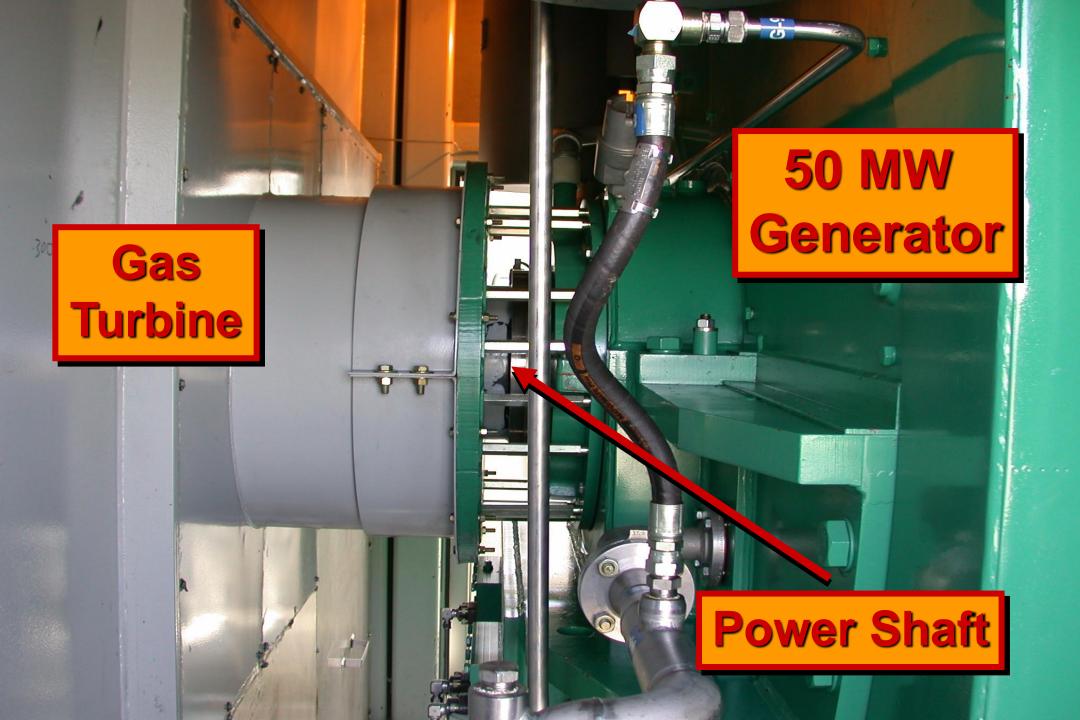


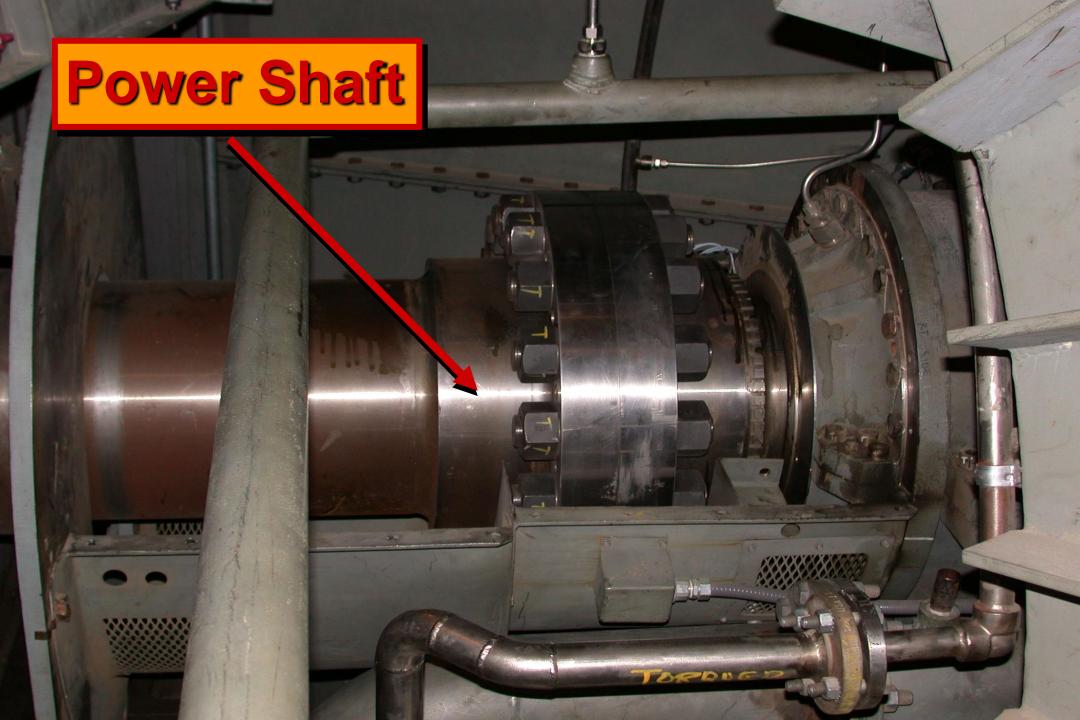
GE LM6000 Gas Turbine



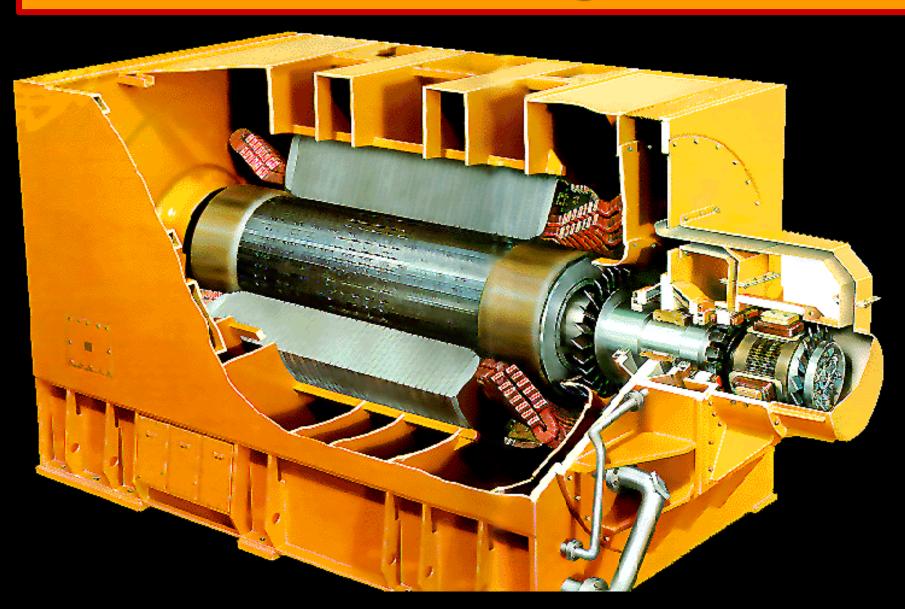
Exercise

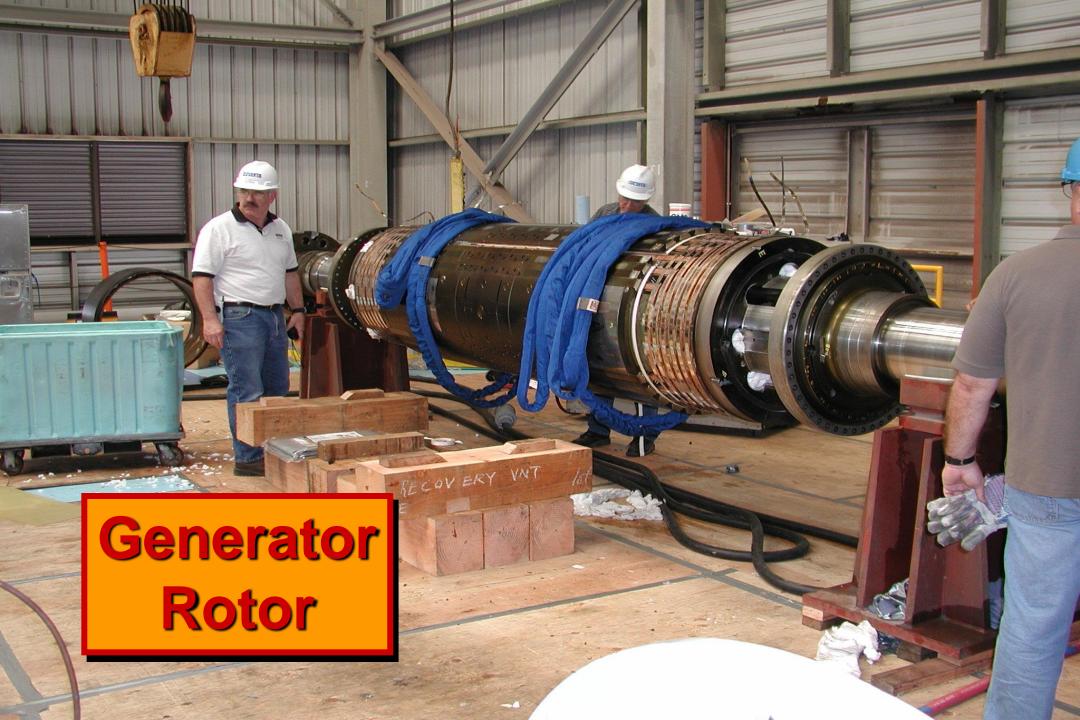


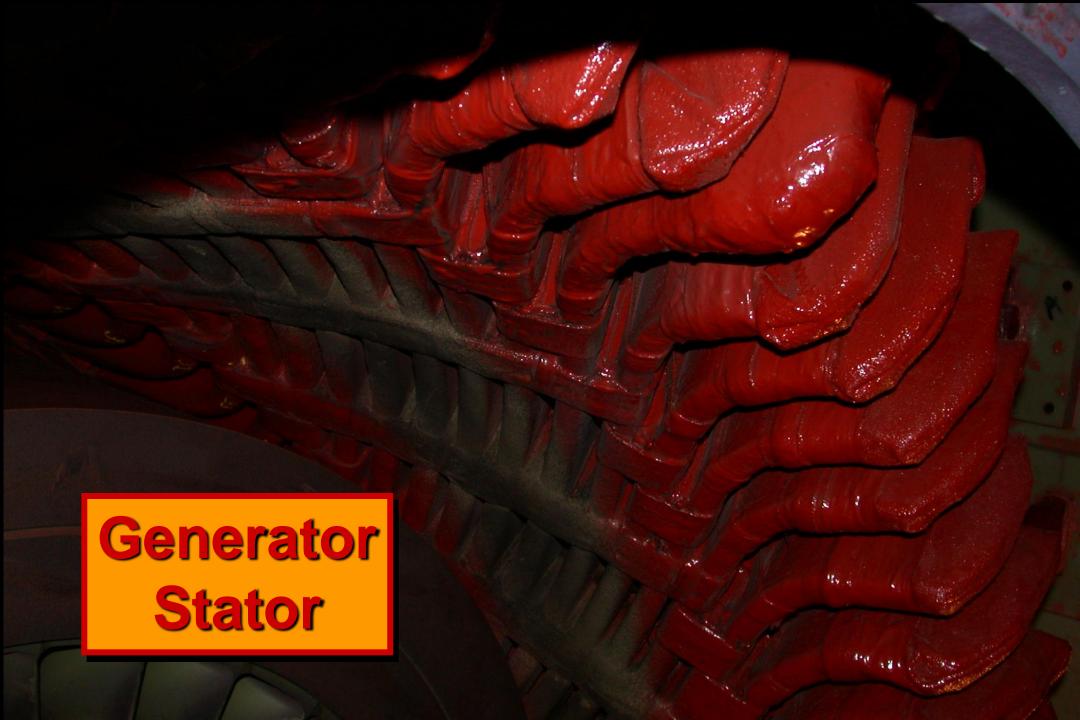




Brush DAX Turbogenerator











Combined Cycle Power Plants

XPLANATIONS" by XPLANE

Combined Cycle Power Plants

ombined cycle is the technology of choice for the majority of natural gas-fired power plants now coming online. The reasons are compelling: By using otherwise wasted exhaust heat from gas turbines to produce steam that drives an additional turbine, combined-cycle plants get the most possible energy from precious

resources. The plants can be built quickly, their installed cost is low, and their startup time is fast. In addition to being energy and cost efficient, combined cycle plants make it easier to adhere to environmental regulations. Bechtel offers a wide range of customizable PowerLine™ designs for combined-cycle plants.

3 Heat Recovery Steam Generator

Hot exhaust from the gas turbine goes to the heat recovery steam generator, where it is used to boil water and create steam. In some cases the exhaust gas is further heated to provide more power output. Pollution control systems are implemented at this stage.

Water Treatment System

Water for the steam cycle, cooling cycle, and other processes is treated to remove minerals, organic material, suspended solids and other contaminants.

4 Steam Turbine Generator

Superheated steam from the heat recovery steam generator is used to drive the steam turbine, which turns a generator to produce more electricity.

Generator Turbine

Steam

Condenser

Condenser

Expanded steam from the turbine is condensed before returning to the heat recovery steam generator. A closed circulating system preserves the quality of the water.

2 Gas Turbine Generator

The gas turbine generator comprises an air compressor, turbine, and generator on a single shaft. A compressed air and natural gas mixture is ignited in the combustor at high temperature, producing energy to turn the generator.

Compressor

Inlet

Exhaust Cylinder

Combustor

HOTAU

Inlet Air System

Air to the gas turbine is filtered to enhance performance and reliability. The air is also cooled using evaporative coolers or mechanical chillers to further increase power output.

6 Cooling Tower

Cooling towers are commonly used to remove heat from the steam cycle. Water from the condenser is cooled by evaporation as it passes over splash fill surfaces.

7 Main Step-up Transformer

Power generated by the gas turbine generator and the steam turbine generator is converted to the voltage required for transmission on the local electricity grid.

#2002 XPLANE.co

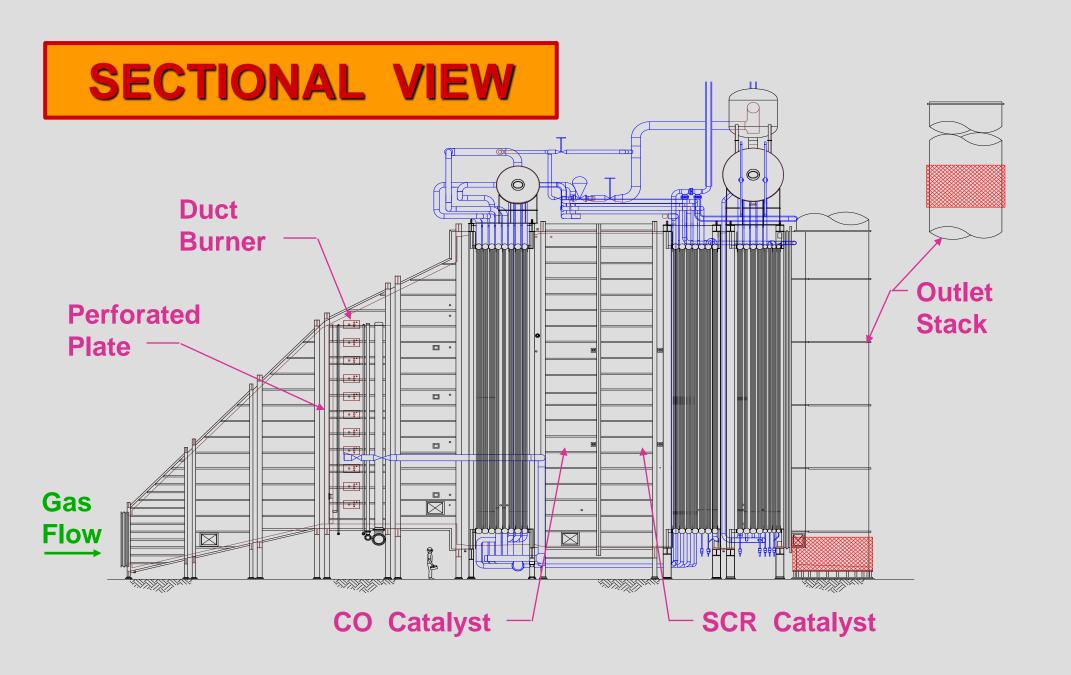
As Seen in Bechtel Briefs O2 XPLANATIONS™ by XPLANE®



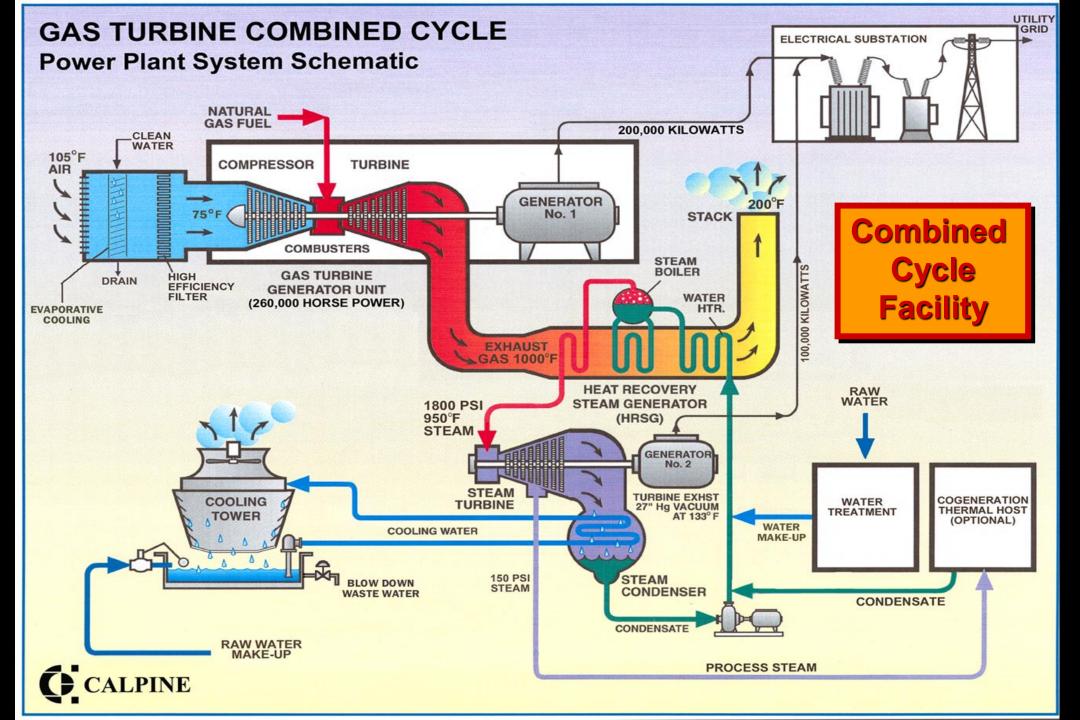
Heat Recovery Steam Generator Unit



Combined Cycle with HRSG

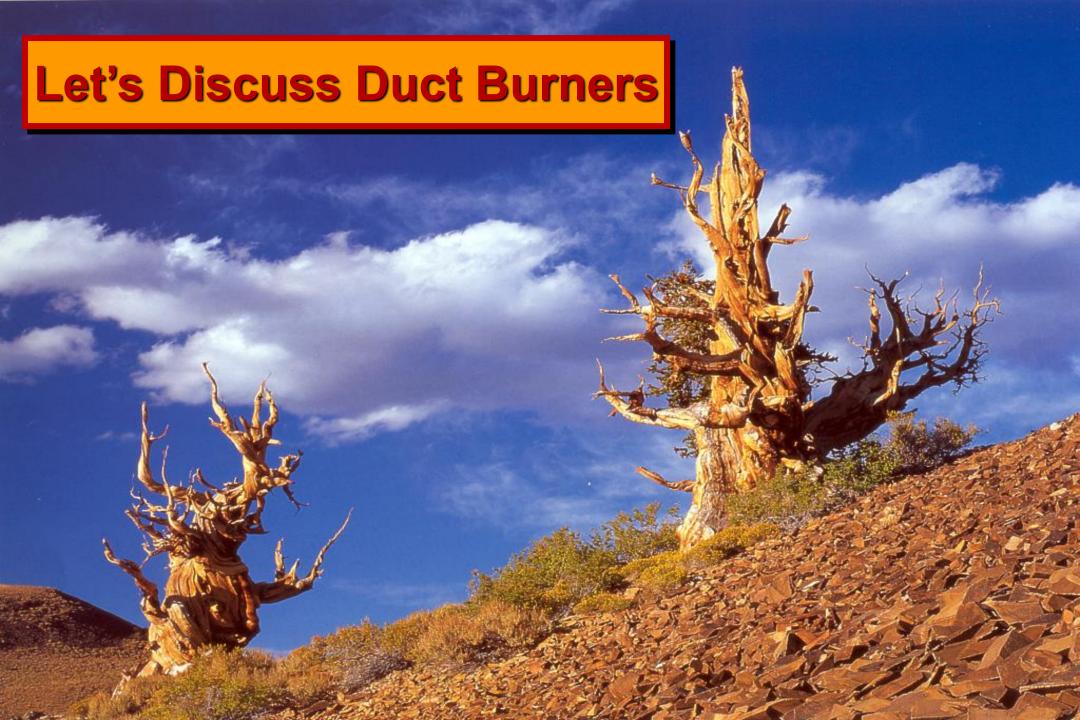


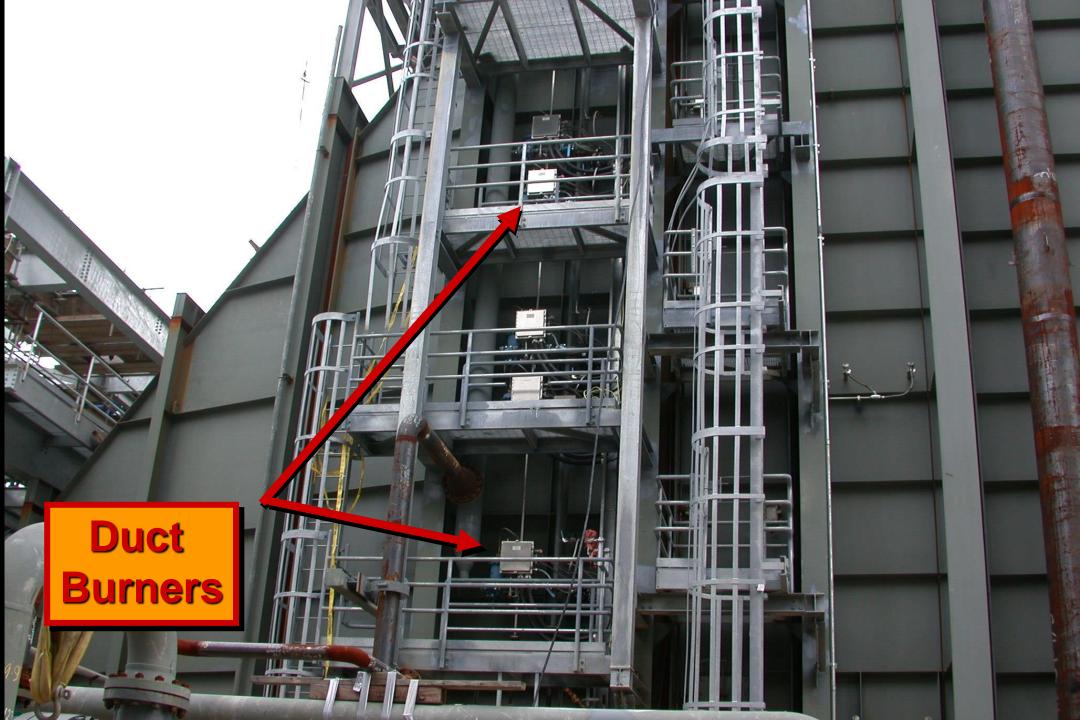




GAS TURBINE COMBINED CYCLE COGENERATION PROJECT **Cogeneration System Schematic** CO REMOVAL CATALYST NOXVOC REMOVAL CATALYST -200°F **ELECTRICAL SUBSTATION** (OPTIONAL) 300,000 KILOWATTS LOW PRESSURE INTERMEDIATE STEAM DRUM HIGH PRESSURE PRESSURE STEAM DRUM STEAM DRUM STACK AMMONIA INJECTION NATURAL GAS FUEL SUPPLY **EVAPORATIVE** SILENCER OPTIONAL Ambient Air 105°F 1200°F COMBUSTION 200,000 Kilowatts 1000°F STEP-UP GENERATOR TRANSFORMER BREAKER TURBINE GENERATOR DUCT BURNER (OPTIONAL) HEAT RECOVERY STEAM GENERATOR HIGH PRESSURE STEAM (HRSG) 100,000 KILOWATTS CONDENSATE 1,800 PSIG/950°F RETURN BOILER FEED PUMP STEAM TURBINE COGENERATION THERMAL 150 PSIG HOST STEP-UP GENERATOR BREAKER EXCITER GENERATOR **PROCESS STEAM** ADMISSION STEAM TRANSFORMER CONDENSER WATER TREATMENT DEMIN WATER STORAGE TANK ANION MAKEUP WATER THERMAL HOST SITE PROJECT WATER FORWARDING **DEMINERALIZER SYSTEM** RAW WATER MAKEUP WASTEWATER BLOWDOWN (WASTEWATER) CONDENSATE CALPINE





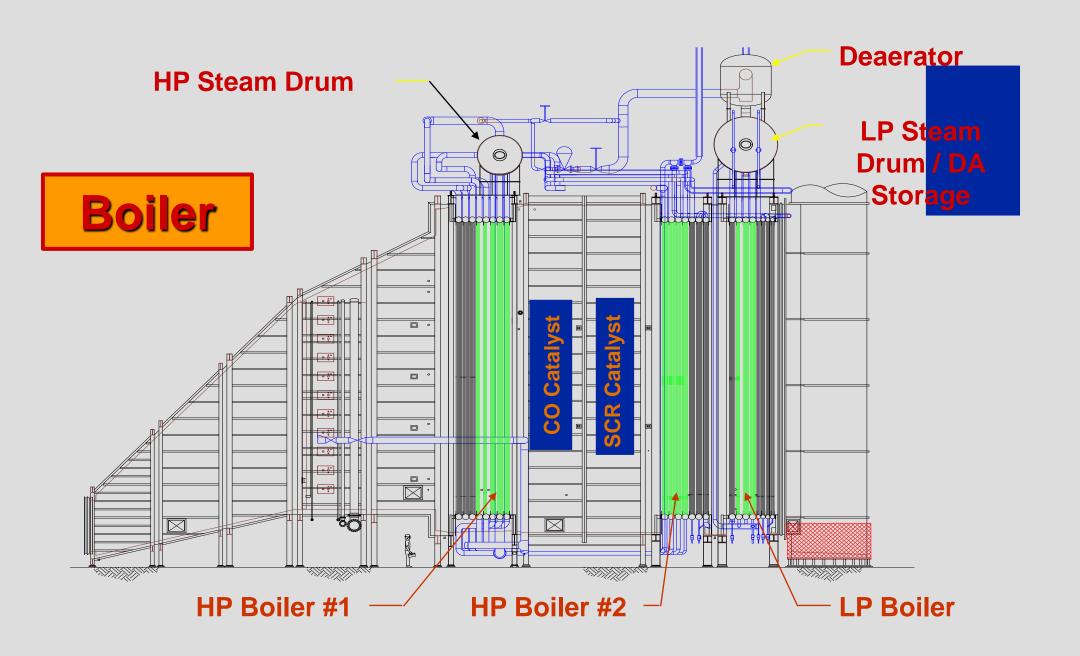




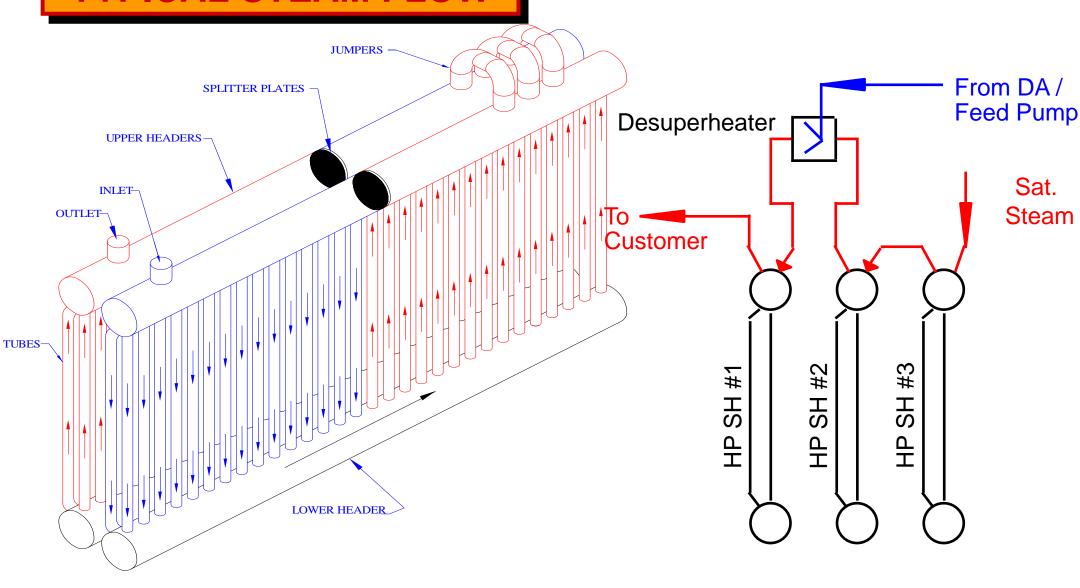
HRSG Overview

- Superheater
 - take saturated steam from the drum and increase the temperature of the steam

- Evaporator
- **◆Economizer**



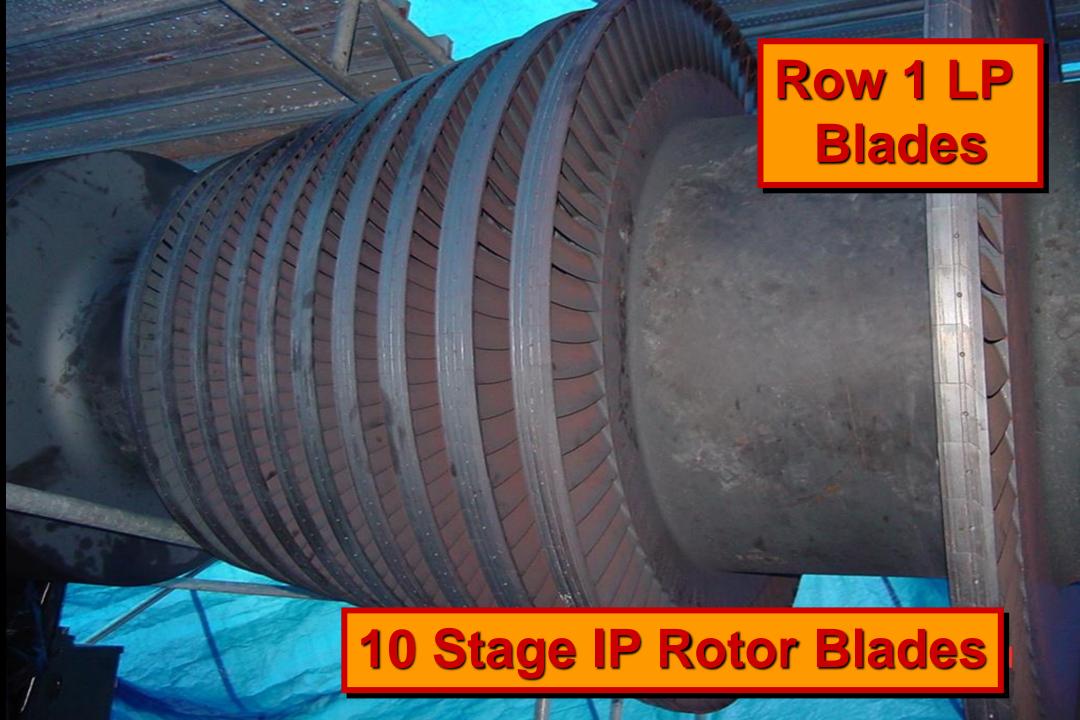
TYPICAL STEAM FLOW



















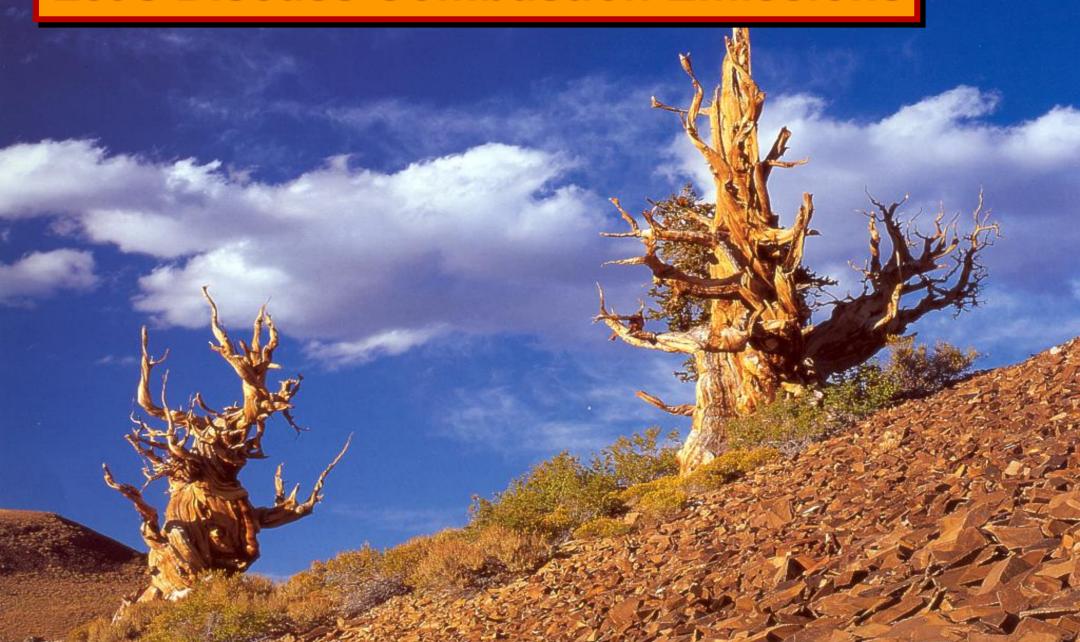








Let's Discuss Combustion Emissions





Emissions From Gas Turbines

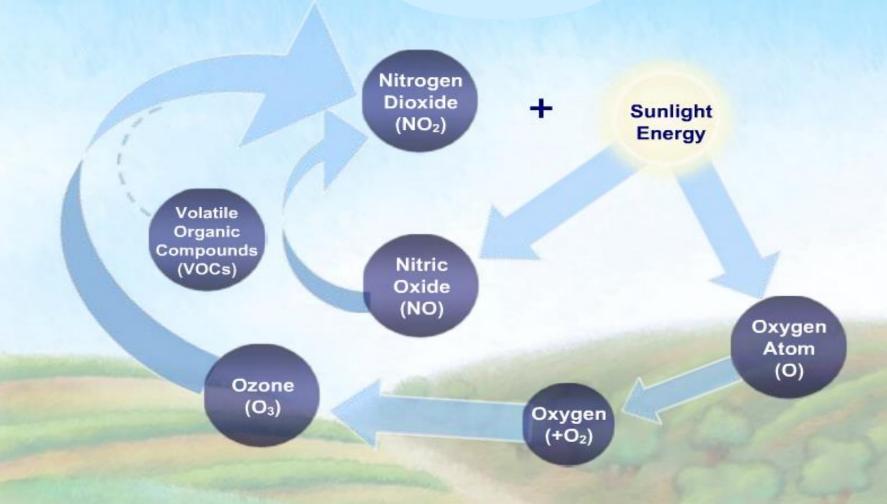
Fuel
+
Air
(N₂, O₂)



- ♦ H₂O
- **♦ CO**₂
- ◆ CO
- VOC
- ♦ NO_X
- ◆ SO_X
- ◆ PM



Ozone Photochemistry

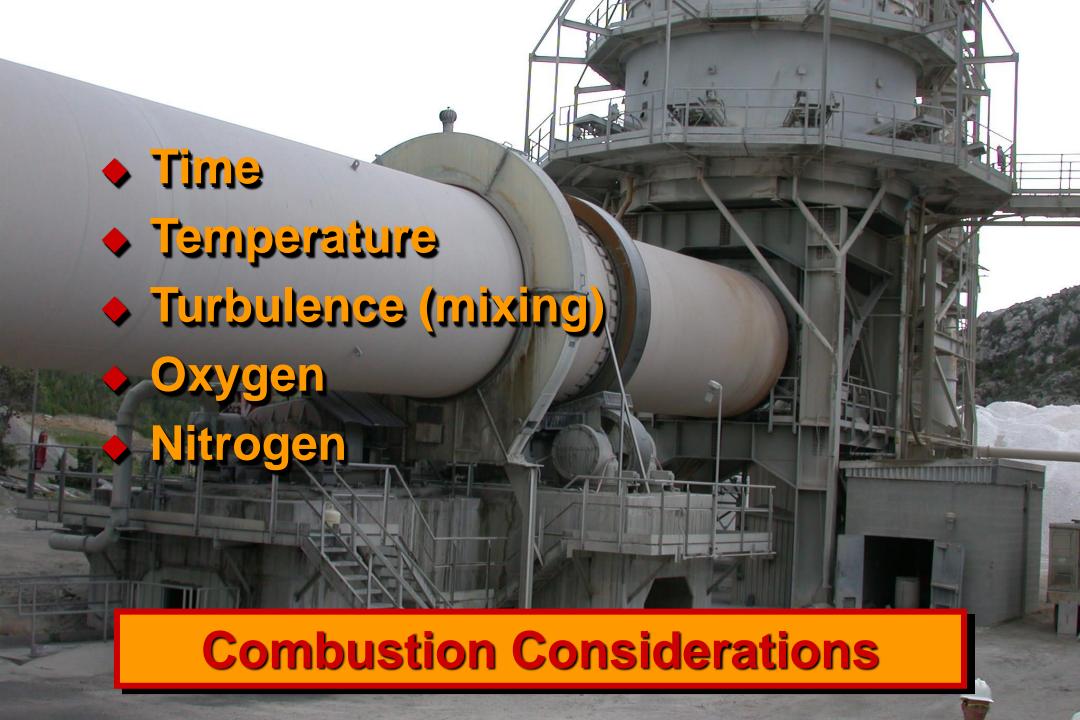


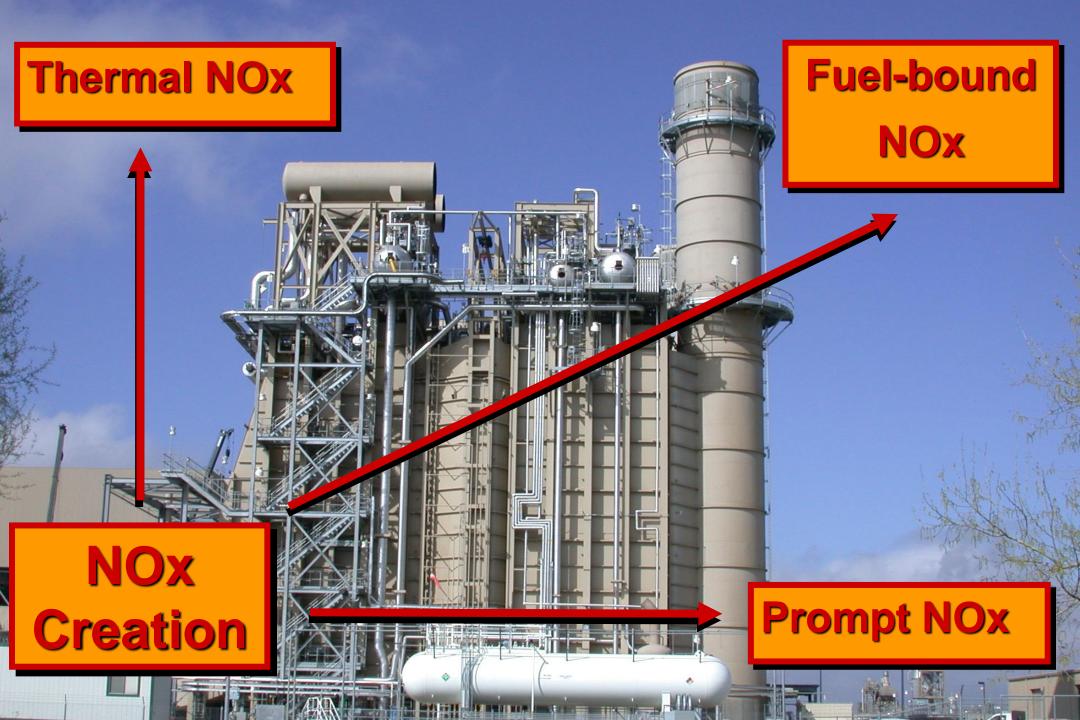


Emissions Control Methods

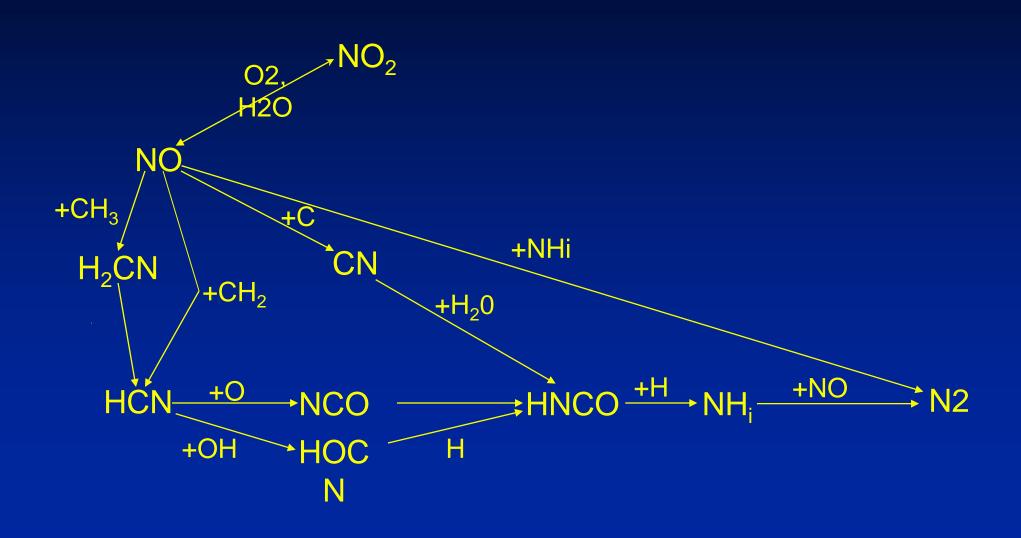
- ◆ Engine design
- Proper maintenance
- ◆ Operations
- Fuel types
- Combustion modifications
- **◆ Exhaust treatment**



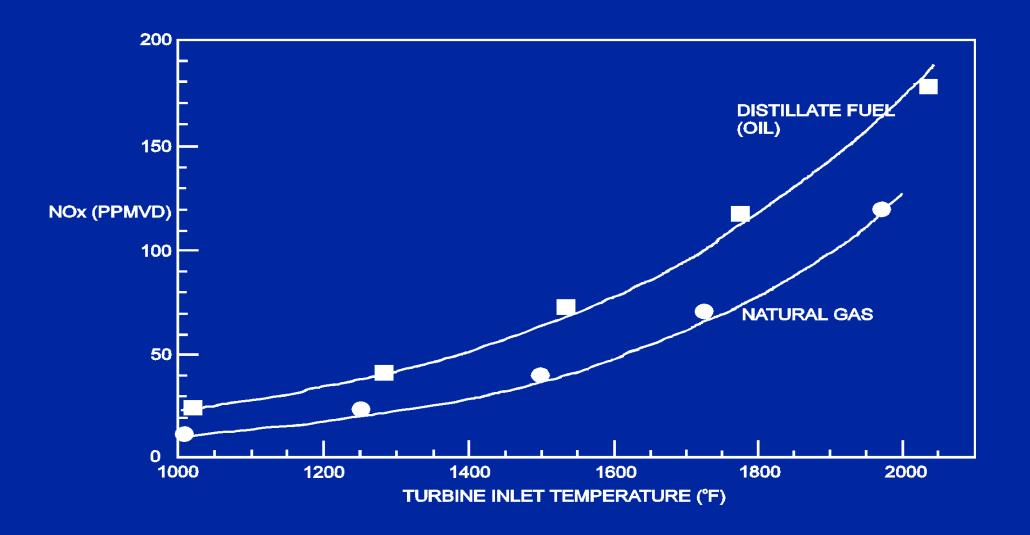




PROMPT NOX



NOx vs. Turbine Inlet Temperature



Thermal NOx vs. Equivalence Ratio

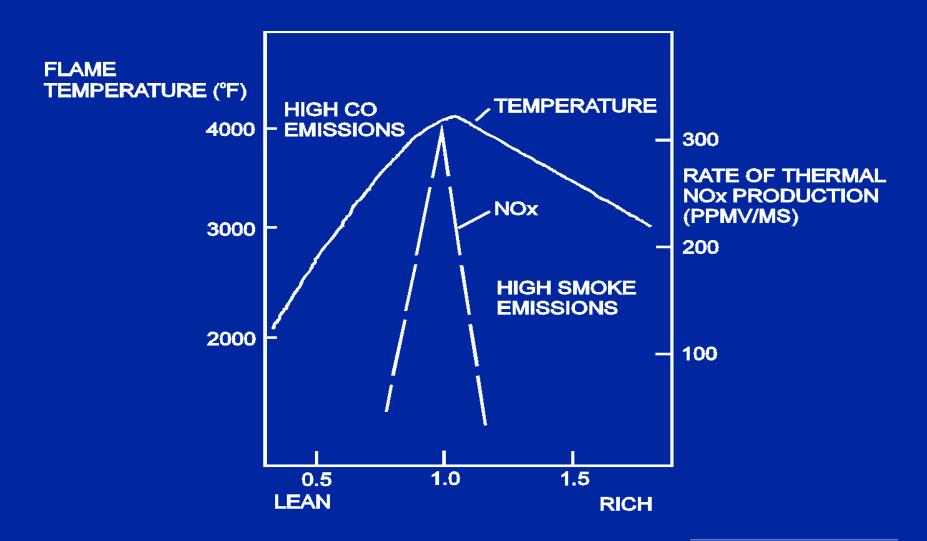
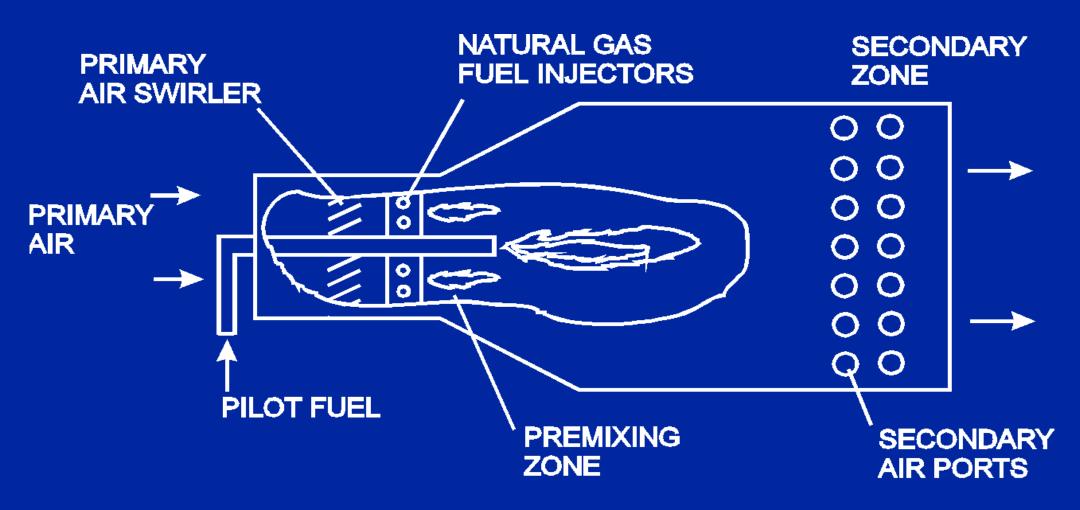
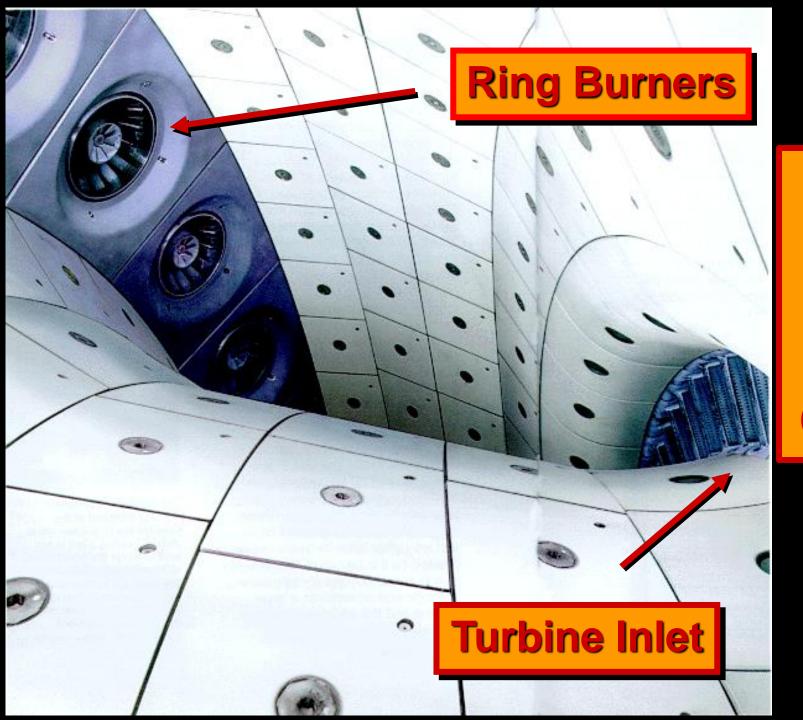


Figure 301.2

Lean Premix Combustor



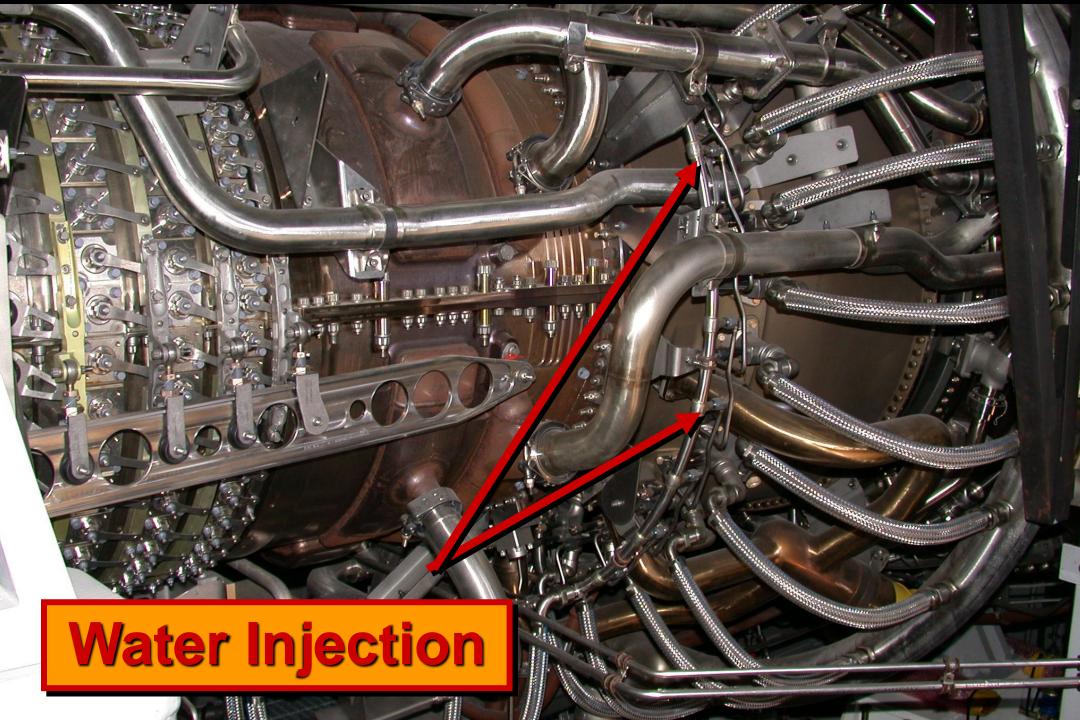




Siemens
Hybrid
Burner
Ring
Combustor

Graphic Courtesy of Siemens

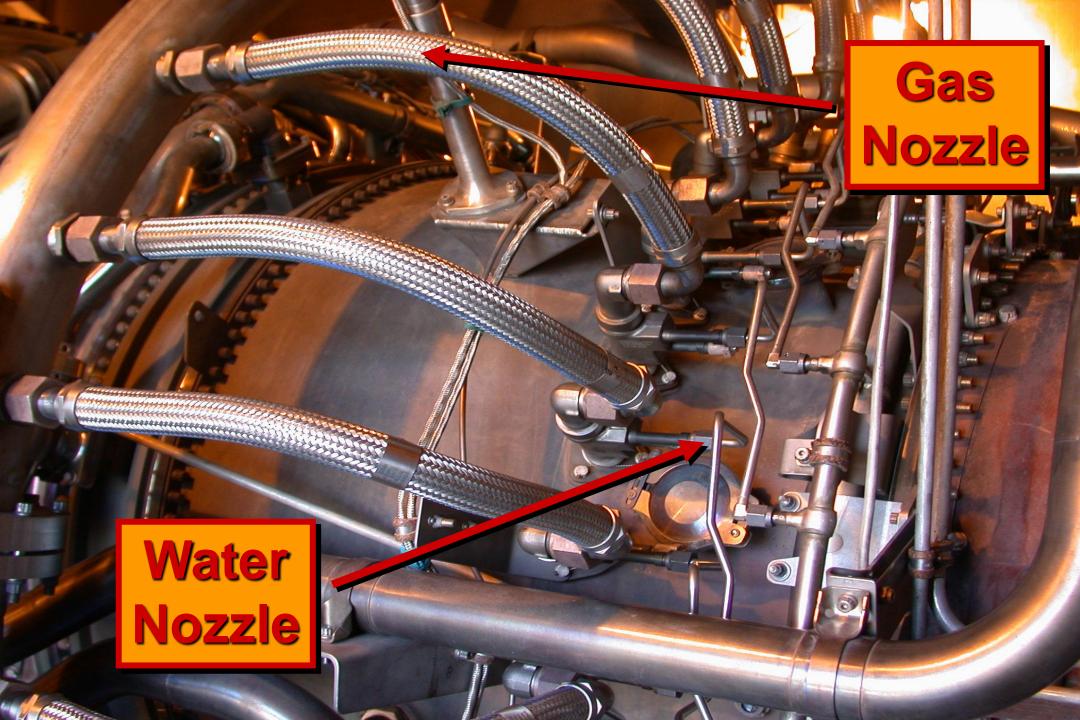




Water & Steam Injection NOx Control

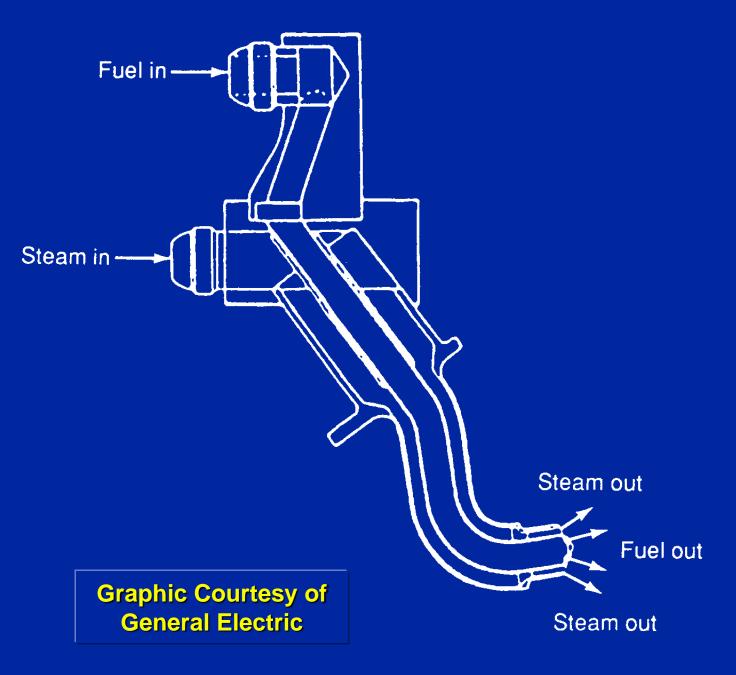
- Advantages
 - Reduces NOx
 - Increases power output
- Disadvantages
 - Water treatment expense
 - Increased fuel use
 - Increases HC
 - Increases CO
 - Increased wear & maintenance



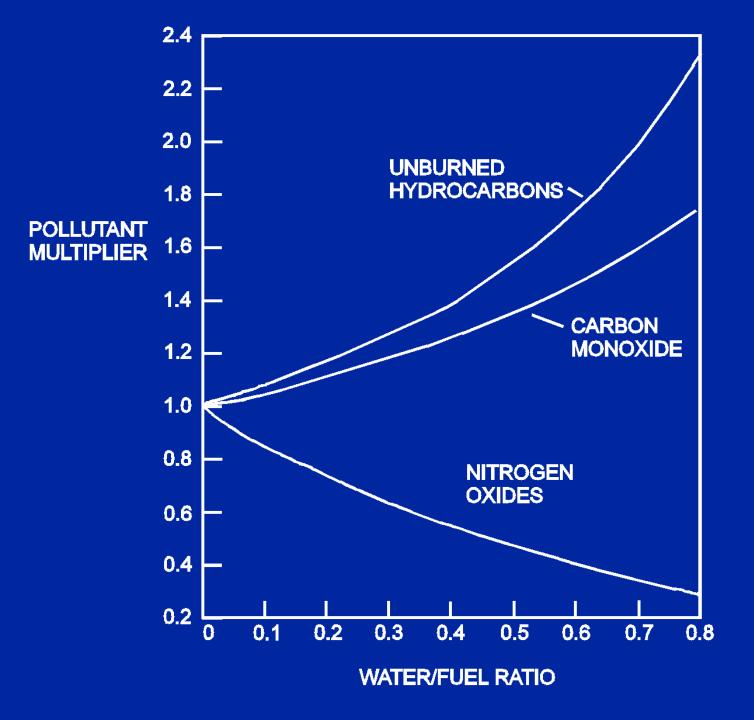






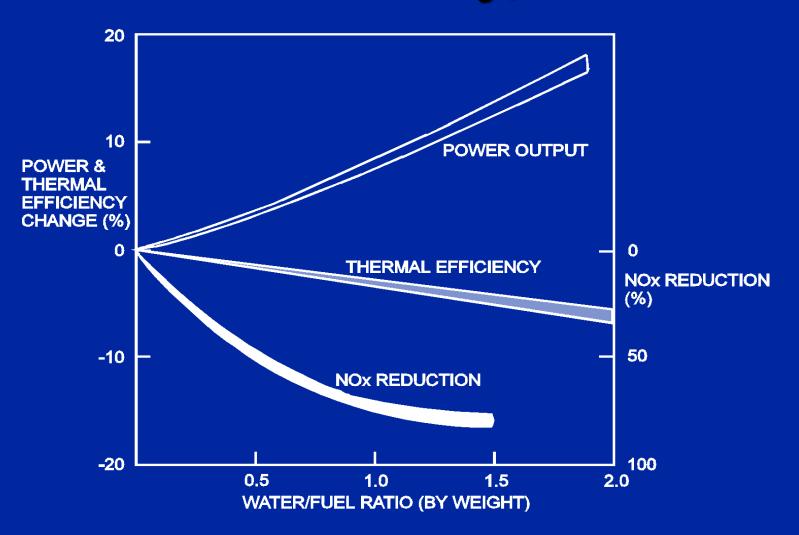


Gas/Steam Fuel Nozzle

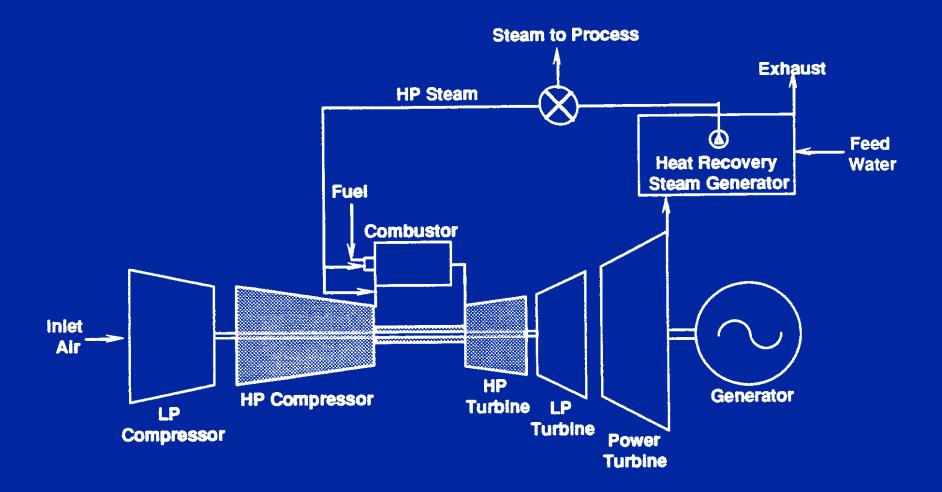


NOx, and **Unburned** HC VS. Water Injection

Effect of Water/Fuel Ratio on NOx, Thermal Efficiency, and Power Output

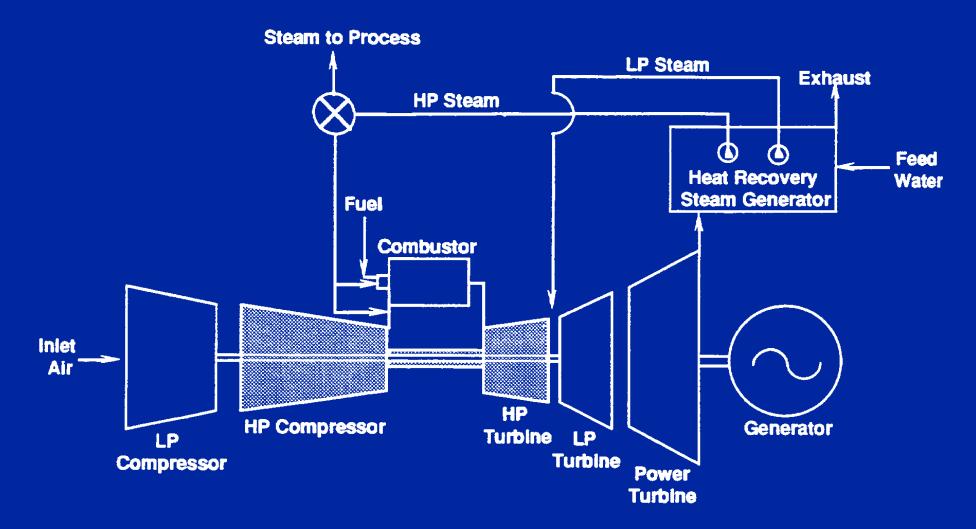


Partial STIG

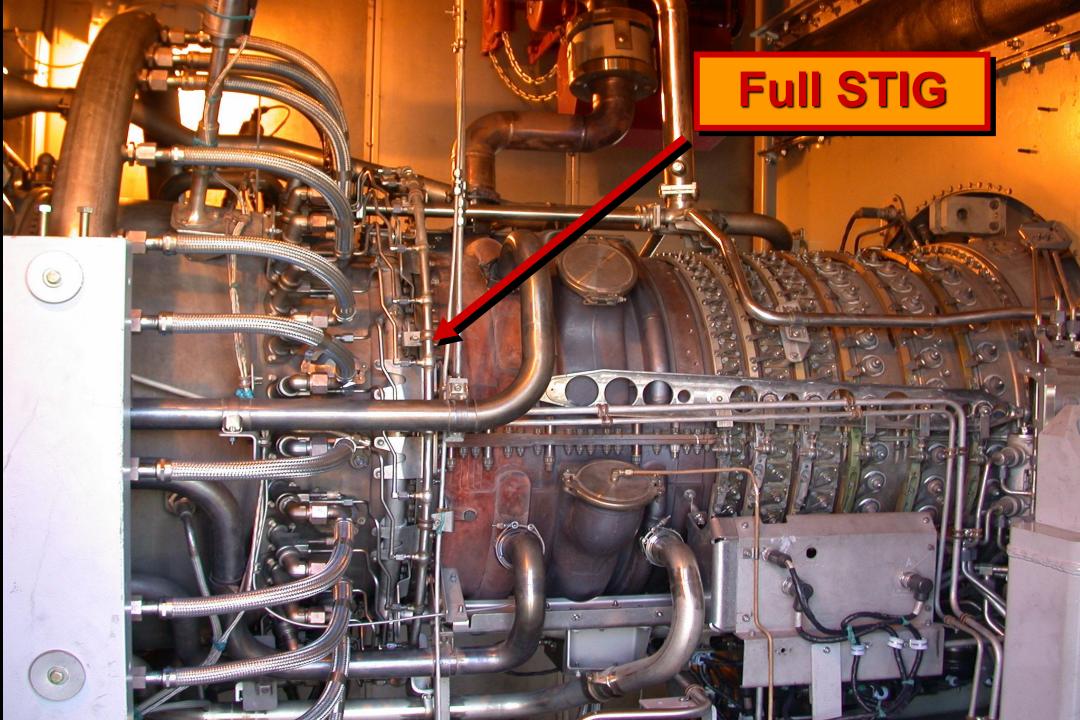


Graphic Courtesy of General Electric

Full STIG



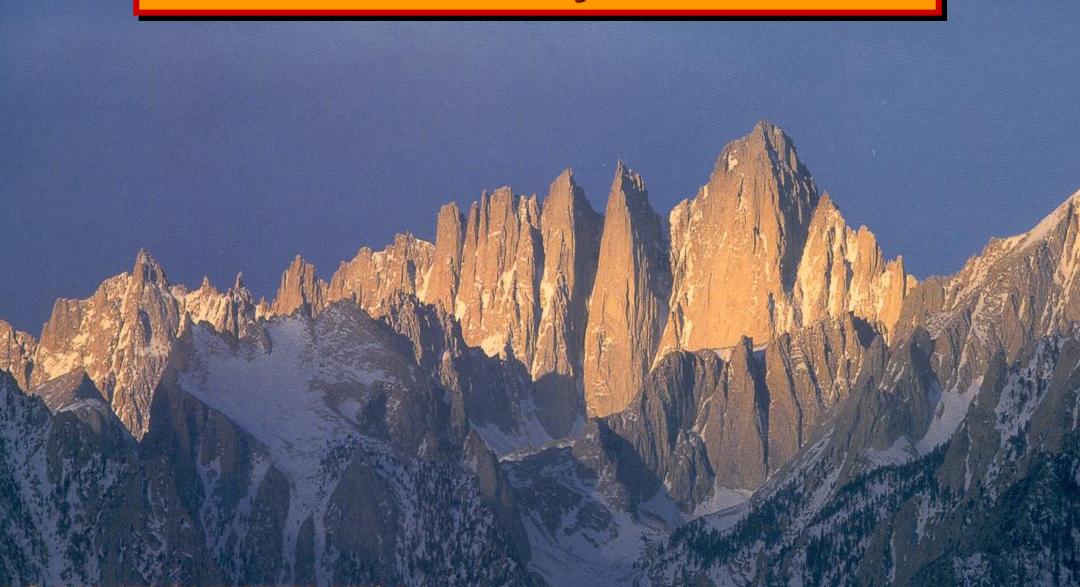
Graphic Courtesy of General Electric



Water and Steam Injection - Summary

- ◆ NOx reduced
- Power output increased
- ◆ Thermal efficiency decreased
- ◆ Fuel flow rate increased
- Maintenance frequency increased

Let's Discuss Catalytic Conversion

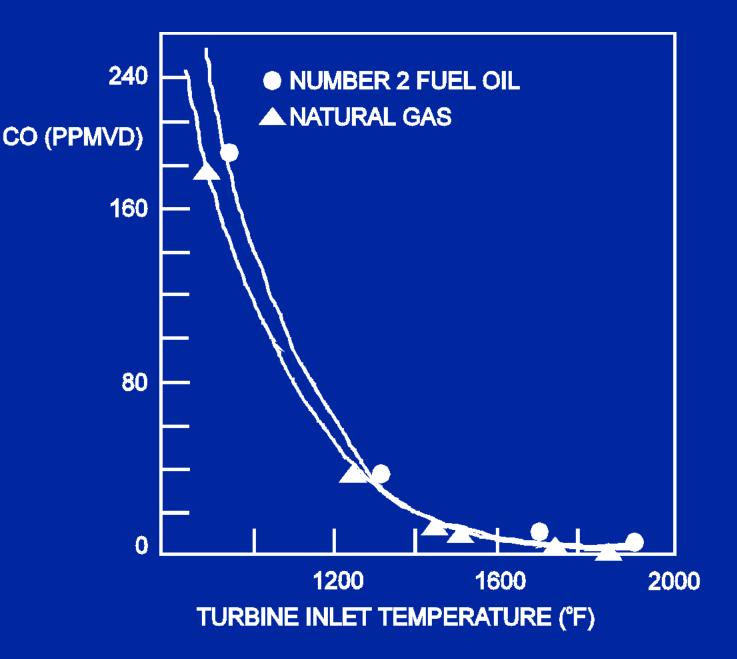


Catalytic Conversion



♦ NOx is reduced ⇒ N₂ Reduction catalyst

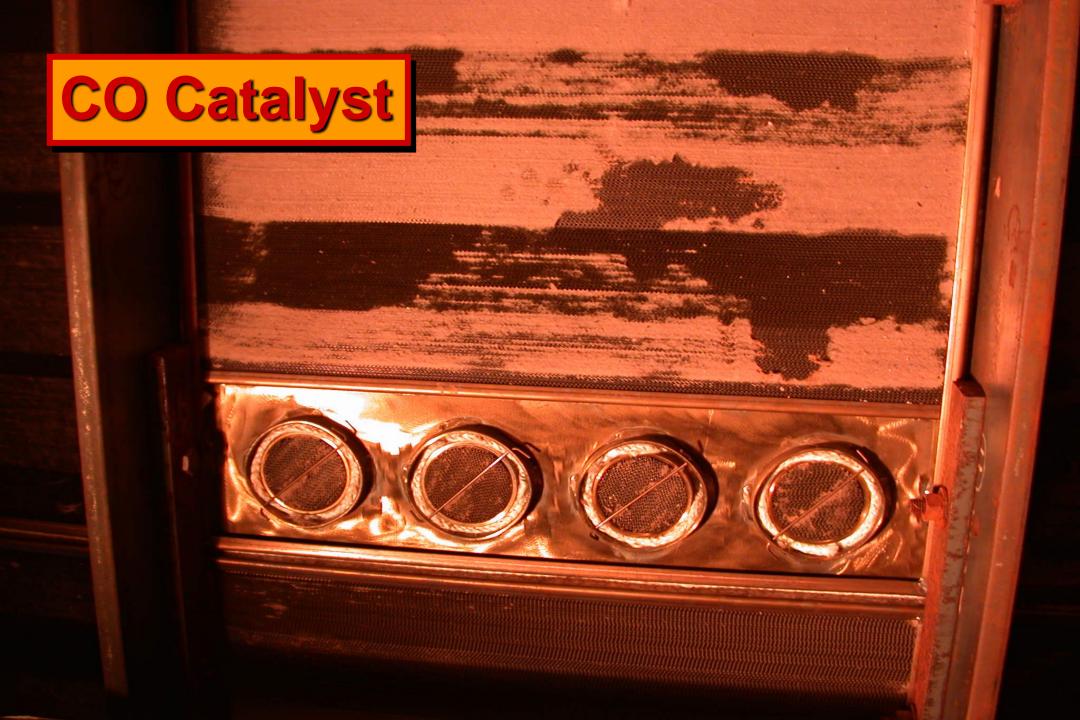




vs.
Turbine
Inlet
Temp

CO Catalyst

- \bullet 2CO + O₂ \Rightarrow 2CO₂
- ◆ 700 to 1000 °F operating temp
- ◆ 90% efficient
- ◆ Pressure drop 1-2 in. H₂O
- Problems
 - Expensive
 - High maintenance
 - Catalyst replacement & disposal

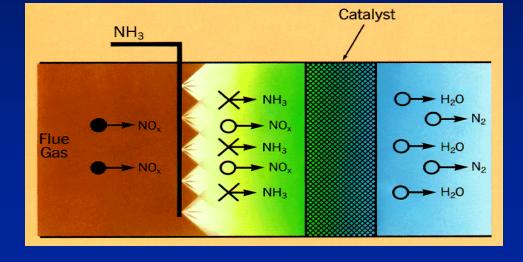




Let's Discuss Selective Catalytic Reduction (SCR)

Selective Catalytic Reduction (SCR)

- ♦ NOx control thru ammonia (NH₃) injection
- ◆ 4NO + 4NH₃ + O₂ → 4N₂ + 6H₂O
- ◆ 2NO₂ + 4NH₃ + O₂ \rightarrow 3N₂ + 6H₂O
- **◆ 90-95% control**
- Problems
 - Expensive
 - High maintenance
 - Ammonia "slip"

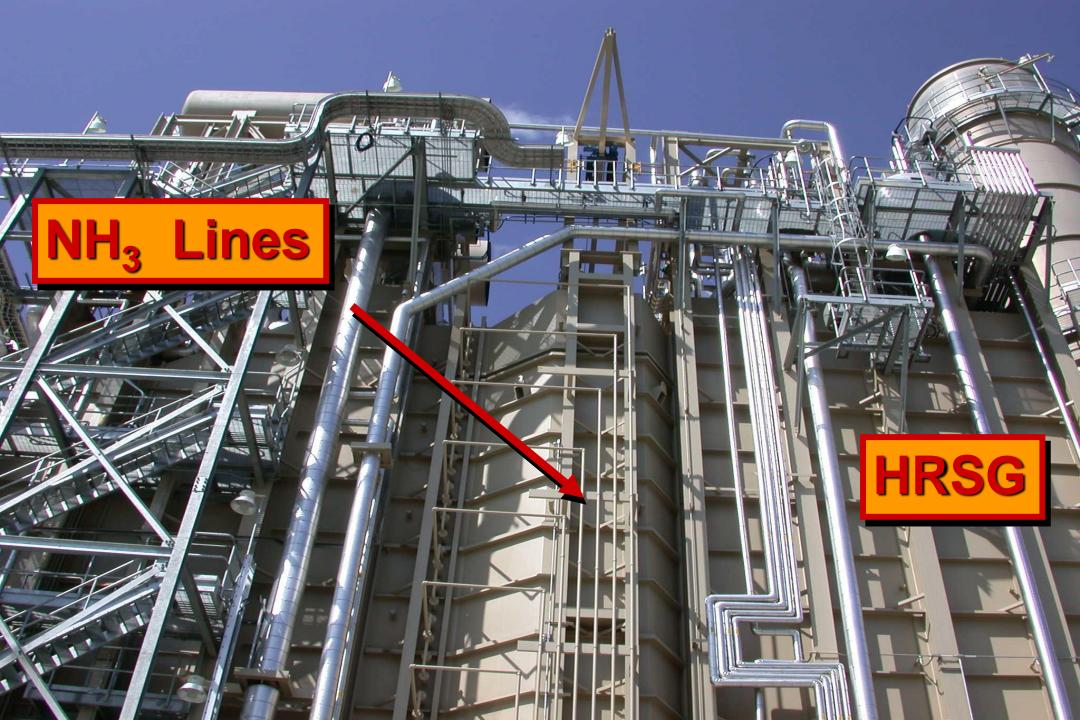


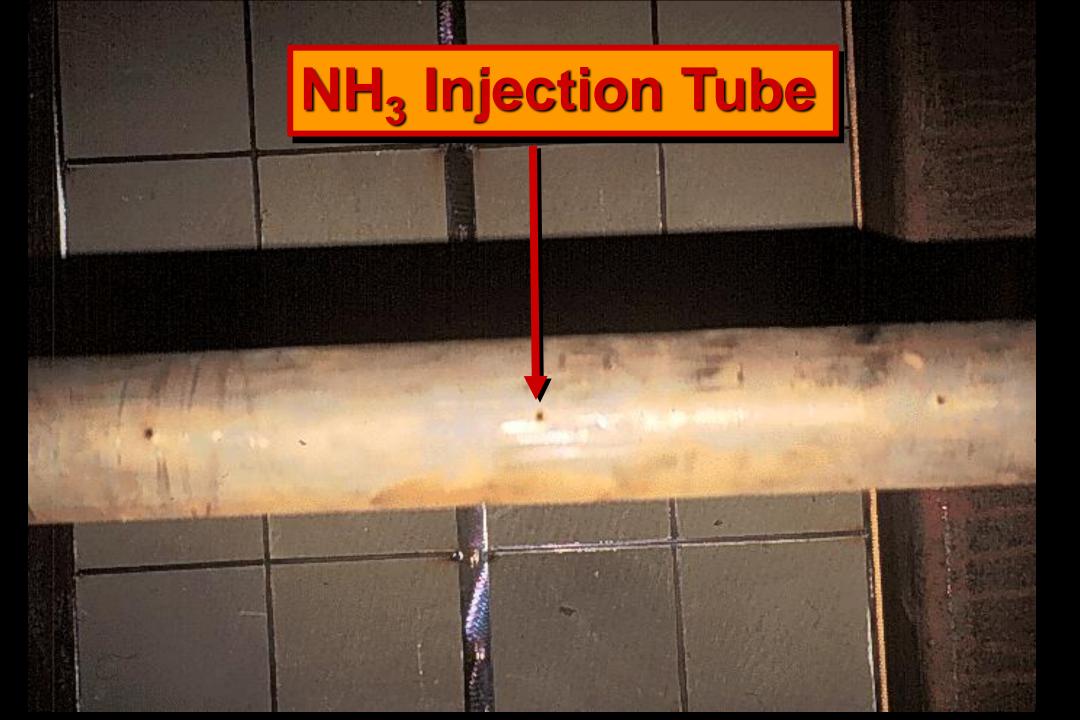
Catalyst replacement & disposal











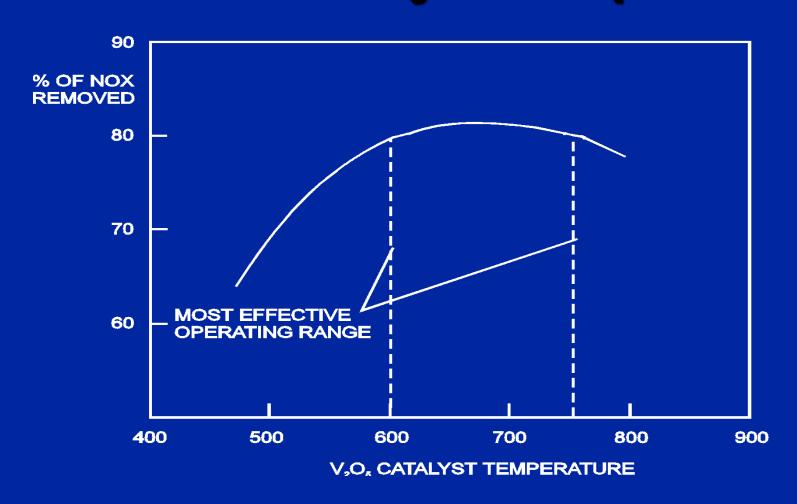
Catalyst
System
Installation







% NOx Removed vs. Vanadium Pentoxide Catalyst Temperature





Regulatory Requirements

- ◆ Federal, state, and local requirements
- ◆ Turbine specific limits
- Permit requirements
- Monitoring requirements
- Visible emission limits
- Nuisance regulations
- Breakdowns & variances



Turbine Regulations

- 40 CFR Part 87 -- Control of Air Pollution From Aircraft and Aircraft Engines
- 40 CFR Part 60 Subparts GG & KKKK -- Standards of Performance for Stationary Gas Turbines (NSPS)
- ◆ Acid Rain Provisions (Parts 72, 73, 74, 75, 76, 77, & 78)
- Stationary Combustion Turbines NESHAP -- YYYY
- State Regulations, including VE
- SIP Requirements
- Local Regulations

Gas Turbine Exemptions

- Emergency use
- Military and military training
- Firefighting and flood control
- Research and development
- Certain geographical areas
- Low output
- Minimal usage



EPA Stationary Gas Turbine Limits

NSPS	NO _x	Sulfur in Fuel	SO ₂	
Subpart GG (1979- 2005)	Small – (150 x 14.4/Y) + F ppm _{vd} @15%O2 Large – (75 x 14.4/Y) + F ppm _{vd} @15%O2	0.8% by weight	150 ppm _{vd} @15%O2	
Subpart KKKK (2005+)	15 to 150 ppm _{vd} @15%O2 depending on size, fuel and location	26 ng SO ₂ /J heat input	110 ng/J gross output (65 ng/J input for biogas)	
NESHAP		Formaldehyde		
Subpart YYYY		91 ppb _{vd} @15%O2		

BACT Summary for Stationary Gas Turbines

	NO _x	CO	VOC	PM ₁₀	SO _x
Simple- Cycle	2.0 ppmvd @ 15%O2	6 ppmvd	2 ppmvd OR 0.0027 Ibs/MMBt u (HHV)	Equiv. to natural gas with fuel sulfur < 1 grain/100 scf	Equiv to natural gas with fuel sulfur < 1 grain/100 scf (< 0.55 ppmvd)
Combined- Cycle & Cogen	2.0 ppmvd @ 15% O2	3.0 ppmvd	2 ppmvd OR 0.0027 Ibs/MMBt u (HHV)	Equiv. to natural gas with fuel sulfur < 1 grain/100 scf	Equiv to natural gas with fuel sulfur < 1 grain/100 scf (< 0.55 ppmvd)

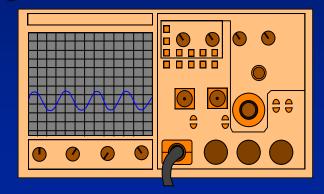
Typical Permit Conditions

- ◆ Fuel
- Hours of operation
- ◆ Water/steam and NH3 injection rates
- Emissions limits
- Continuous Emission Monitoring (CEM) requirements
- Source testing requirements
- Logs



Monitoring Requirements

- Fuel consumption
- ◆ Water/fuel ratio
- Sulfur and nitrogen content of fuel
- ◆ State/local rules may include CEMs for:
 - NOx
 - -SOx
 - -CO
 - $-\mathbf{O_2}$



- CEMs should meet 40CFR60 App. B & F specs



Reasons for Inspections



- Compliance determination
- Complaint investigation
- Source plan approval
- Review or renewal of permits
- Special studies

Pre-Inspection

- Prepare inspection report form
- **♦ File review**
- ◆ Regulation review
- Equipment check
- Pre-entry & entry
- Pre-inspection meeting
- Permit check



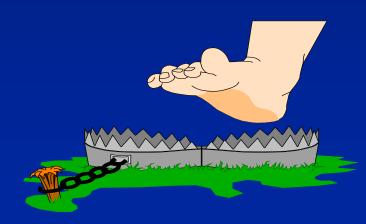
Inspection

- ◆ Visible emission evaluation
- ◆ General upkeep & maintenance
- Monitoring instruments & records
- Fuel type and quality
- ◆ Maintenance records
- Operational records
- ◆ Source tests/RATA tests



Inspector Safety

- Proper equipment
- Plant warnings
- ♦ Heat
- High pressure steam
- **◆ Electrical hazards**



- Noise
- Moving parts
- Inhalation hazards
- Hazardous materials
- Turbine disintegration

Additional Information

- Turbine MACT Fact Sheet
 - •<u>https://www.epa.gov/sites/production/files/2016-</u> 03/documents/stationary_combustion_turbines_factsheet_2003.pdf
- •Turbine MACT (NESHAPS for Stationary Combustion Turbines)
 March 5, 2004
 - •https://www.govinfo.gov/content/pkg/FR-2004-03-05/pdf/04-4530.pdf
- Amendment to Turbine MACT (Exempts certain equipment)
 August 18, 2004
 - https://www.govinfo.gov/content/pkg/FR-2004-08-18/pdf/04-15529.pdf
- New Amendment to Turbine MACT (SSM applicability and electronic reporting)
 - https://www.epa.gov/sites/production/files/2020 01/documents/frn_combustion_turbines_rtr_final_rule.pdf
- •NSPS for Stationary Combustion Turbines
 - https://www.govinfo.gov/content/pkg/FR-2006-07-06/pdf/06-5945.pdf

