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
How does a Turbine Work?

Simple Open Cycle Gas Turbine

Turbojet Engine
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
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
Important Terms

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

Gas Turbine Power Plant

Turbine Inlet Air
Turbine Inlet Air Filters

Air Filter Chamber

High Pressure Water Line

Compressor Section
General Electric 9HA
(397 MW – 532KHP)
Let's Discuss Gas Turbine Air & Gas Flows

Combustor Liner and Air Flow

LM6000 Fuel Manifold

Fuel Lines

Water Injection
Let's Discuss Turbine Sections

Siemens Hybrid Combustor & Turbine Blades

Graphic Courtesy of Siemens
Let's Discuss Turbine Air Cooling

Inlet Air Cooling
Let’s have some fun!!
Let's Discuss Steam Generation
Combined Cycle w/By-pass

Let’s Discuss Duct Burners
HRSG Overview

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

- **Evaporator**

- **Economizer**
Steam Turbine

LP Steam Turbine

Row 1 LP Blades

10 Stage IP Rotor Blades
Let's Discuss Dry Air-Cooling

Steam Turbine to Dry Air Cooling

Dry Air-Cooled Condenser
Prometheus Tree – 4,844 years old

Emissions From Gas Turbines

Fuel + Air ($N_2$, $O_2$)

- $H_2O$
- $CO_2$
- $CO$
- VOC
- NO$_X$
- SO$_X$
- PM

Ozone Photochemistry

Air Resources Board

- Nitrogen Dioxide (NO$_2$) + Sunlight Energy
- Volatile Organic Compounds (VOC)
- Hydroxide (HO$_2$)
- Ozone (O$_3$)
Let's Discuss Emissions Controls

Emissions Control Methods

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

Combustion Considerations

- Time
- Temperature
- Turbulence (mixing)
- Oxygen
- Nitrogen
NOx Creation

Thermal NOx

Fuel-bound NOx

Prompt NOx

PROMPT NOx

NOx vs. Turbine Inlet Temperature
**Figure 301.2** Thermal NOx vs. Equivalence Ratio

**Lean Premix Combustor**

**Can-Annular Lean Premix Burner**

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Let's Discuss Steam/Water Injection

Water Injection

Ring Burners

Siemens Hybrid Burner Ring Combustor

Graphic Courtesy of Siemens

Turbine Inlet
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 Nozzle

Water Nozzle

Water Treatment
Water Treatment De-Min. Process

Graphic Courtesy of General Electric

Gas/Steam Fuel Nozzle

NOx, CO, and Unburned HC vs. Water Injection
Effect of Water/Fuel Ratio on NOx, Thermal Efficiency, and Power Output

Partial STIG

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**

- CO is oxidized \( \rightarrow \) \( \text{CO}_2 \) Oxidation catalyst
- NOx is reduced \( \rightarrow \) \( \text{N}_2 \) Reduction catalyst

**CO Catalyst**

- \( 2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \)
- 700 to 1000 °F operating temp
- 90% efficient
- Pressure drop 1-2 in. \( \text{H}_2\text{O} \)
- Problems
  - Expensive
  - High maintenance
  - Catalyst replacement & disposal

**CO vs. Turbine Inlet Temp**

- Operating temperature range: 1200 to 1600 °F
- CO concentration in ppmv
- Number 2 fuel oil vs. natural gas
Let’s Discuss Selective Catalytic Reduction (SCR)

- NOx control thru ammonia (NH₃) injection
- 4NO + 4NH₃ + O₂ → 4N₂ + 6H₂O
- 2NO₂ + 4NH₃ + O₂ → 3N₂ + 6H₂O
- 90-95% control

Problems
- Expensive
- High maintenance
- Ammonia “slip”
- Catalyst replacement & disposal
SCR Catalyst & NH₃ Tubes

SCR Catalyst

% NOx Removed vs. Vanadium Pentoxide Catalyst Temperature

5/2/2016
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

Gas Turbine Emission Limits
- NOx values based on turbine heat input and fuel used corrected to 15% O\(_2\)
- SO\(_2\) limited to 0.015% by volume @ 15% O\(_2\)
  - Fuel limited to 0.8% sulfur by weight
- States and districts may have more stringent limits
- CO based on local rules
- Formaldehyde 43 ppb

BACT Summary for Stationary Gas Turbines

<table>
<thead>
<tr>
<th></th>
<th>NO(_x)</th>
<th>CO</th>
<th>VOC</th>
<th>PM(_{10})</th>
<th>SO(_x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple-Cycle</td>
<td>2.0 ppmvd @ 15% O(_2)</td>
<td>6 ppmvd</td>
<td>2 ppmvd OR 0.0027 lbs/MMBtu (HHV)</td>
<td>Equiv. to natural gas with fuel sulfur &lt; 1 grain/100 scf</td>
<td>Equiv to natural gas with fuel sulfur &lt; 1 grain/100 scf (&lt; 0.55 ppmvd)</td>
</tr>
<tr>
<td>Combined-Cycle &amp; Cogen</td>
<td>2.0 ppmvd @ 15% O(_2)</td>
<td>3.0 ppmvd</td>
<td>2 ppmvd OR 0.0027 lbs/MMBtu (HHV)</td>
<td>Equiv. to natural gas with fuel sulfur &lt; 1 grain/100 scf</td>
<td>Equiv to natural gas with fuel sulfur &lt; 1 grain/100 scf (&lt; 0.55 ppmvd)</td>
</tr>
</tbody>
</table>
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
  - O₂
- CEMs should meet 40CFR60 App. B & F specs

Inspections
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
Source Testing & RATA Test

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
- Turbine MACT (NESHAPS for Stationary Combustion Turbines)
  - March 5, 2004
- Amendment to Turbine MACT (Exempts certain equipment)
  - August 18, 2004
- NSPS for Stationary Combustion Turbines
  - http://www.epa.gov/ttn/combust/turbine/fr06jy06.pdf