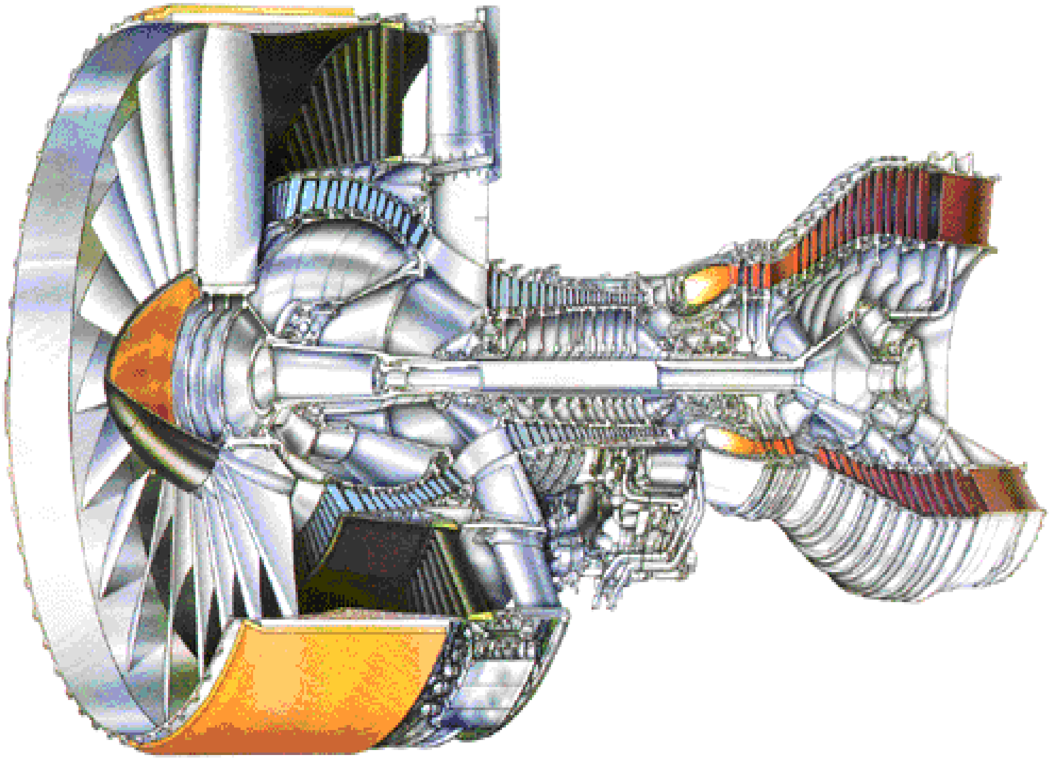
NACT 272

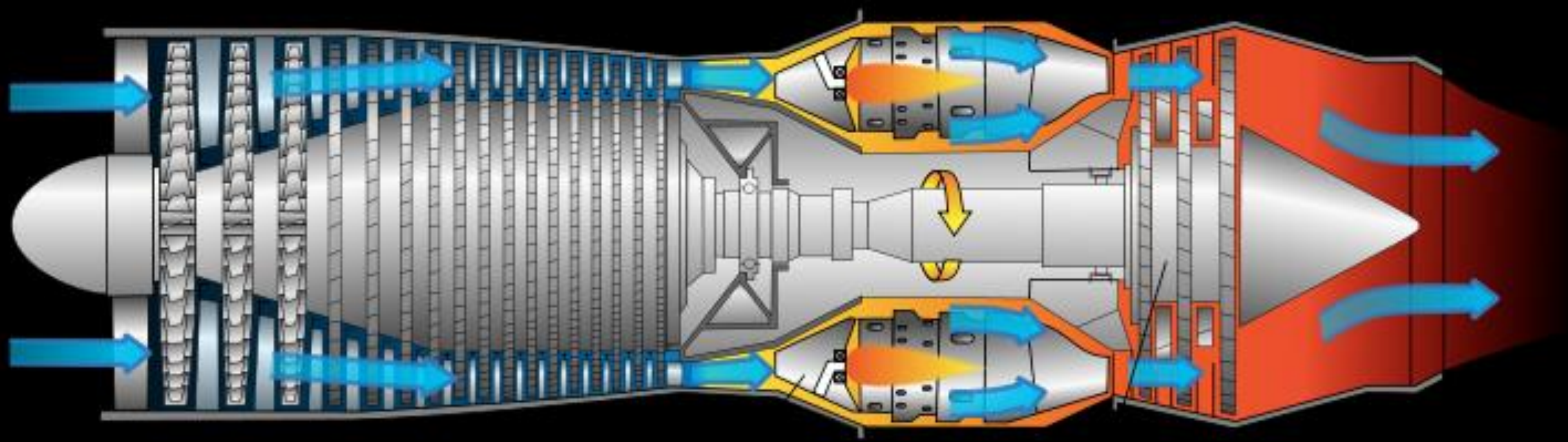


Stationary Gas Turbines

Course Overview

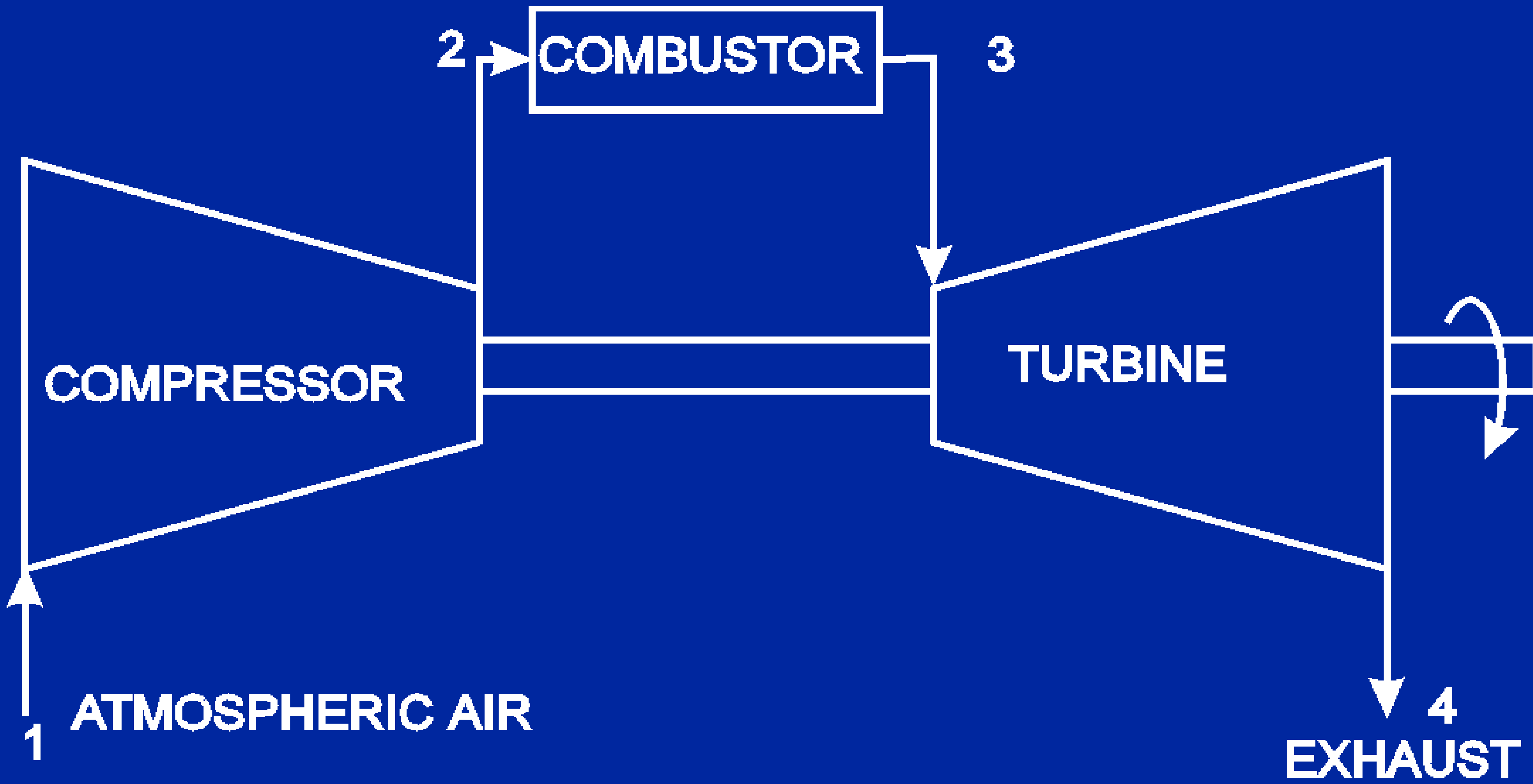
- Gas turbine theory and operation
- Gas turbine uses
- Air pollution control devices
- Gas turbine regulations
- Typical permit conditions
- Inspection procedures
- Continuous emission monitoring
- Source testing requirements

What is a Gas Turbine

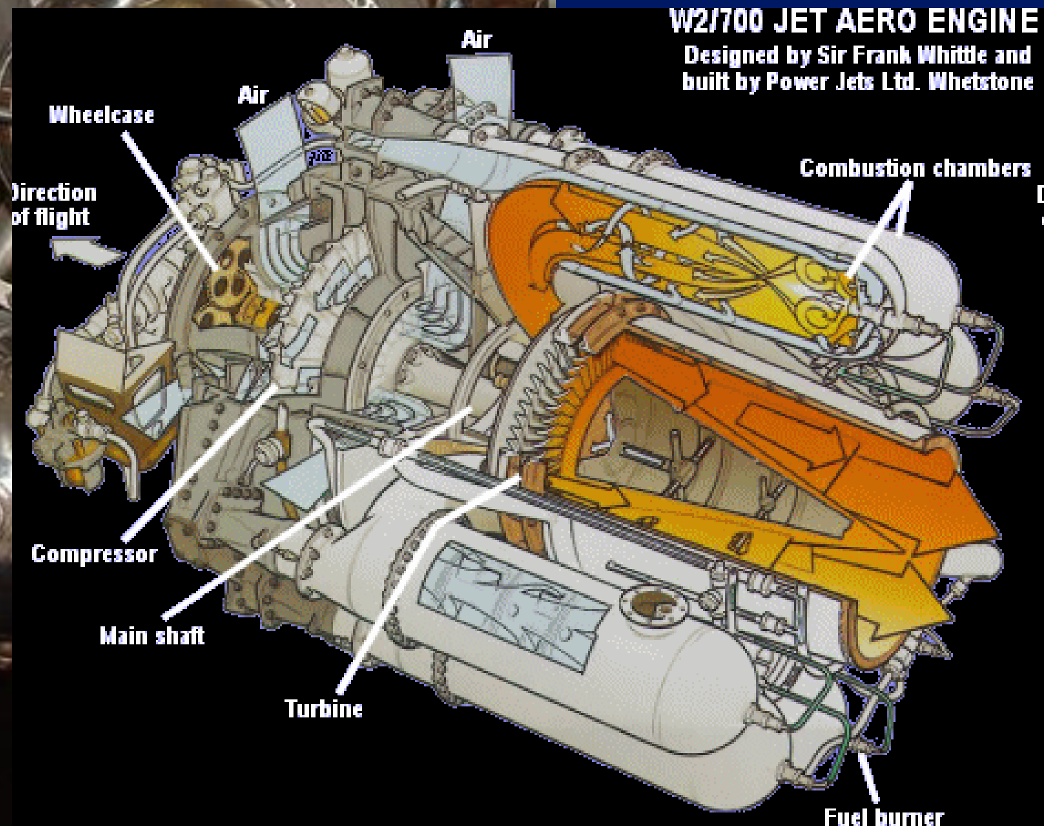


How does a Turbine Work?

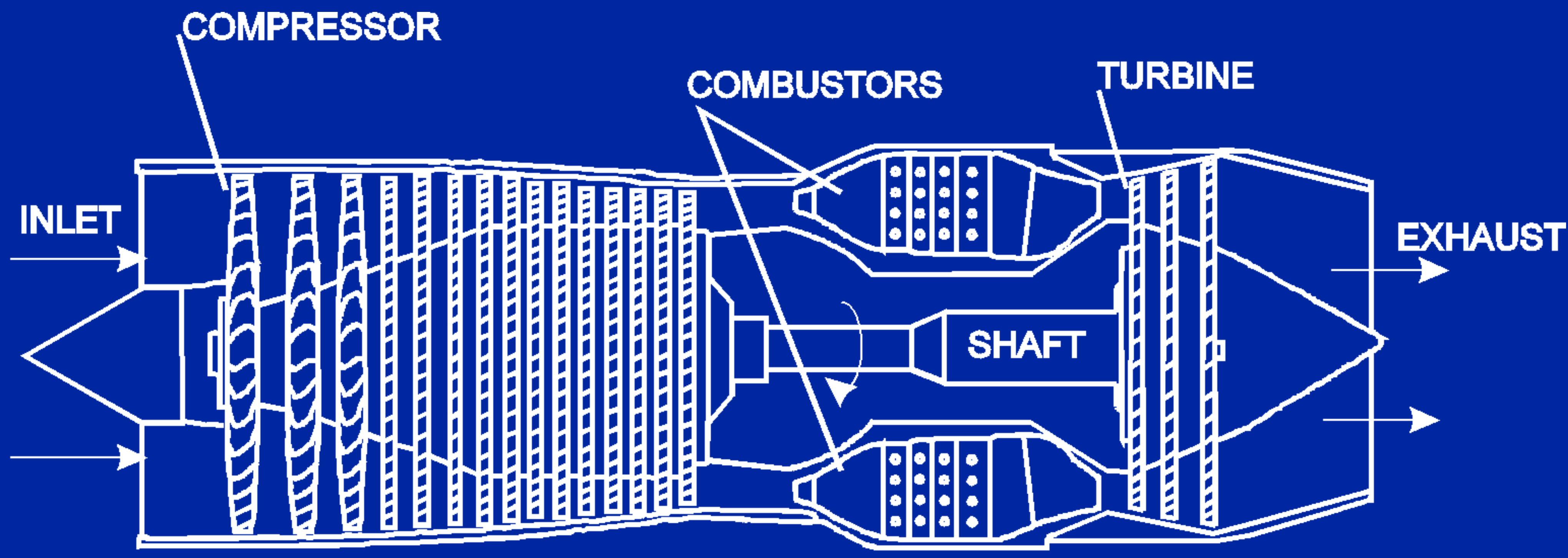
Simple Open Cycle Gas Turbine



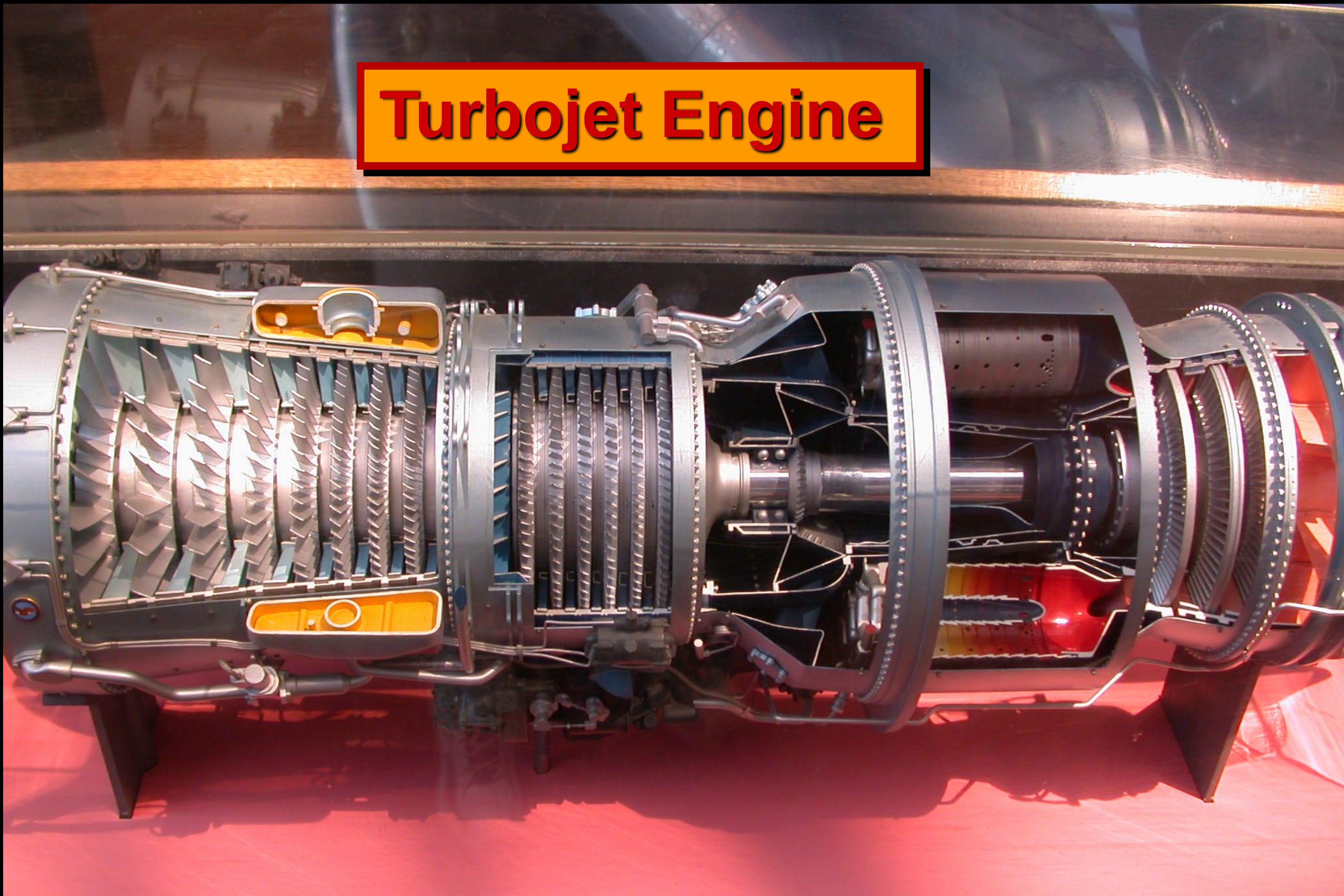
Turbojet Engine



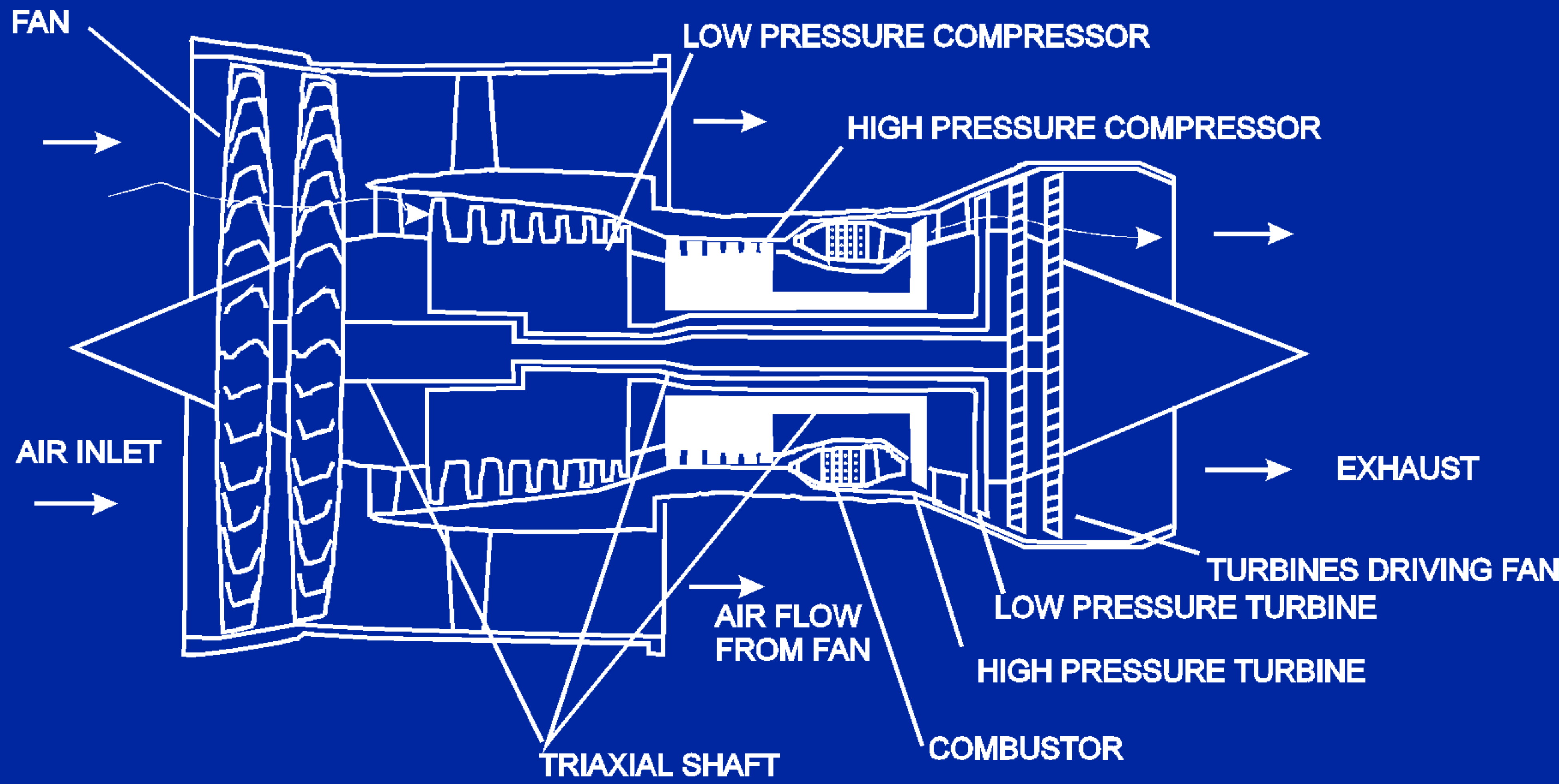
Single Spool Turbojet Engine

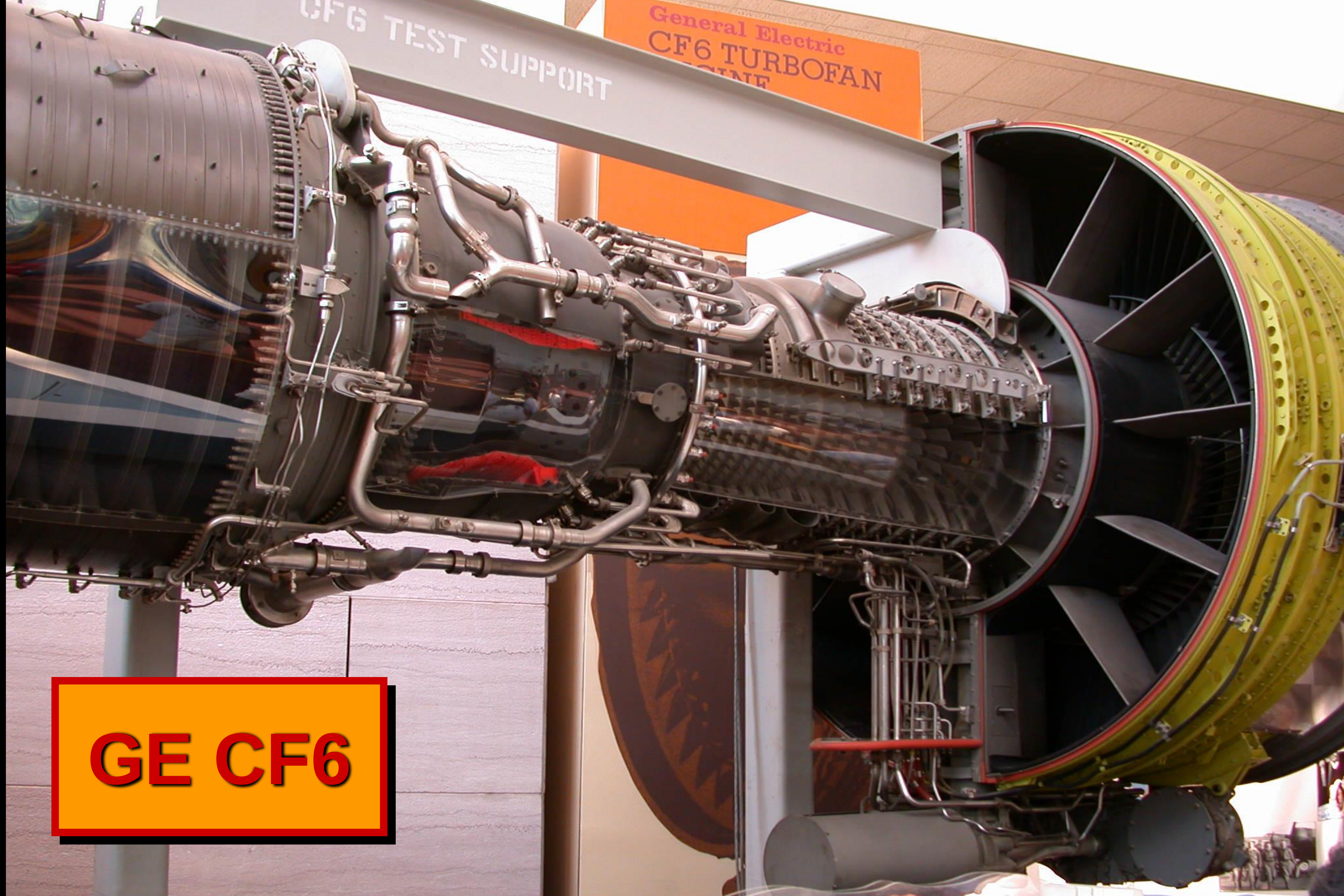


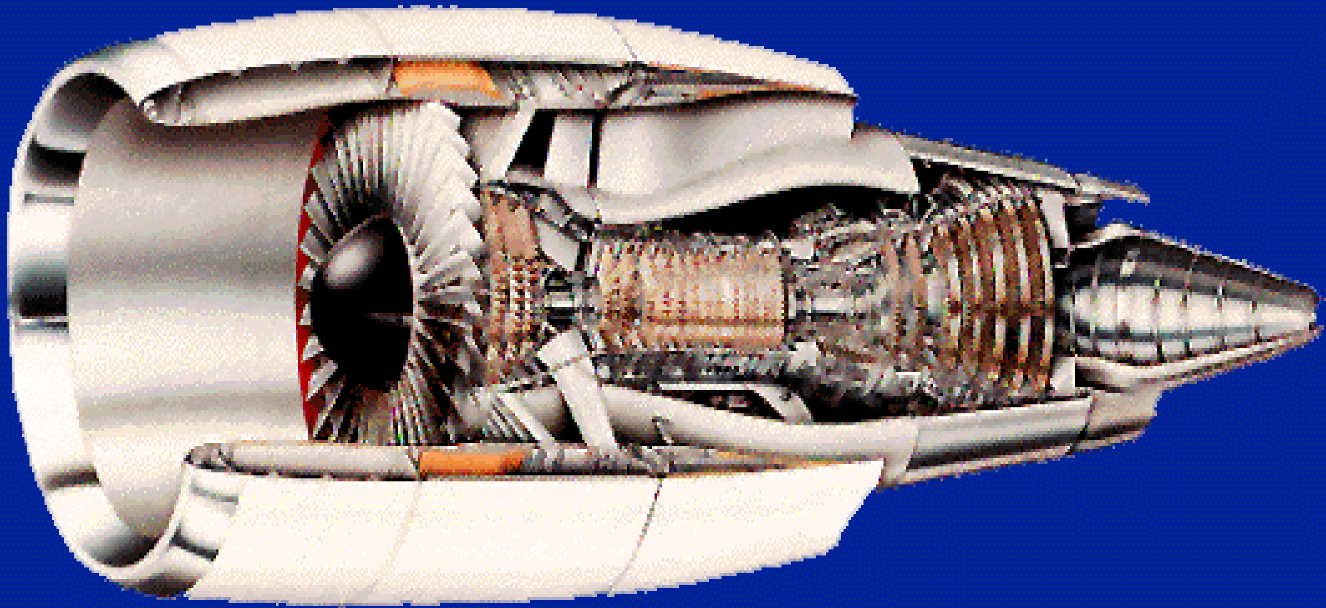
Turbojet Engine



Turbofan Gas Turbine Engine



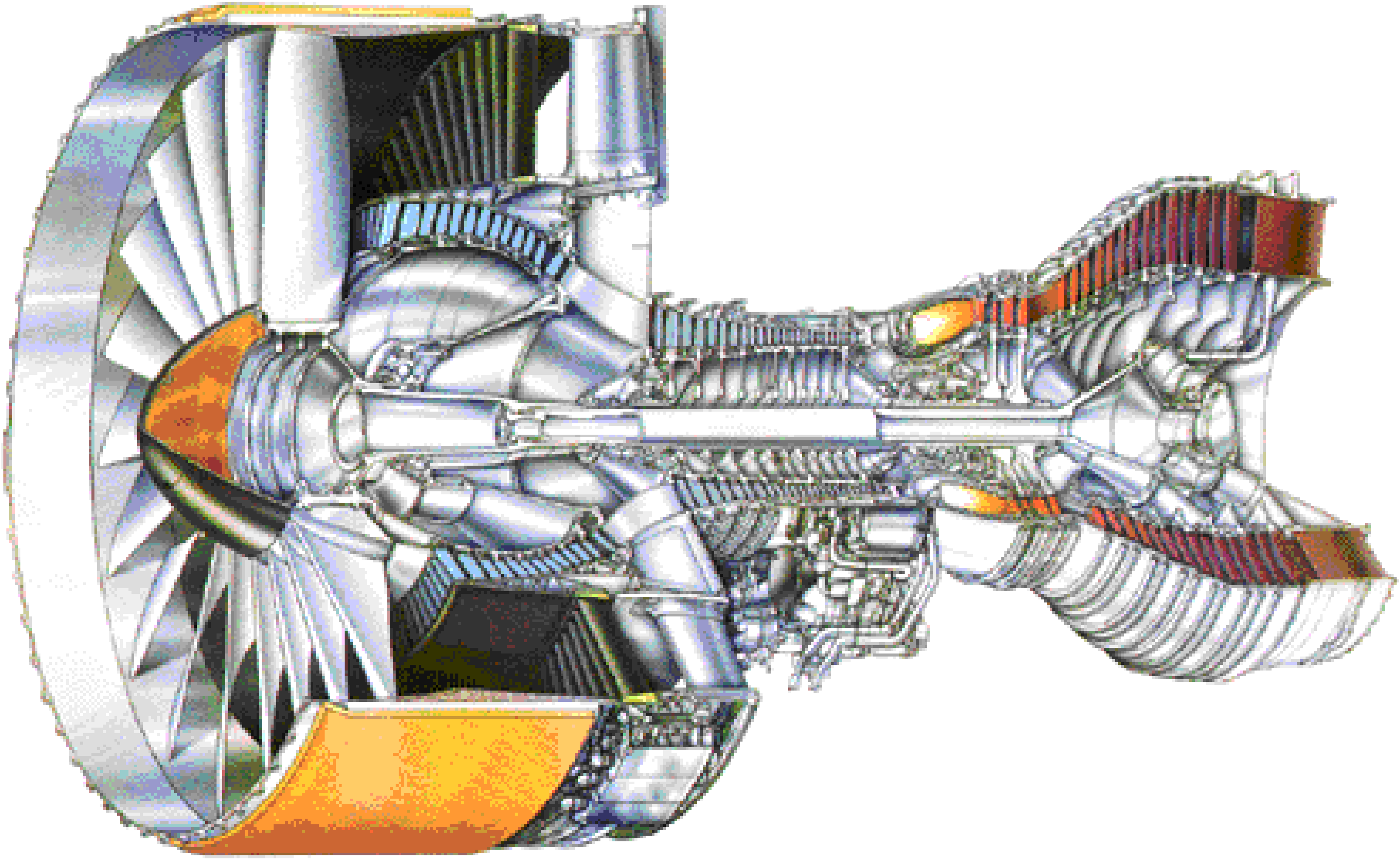

CF6 TEST SUPPORT
General Electric
CF6 TURBOFAN
GE CF6



GE High Bypass Turbofan

Presidential Boeing 747

PW4000 112-INCH FAN ENGINE




Boeing 777 With Pratt
and Whitney PW4000

Jet Aircraft

Stationary Sources

Gas Turbine Uses

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

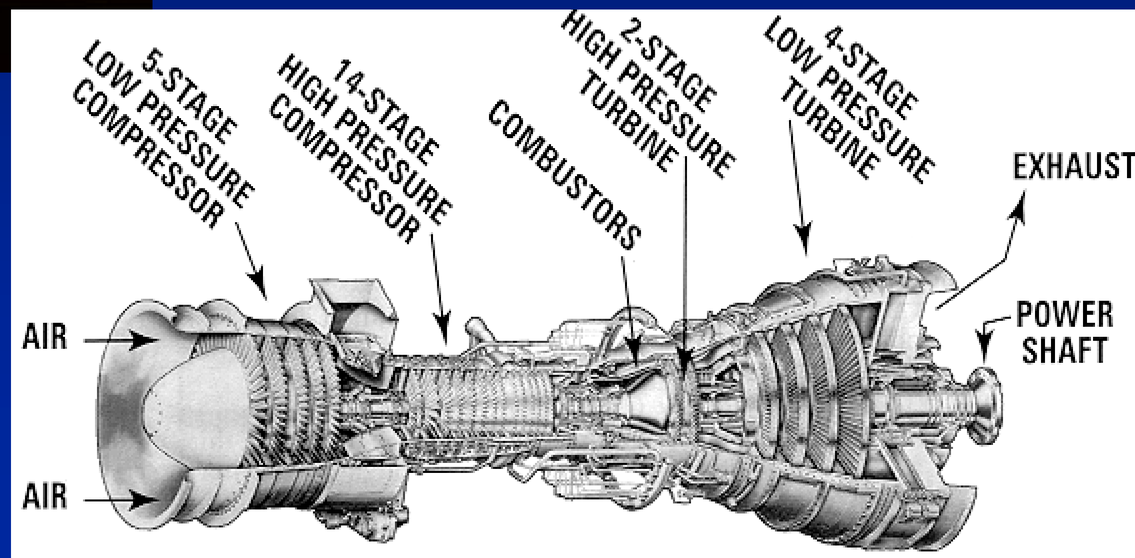
- Relatively small size (power to size ratio)
- Light weight for output (power to weight ratio)
- Requires modest foundation
- Requires no cooling water
- Rapid startup and loading
- Good thermal efficiency
- Low maintenance
- Runs unattended
- Long life

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

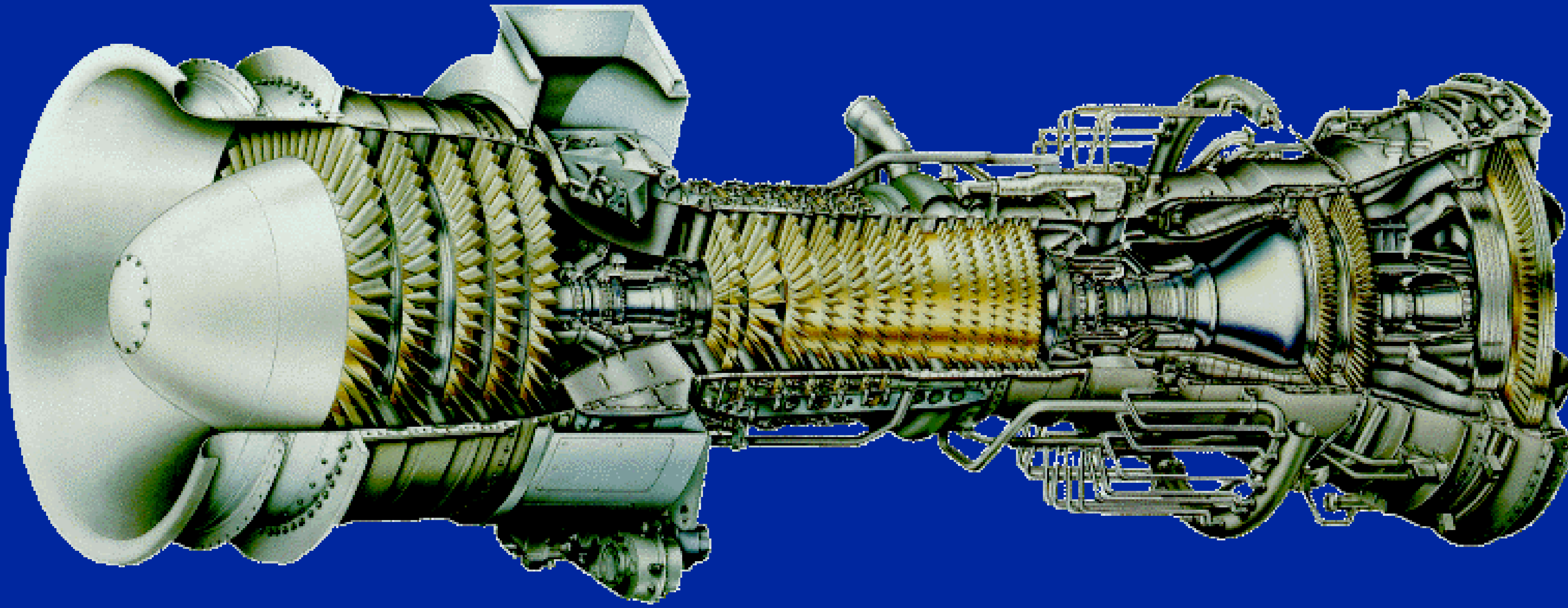
Marine Engines



Aeroderivative Turbines

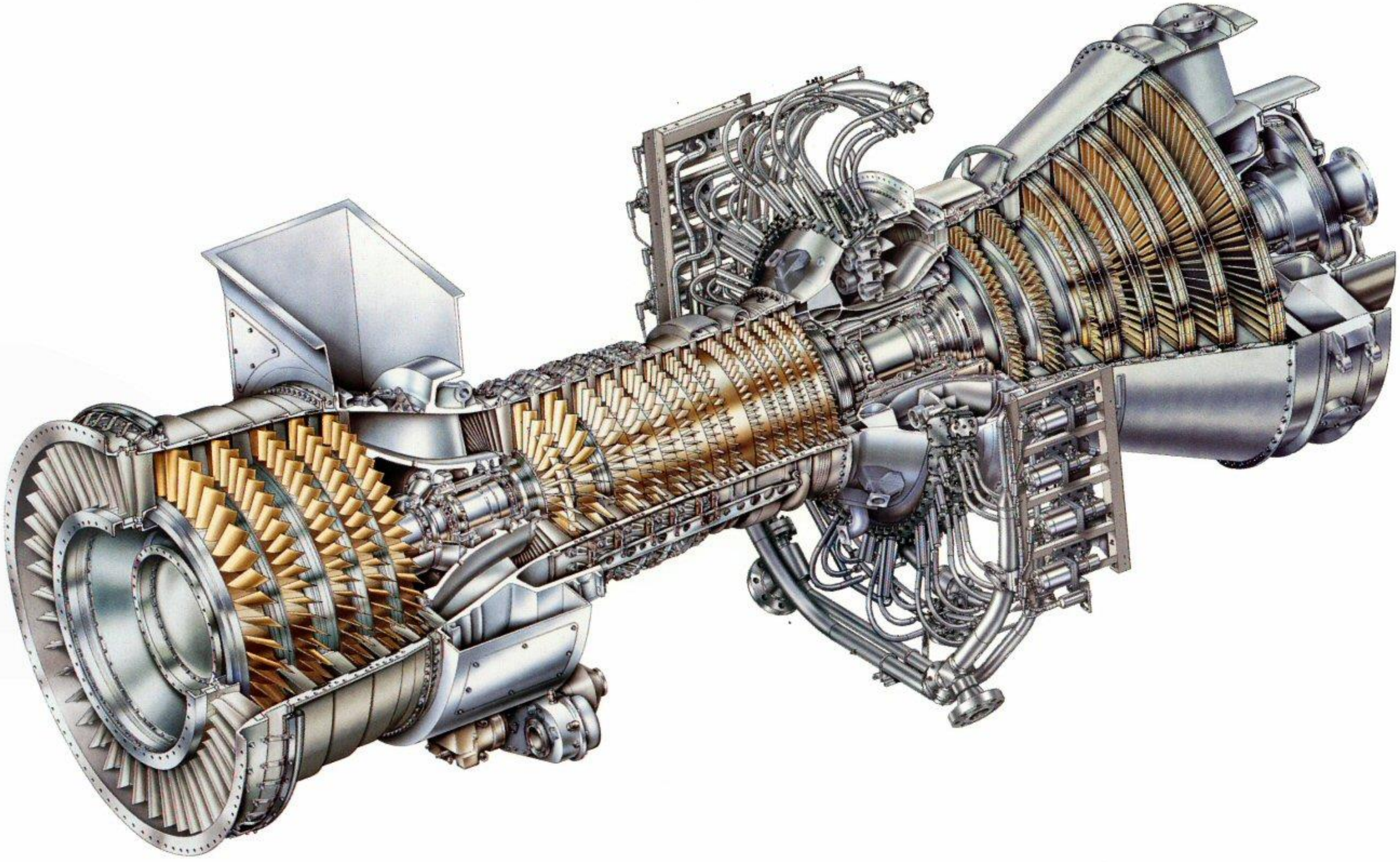
- Based on established product
- High simple cycle efficiency
- High power to weight ratio
- Direct generator drive capability
- Ease and speed of maintenance
- Parts availability

GE LM5000 Gas Turbine

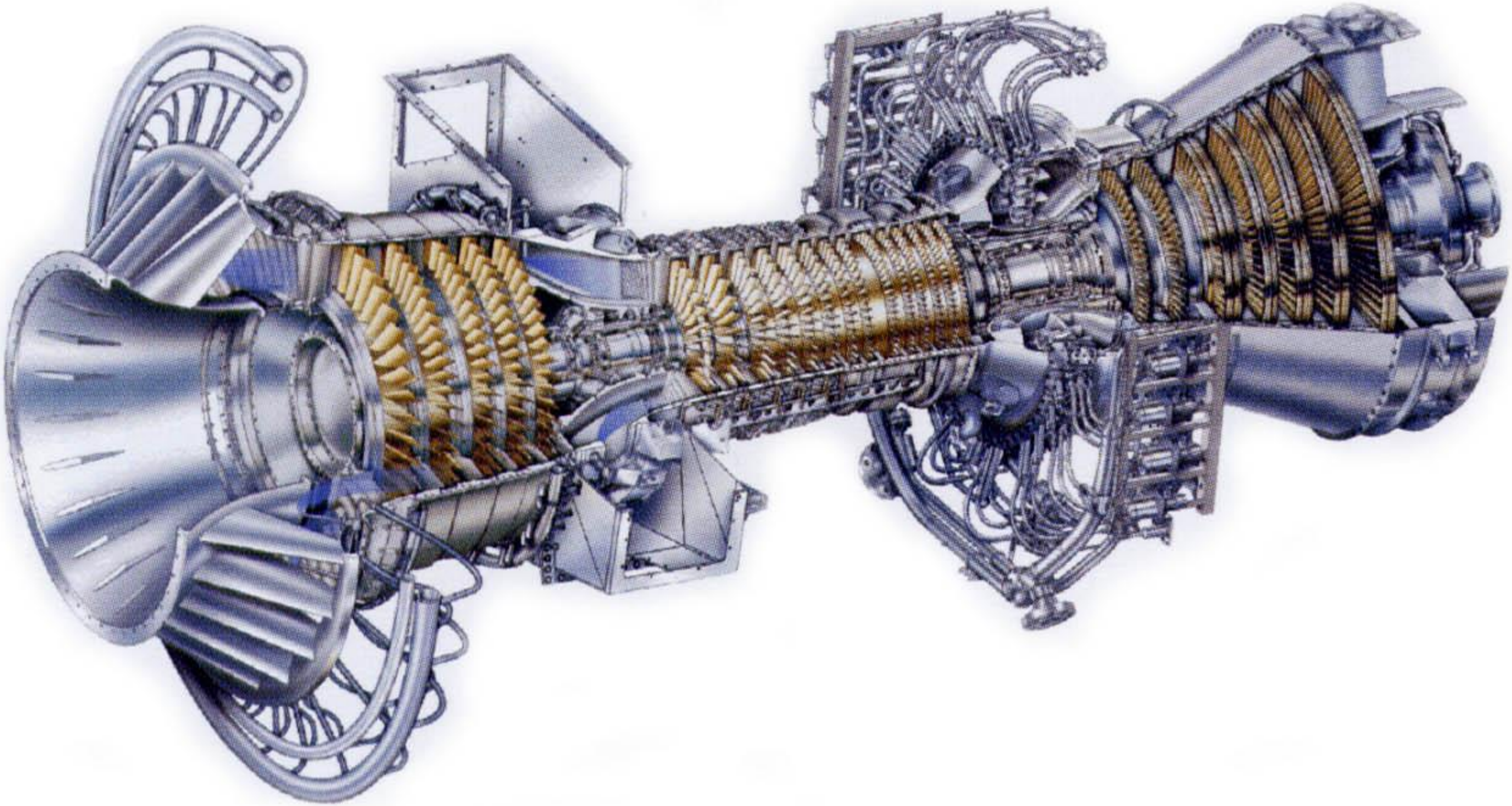


Graphic Courtesy of General Electric

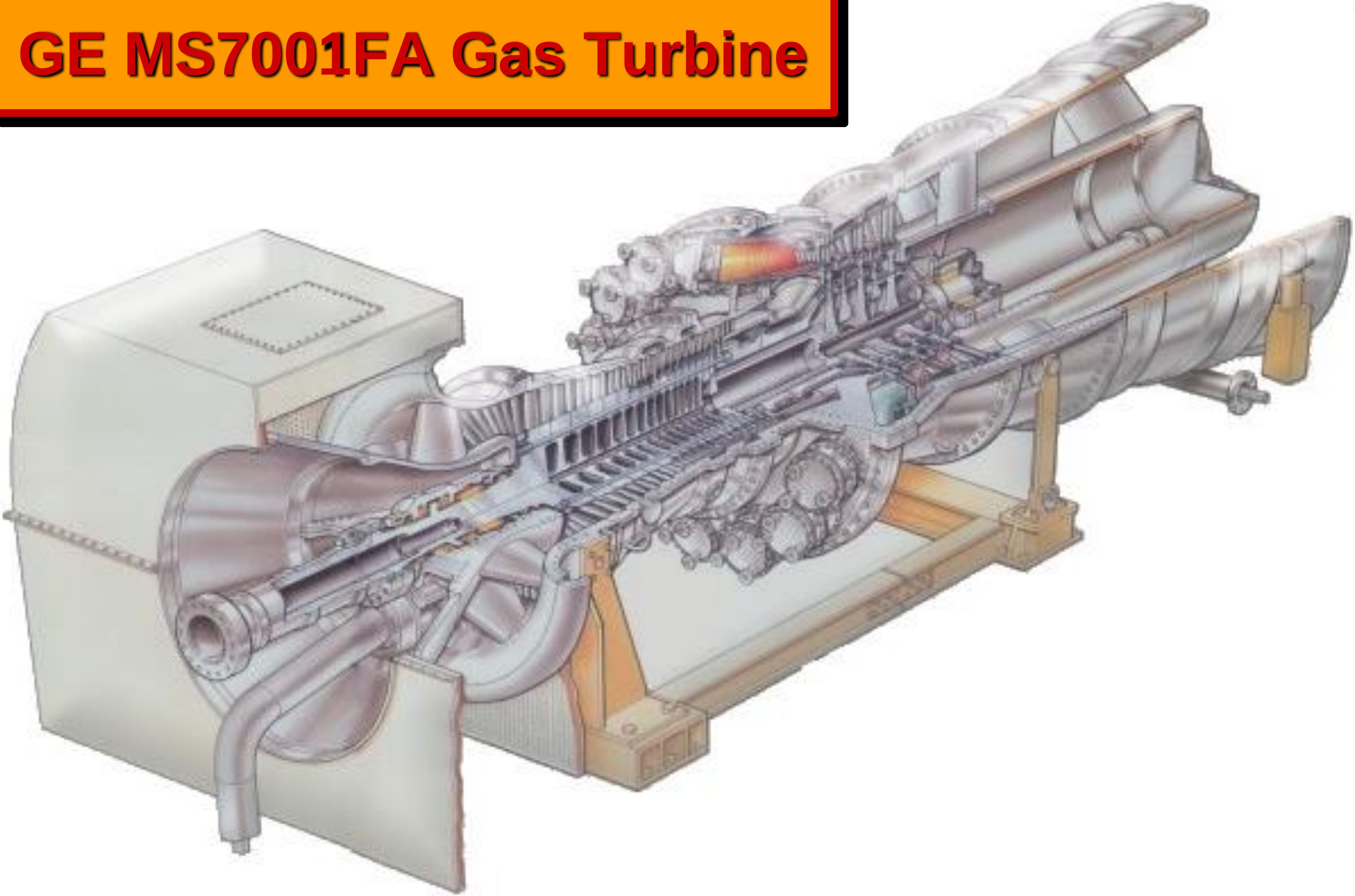
GE LM6000 Gas Turbine



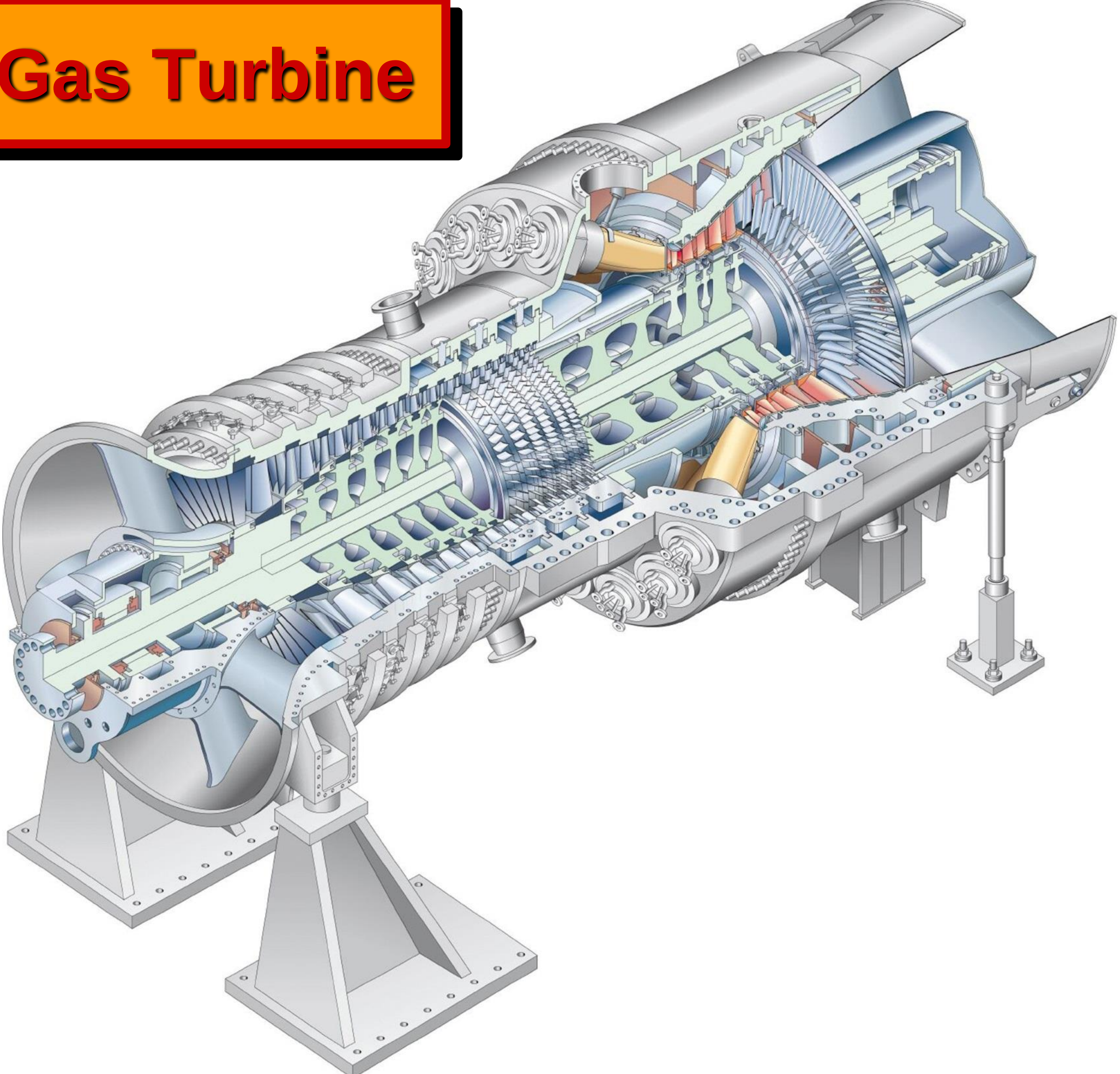
GE LM6000 with Sprint



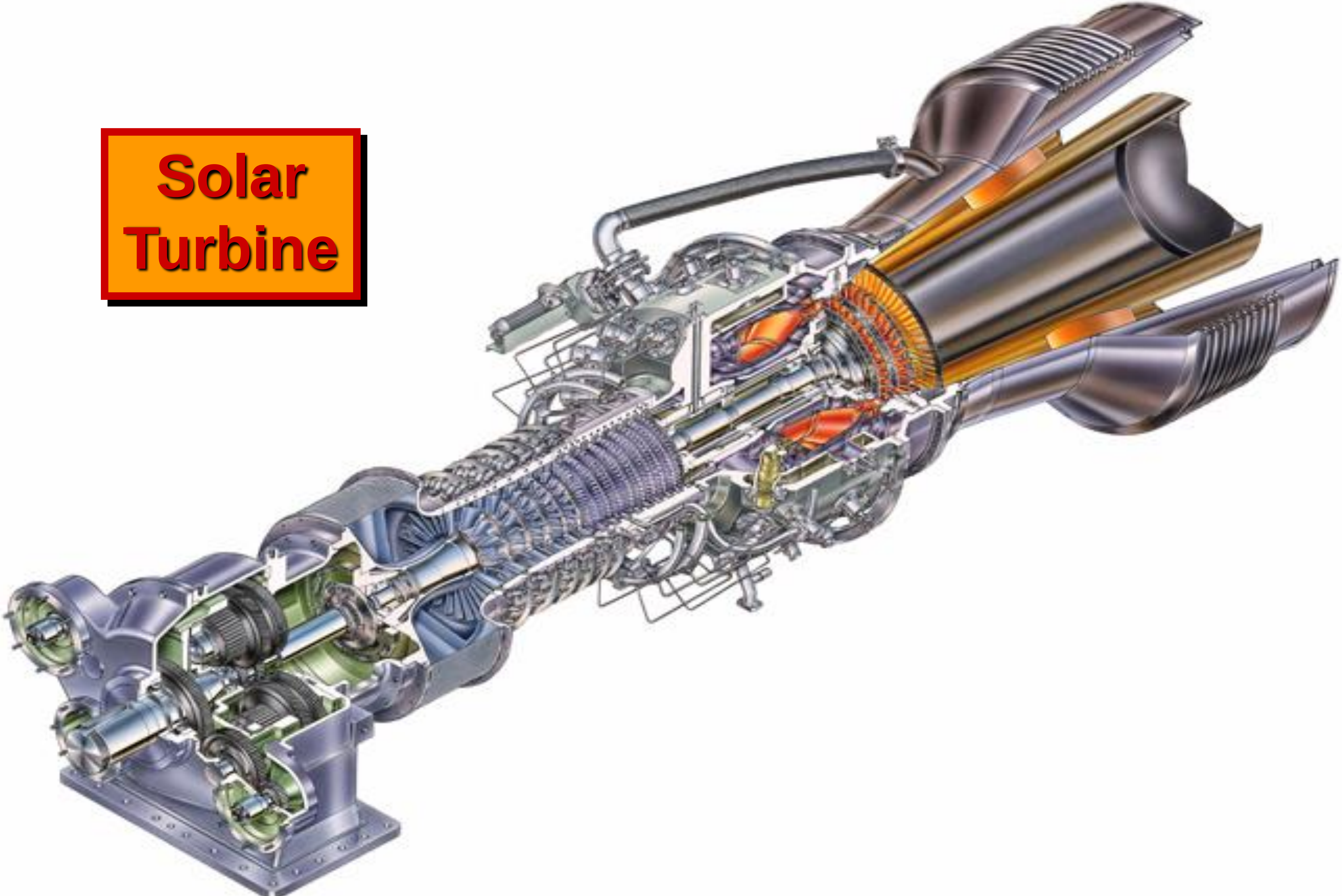
GE MS7001FA Gas Turbine



Siemens Gas Turbine



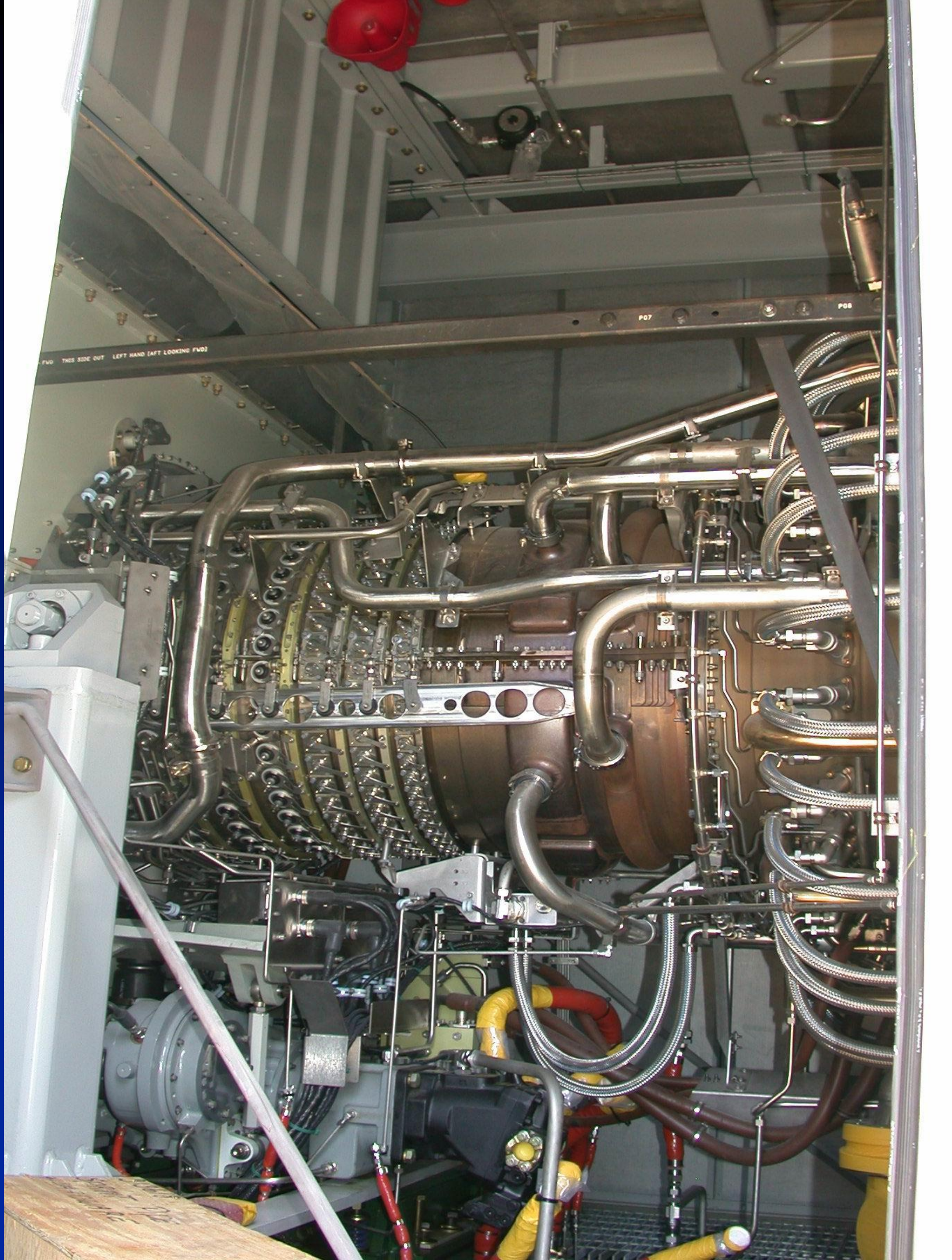
Solar Turbine



Aeroderivative Turbine

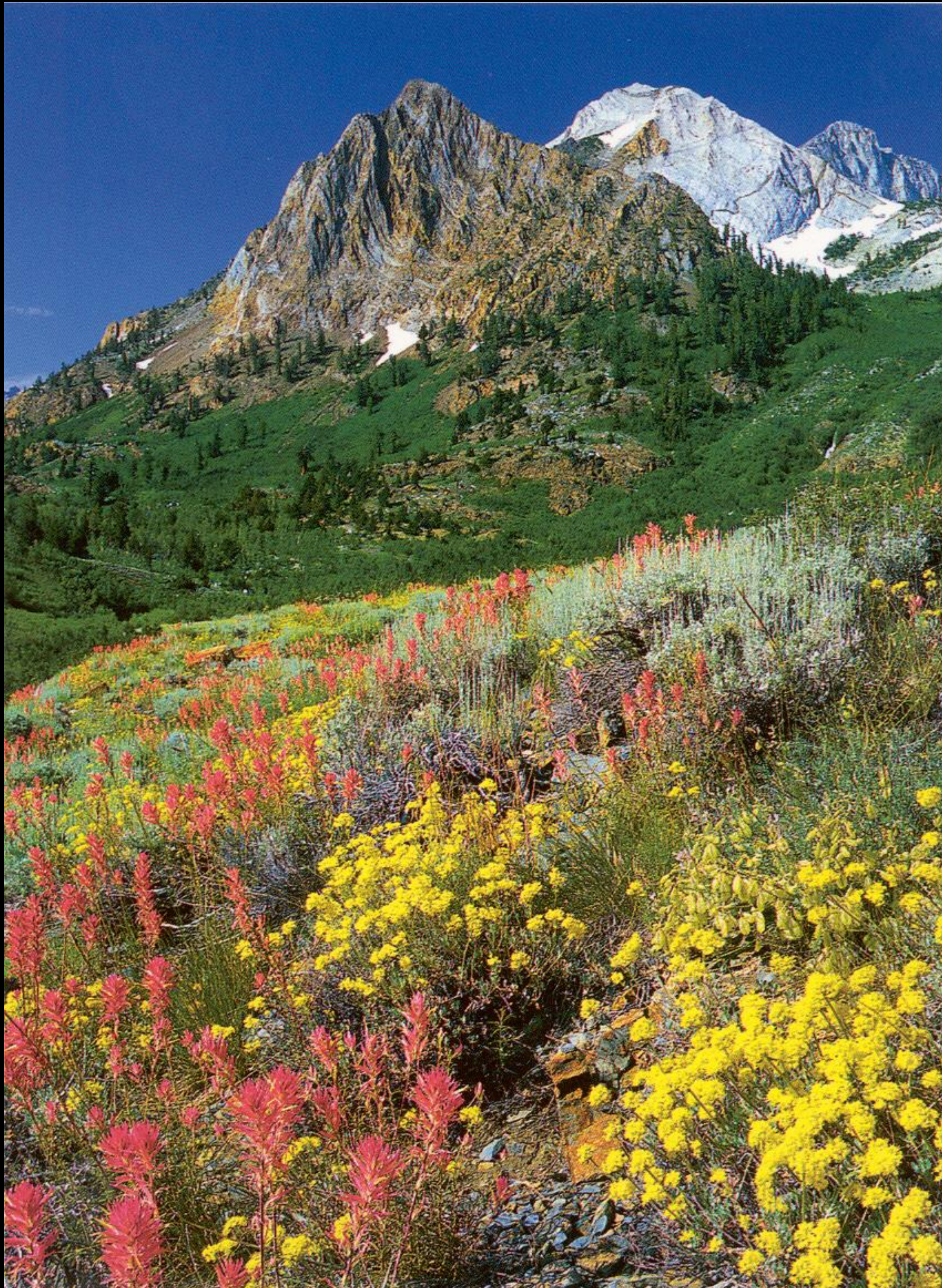
Aeroderivative Turbine

LM 6000 : 50 MW



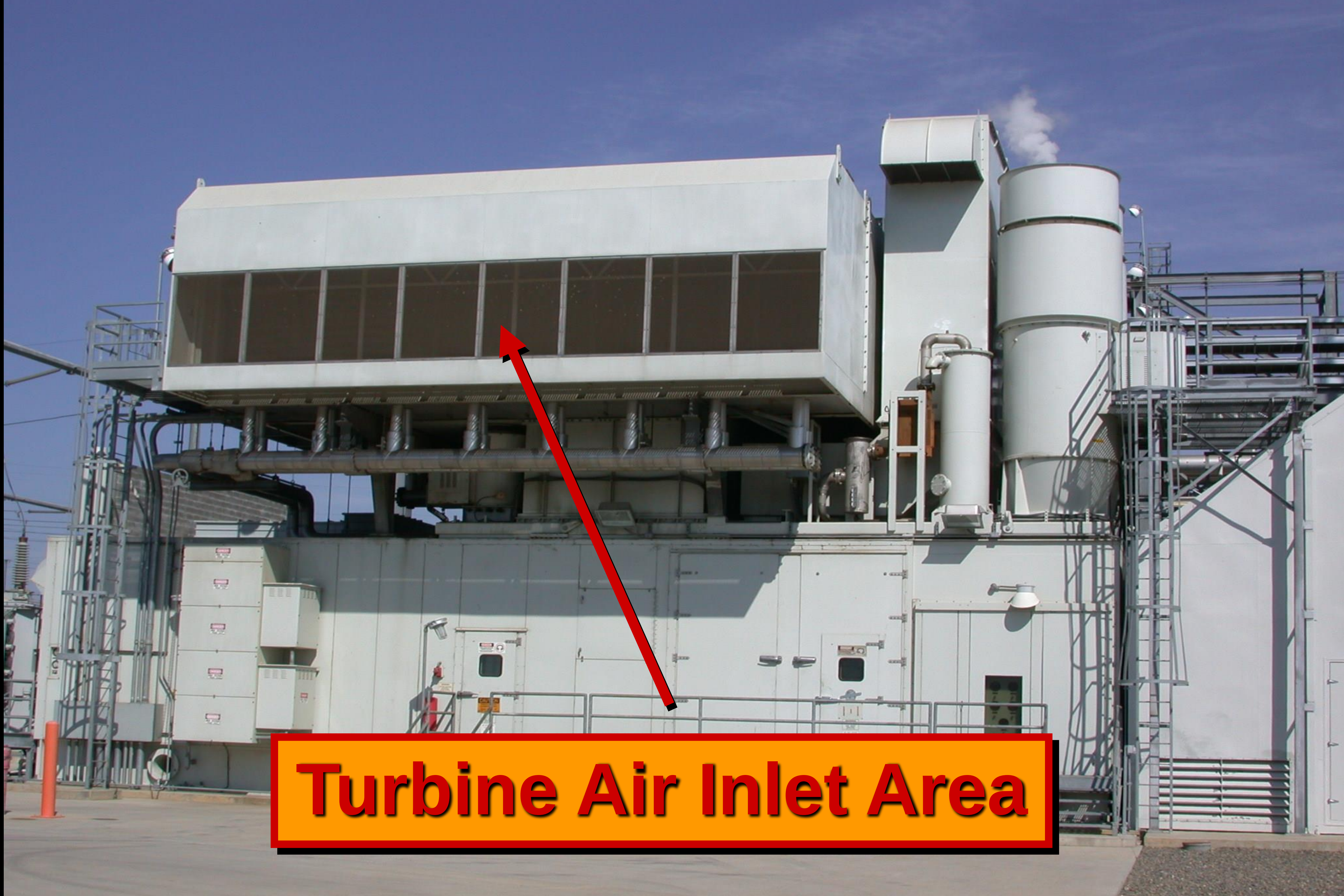
Important Terms

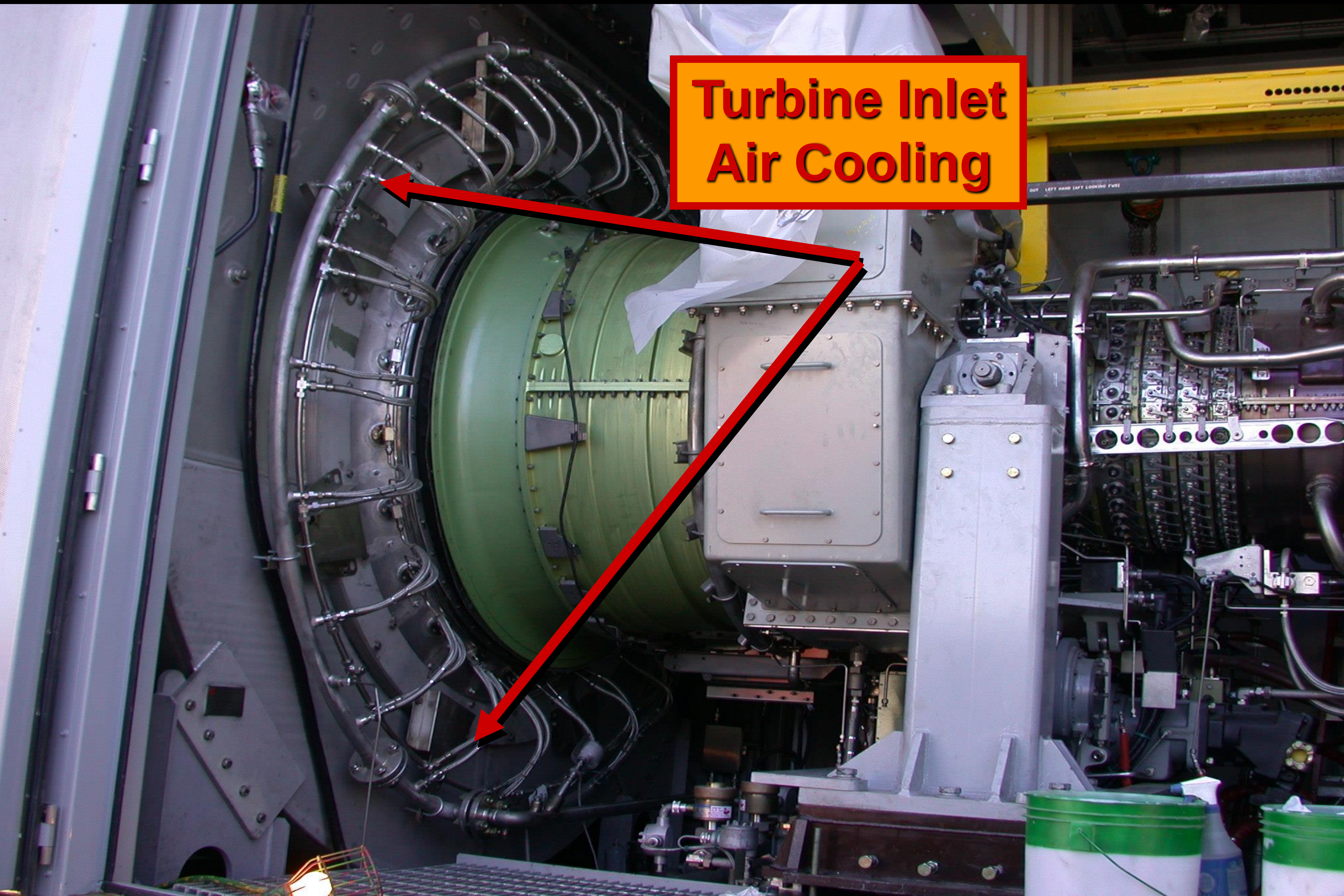
- Power
- Horsepower
- Shaft horsepower
- Megawatt
- Thrust
- Thermal efficiency

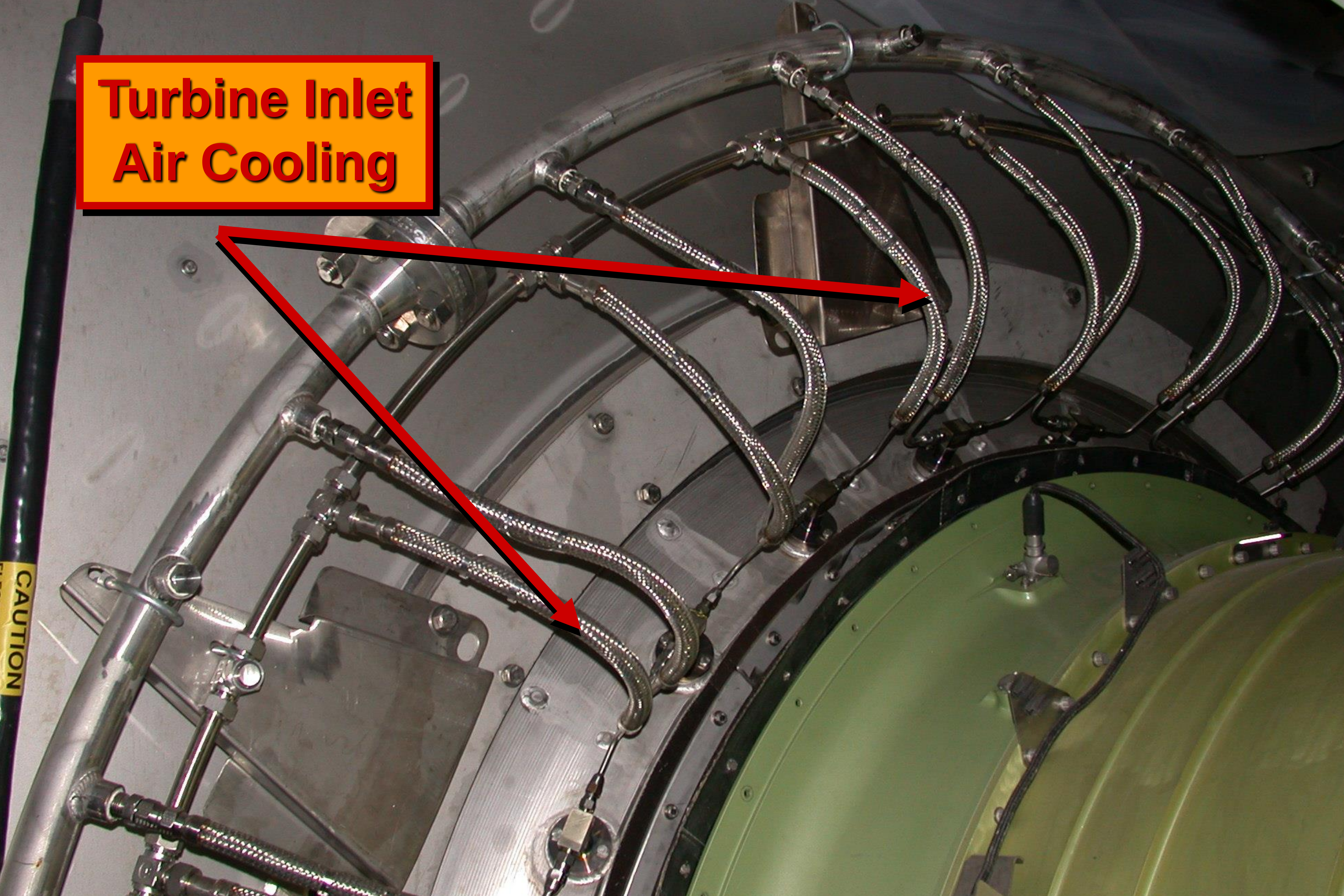


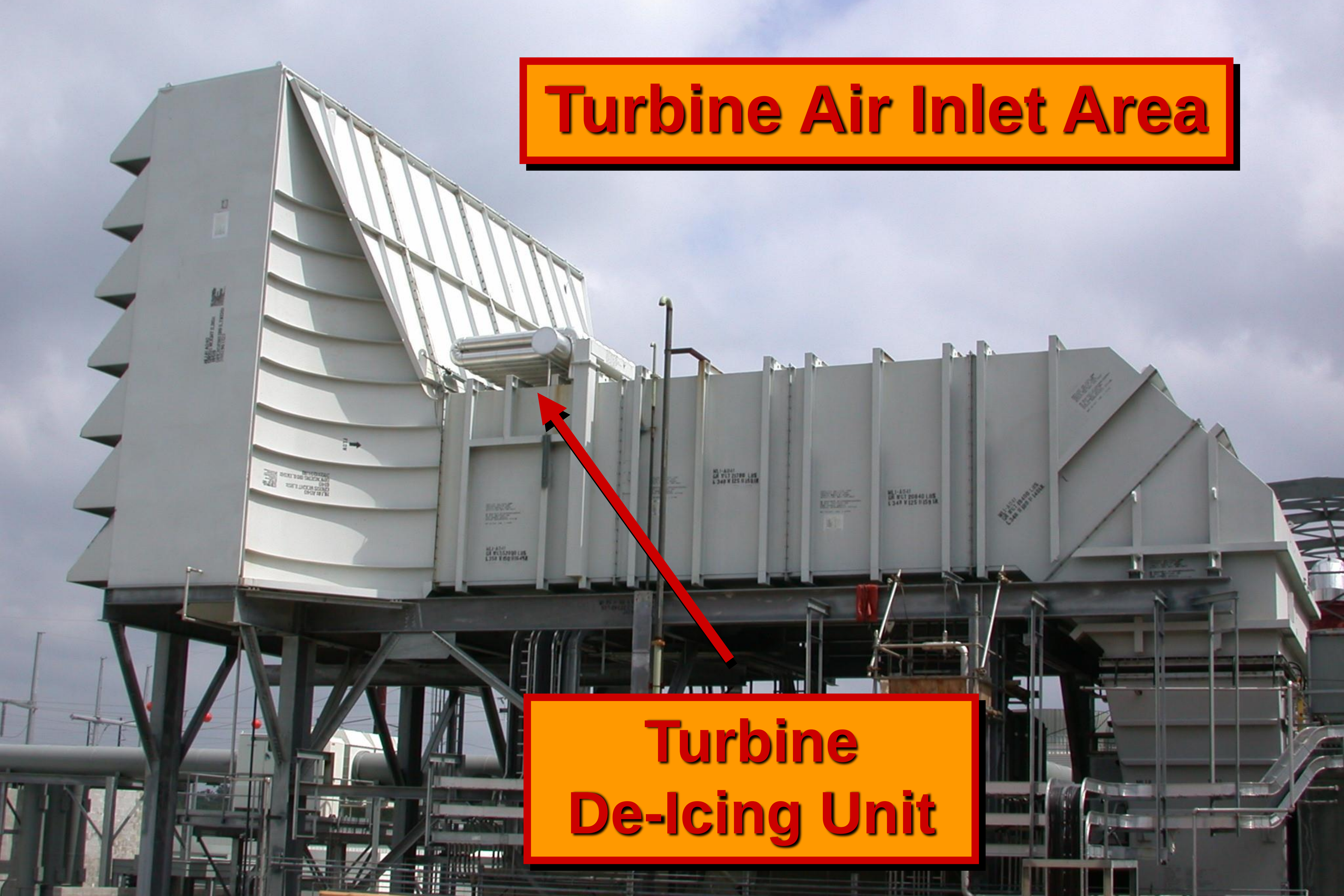
Gas Turbine Power Plant


Turbine
Inlet Air


Turbine Air Inlet Area

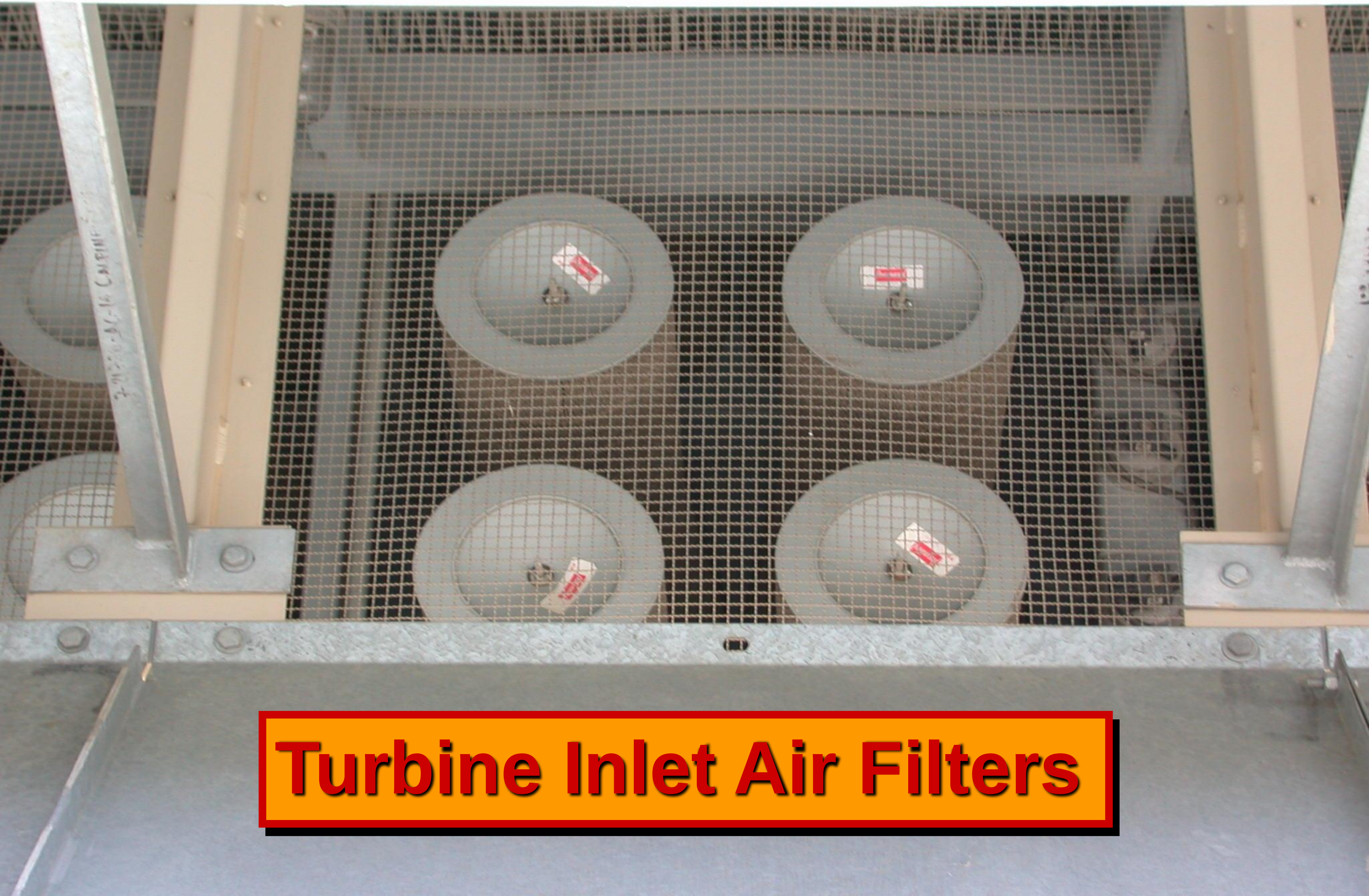

Turbine Inlet
Air Cooling


Turbine Inlet
Air Cooling
CAUTION

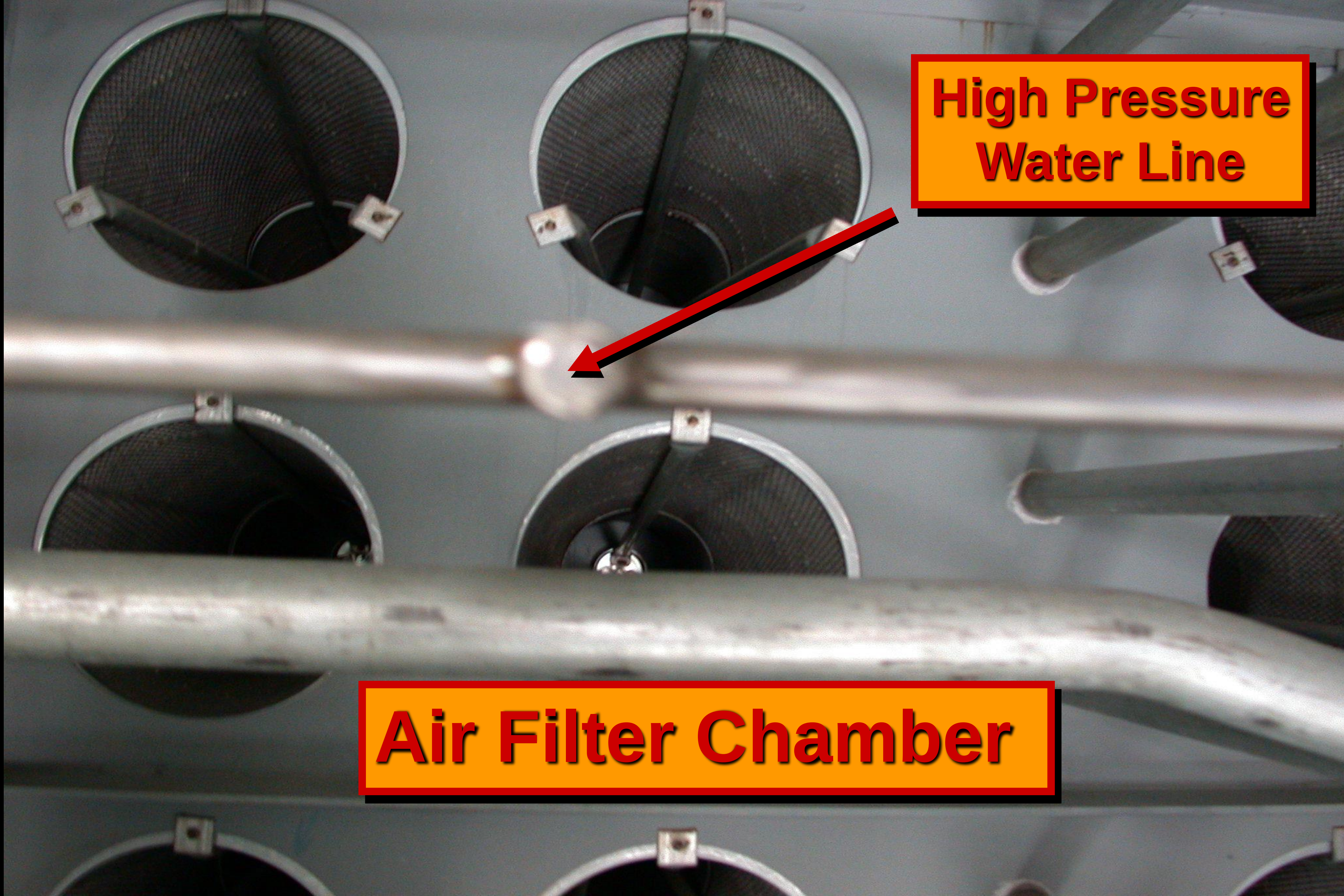

Turbine Air Inlet Area
Turbine
De-Icing Unit


Turbine Air Inlet


Turbine Inlet Air Filters

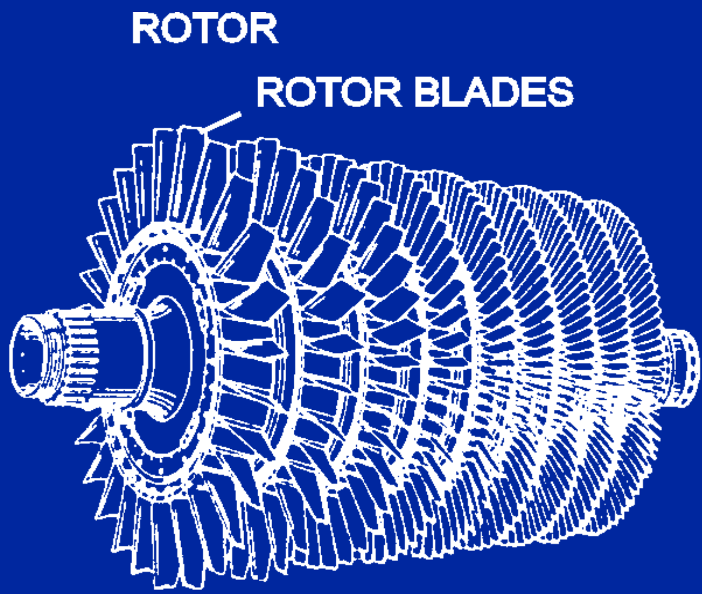


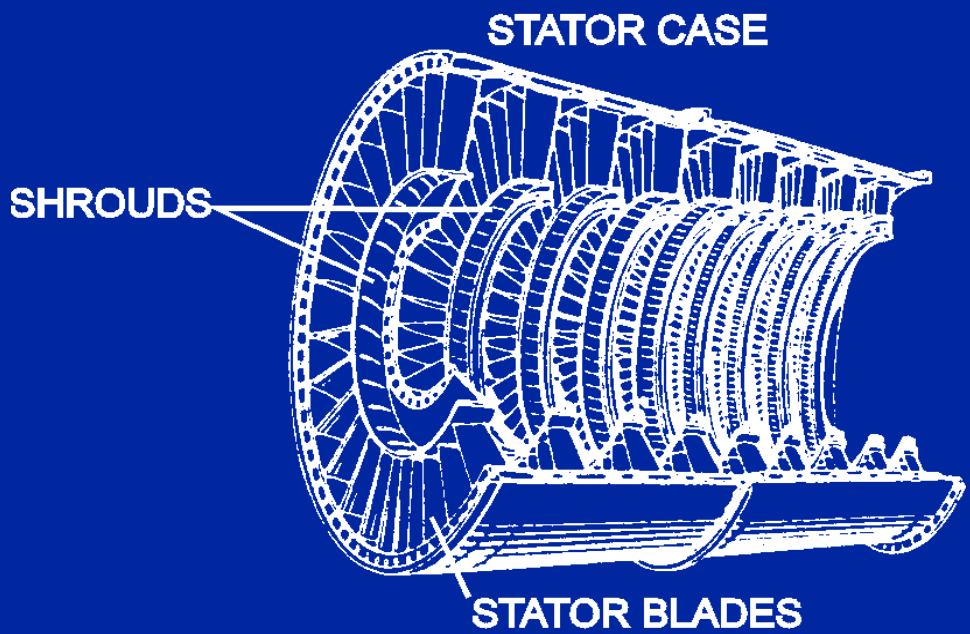
Turbine Inlet Air Filters

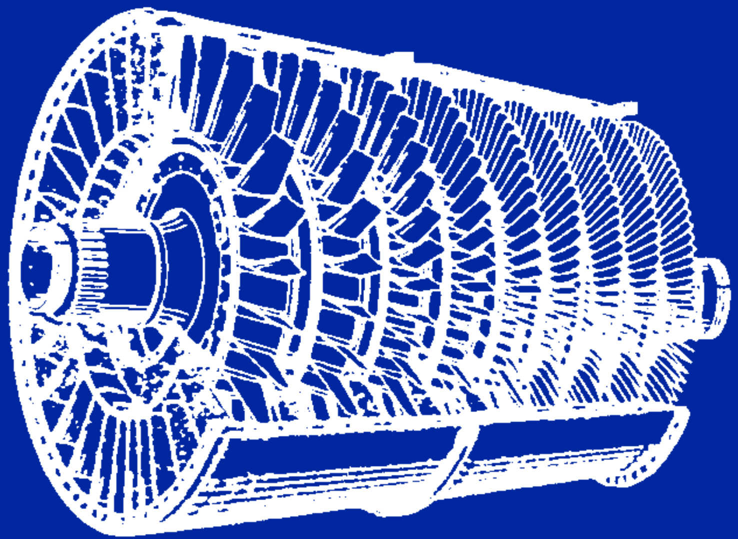

High Pressure Water Line
Air Filter Chamber

Compressor Section

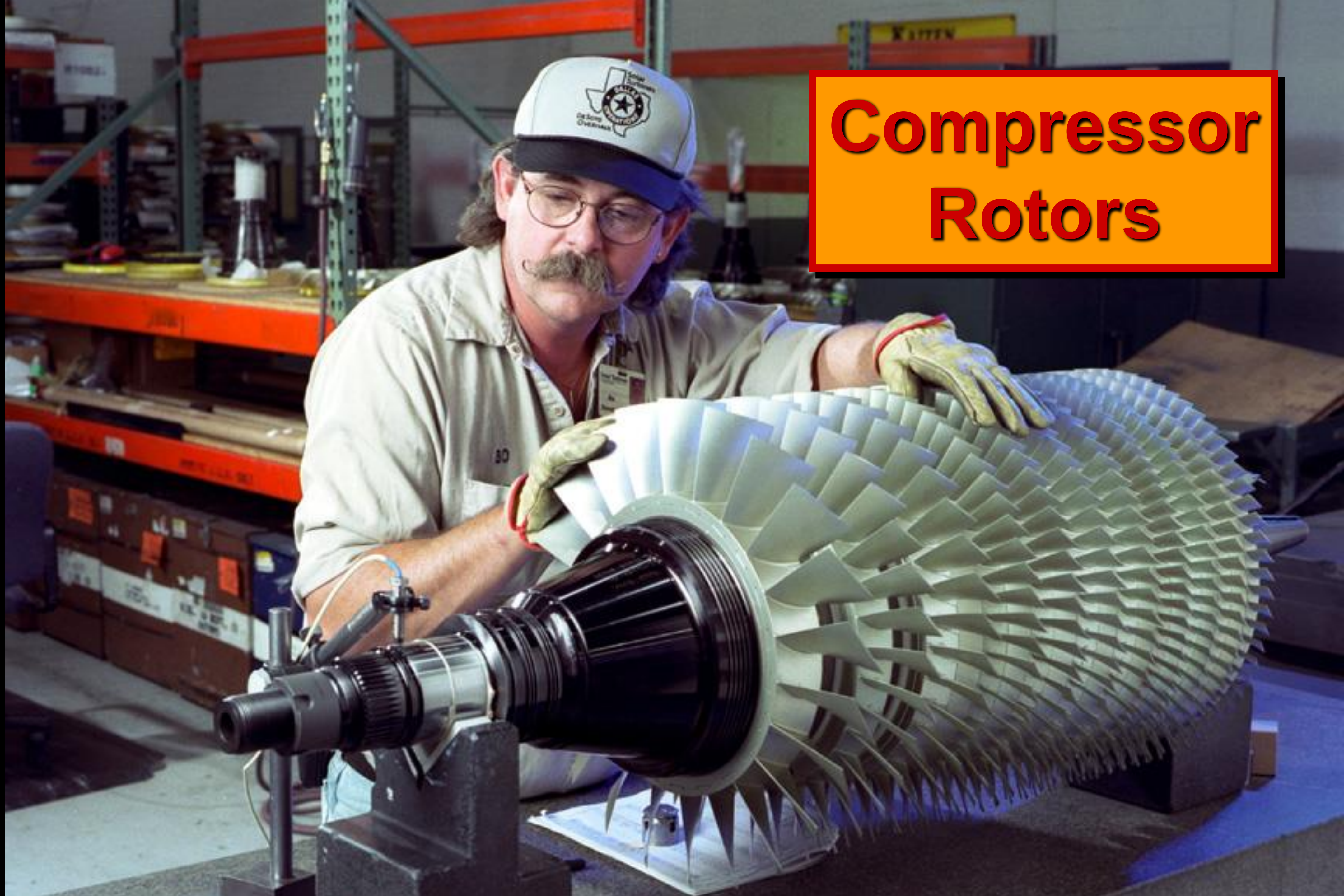
Axial Compressor



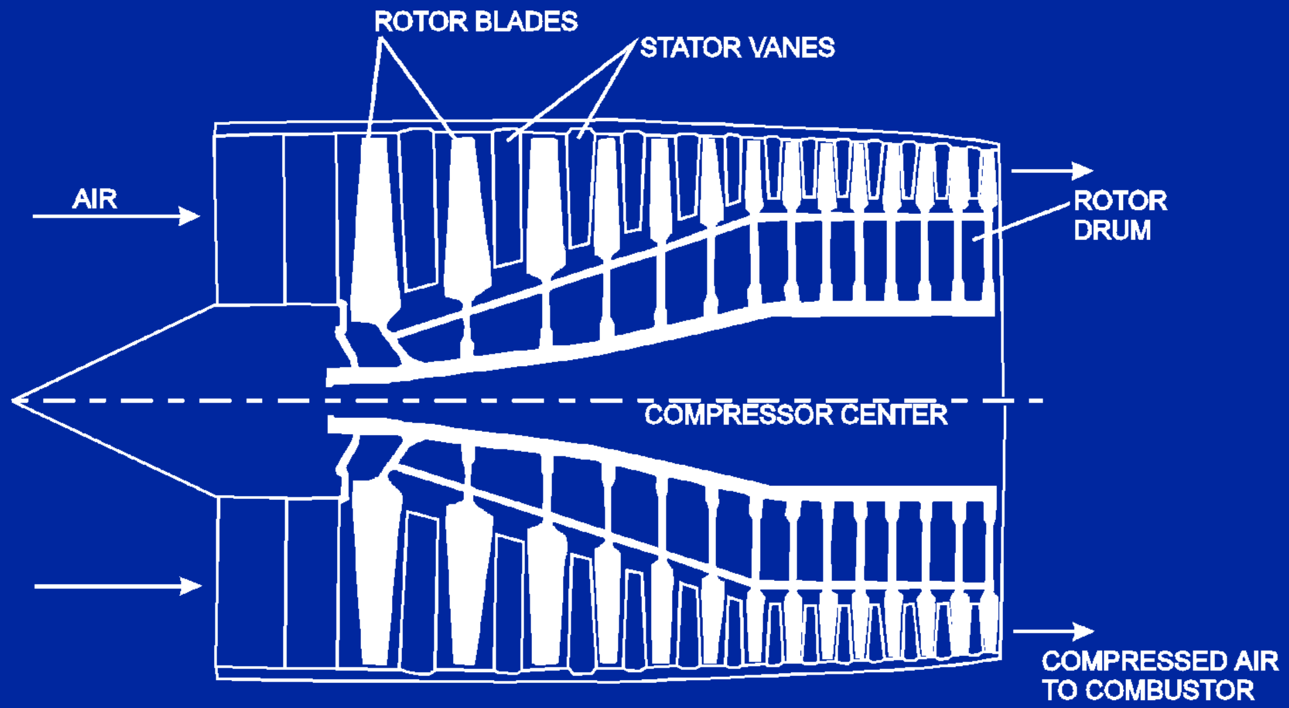


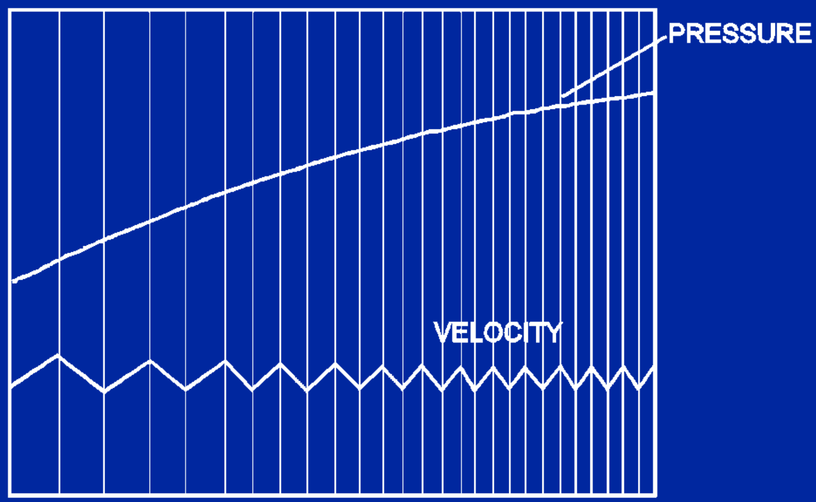


Graphic Courtesy of General Electric


Compressor
Rotors

Velocity & Pressure in an Axial Compressor

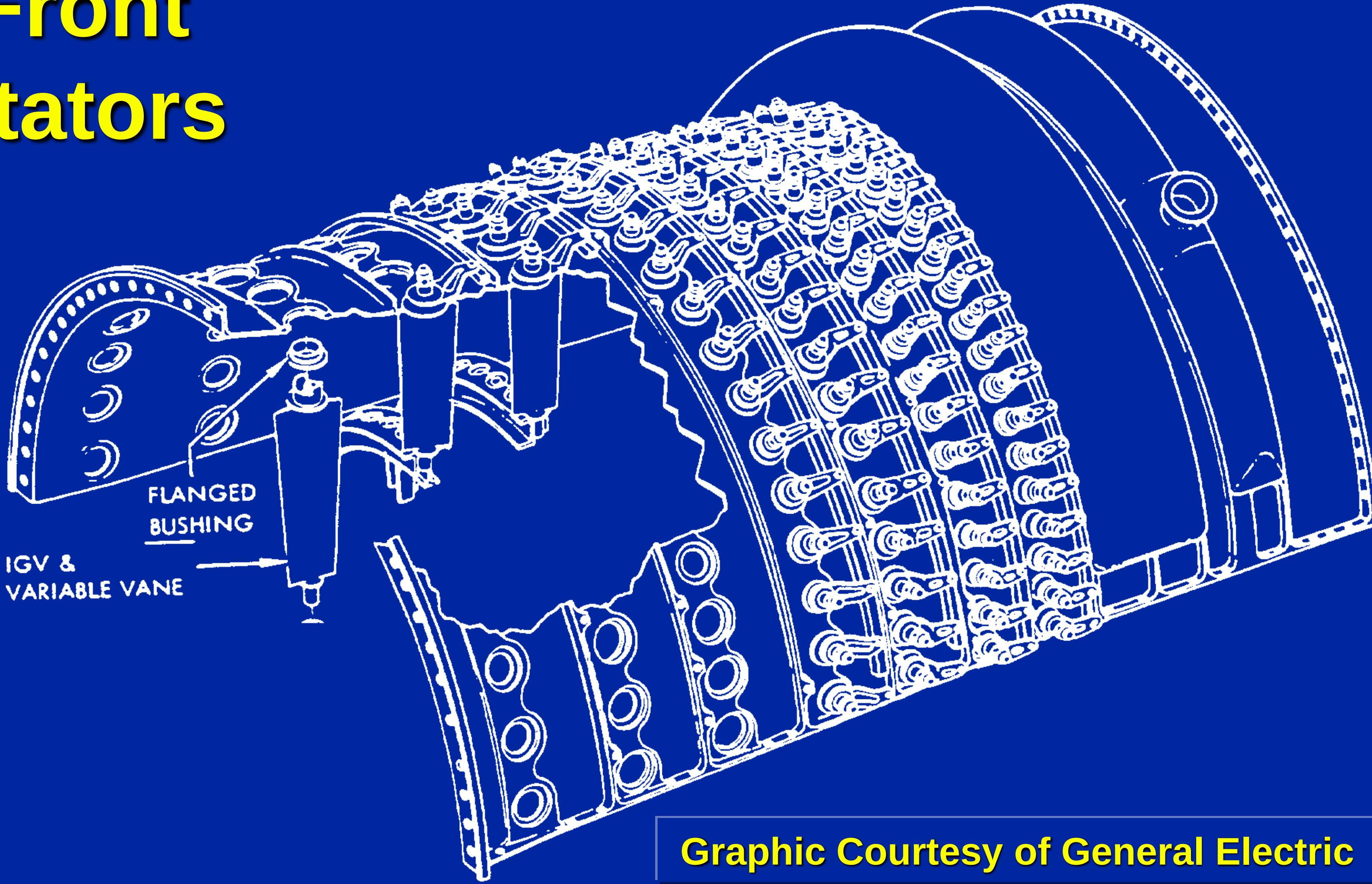




General Electric 9HA

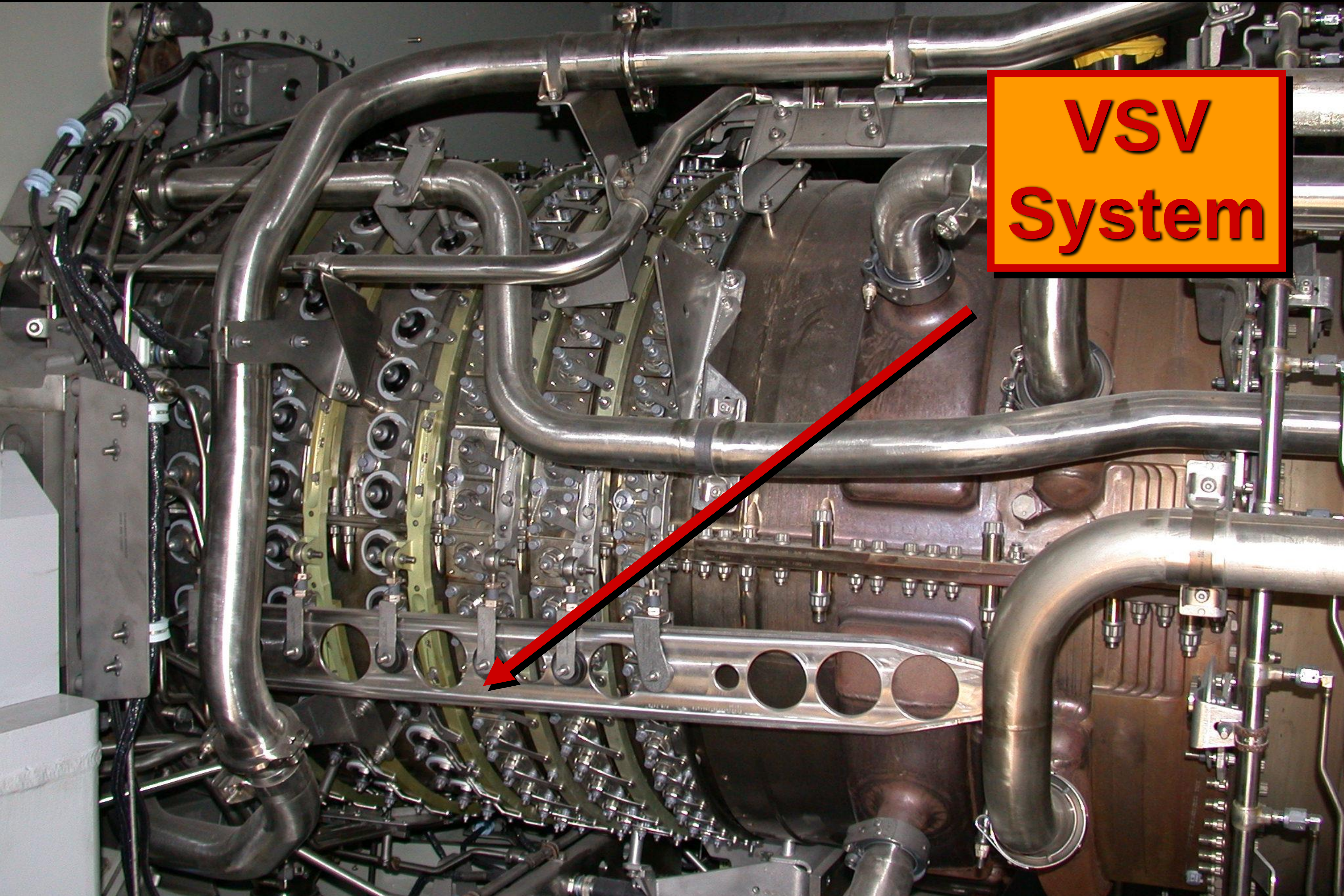
(397 MW – 532KHP)

Compressor Front Stators



Graphic Courtesy of General Electric

Front Stators


VSV
System

Combustor Section

Can Combustor

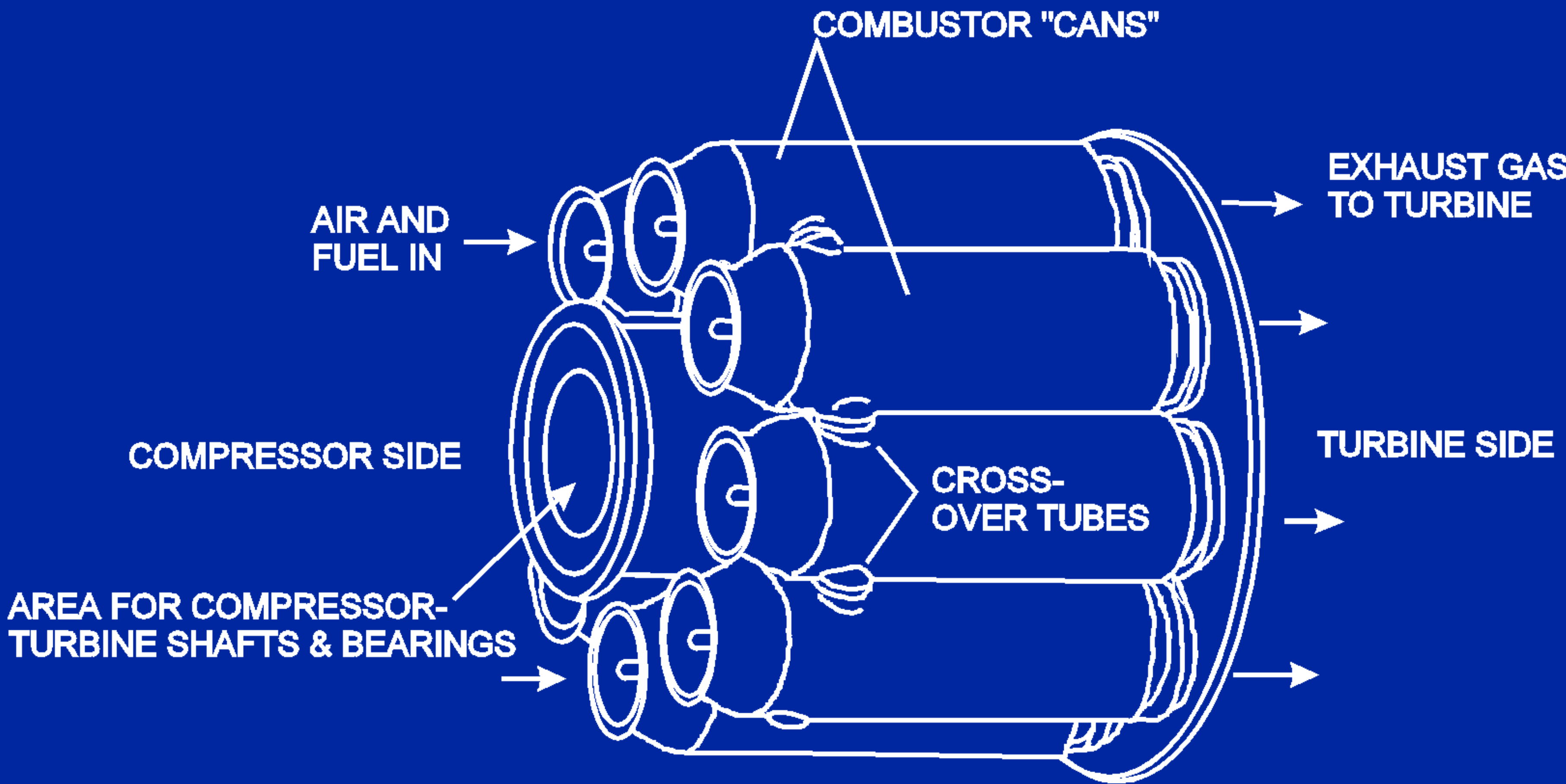
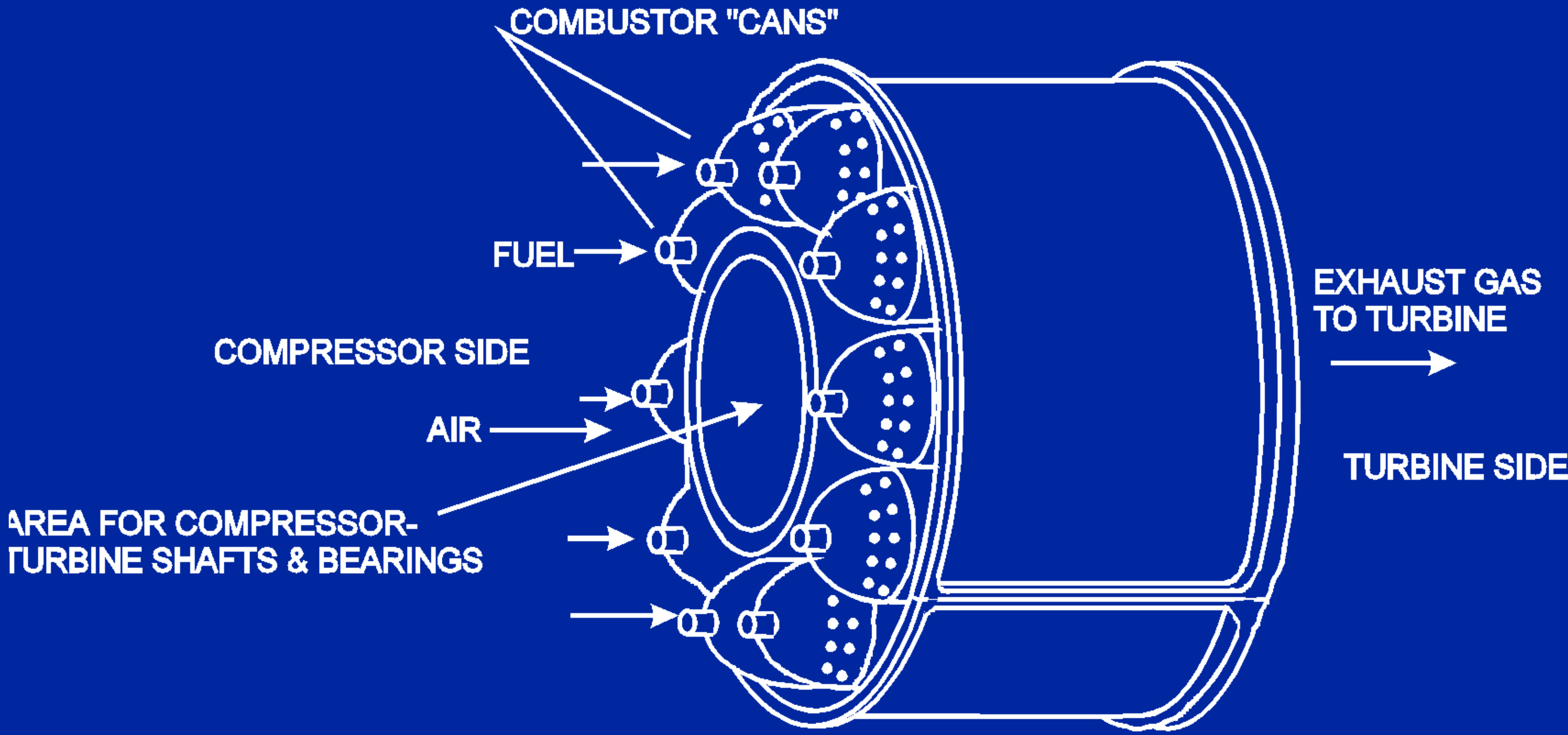


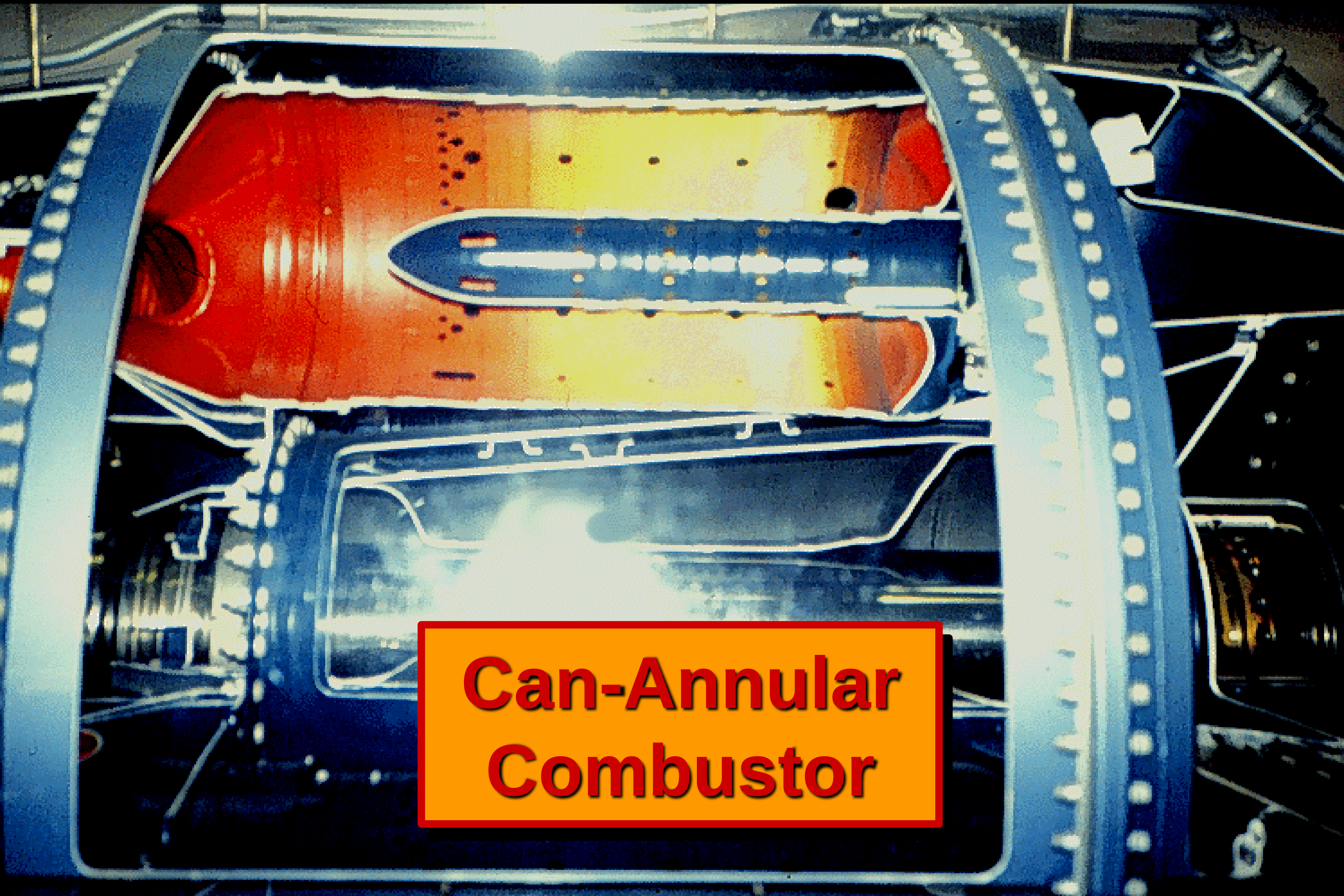
Figure 206.9


External
Can
Combustors
& Cross-
Over Tubes

Can Combustors & Thermocouple

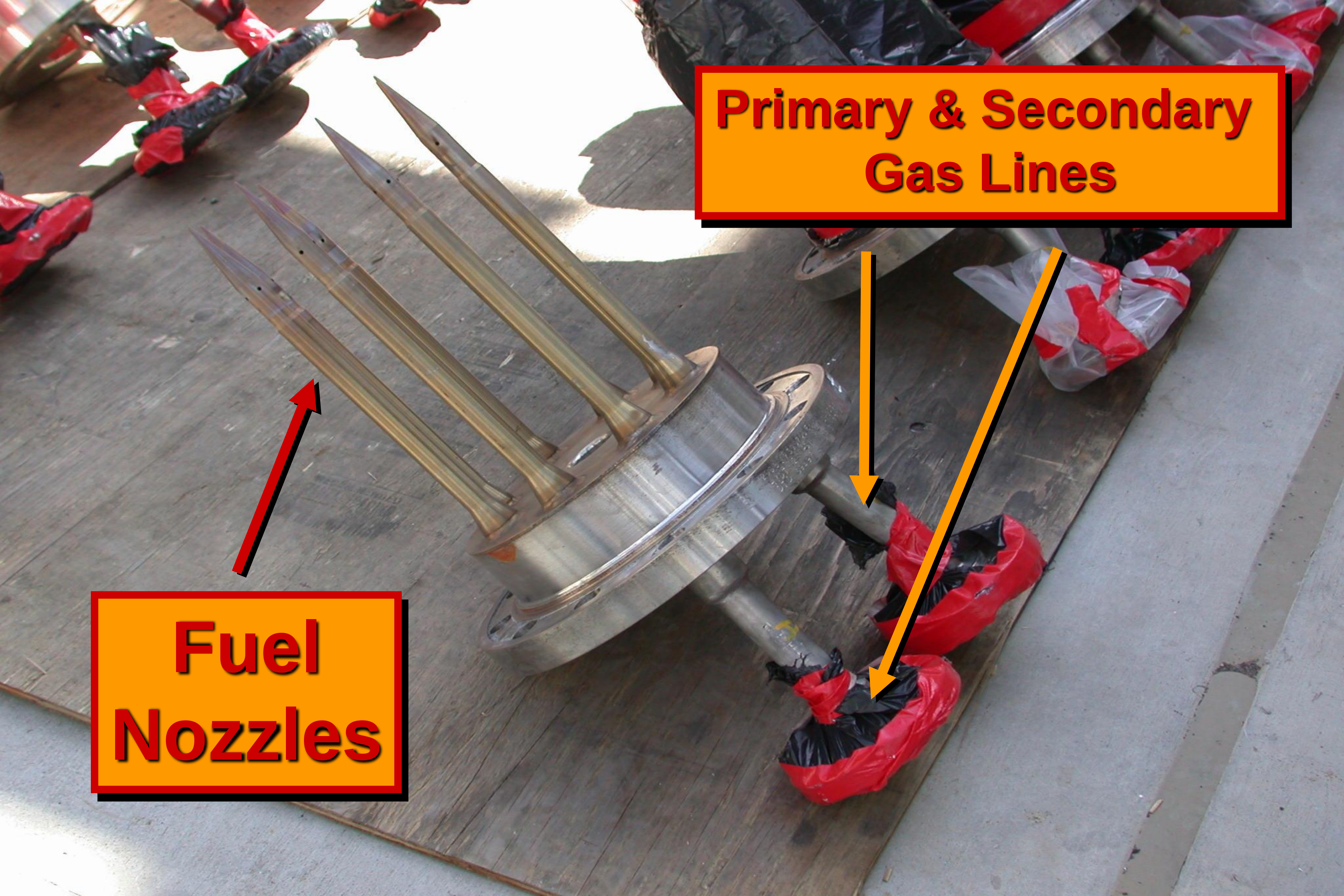
Can-Annular Combustor

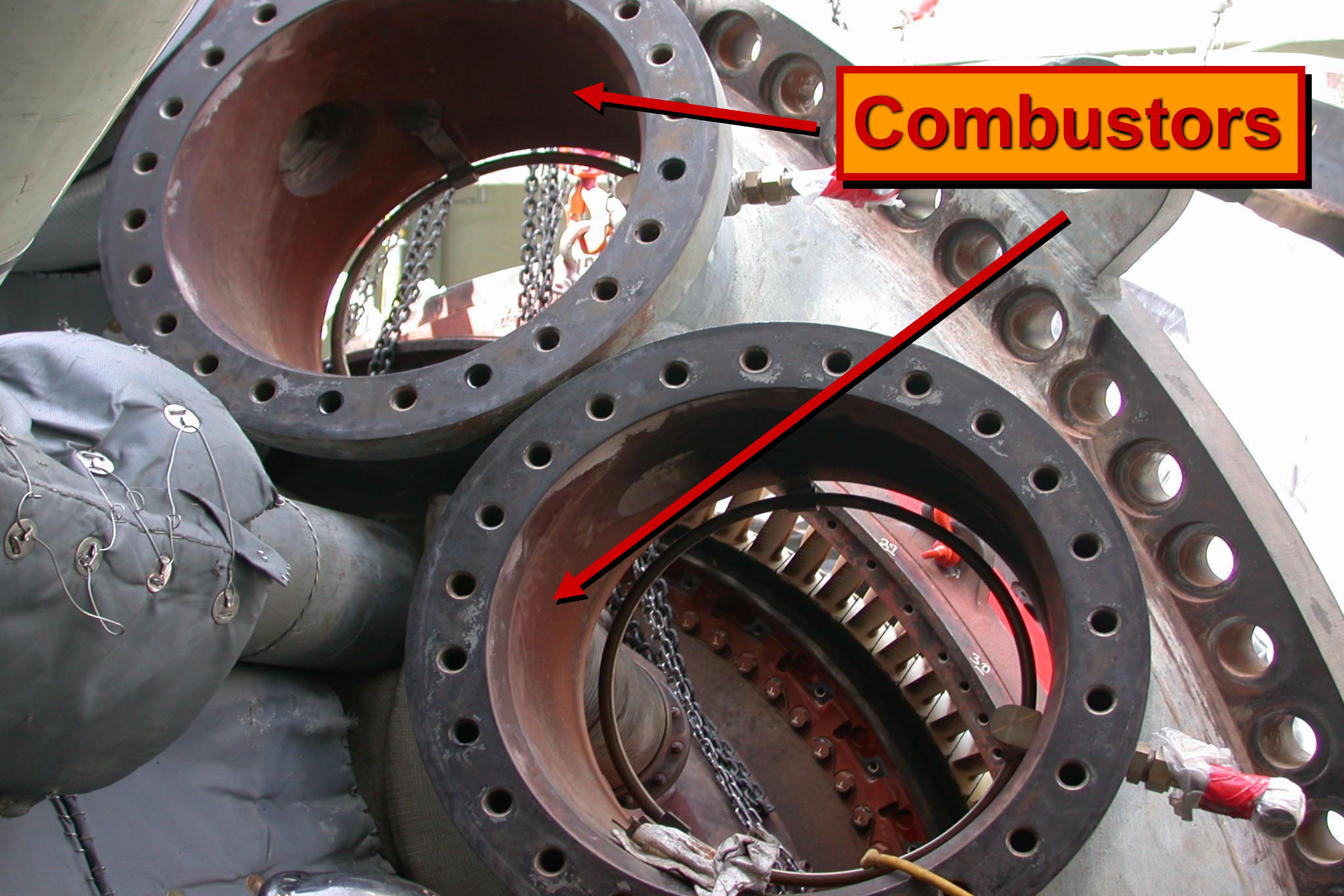


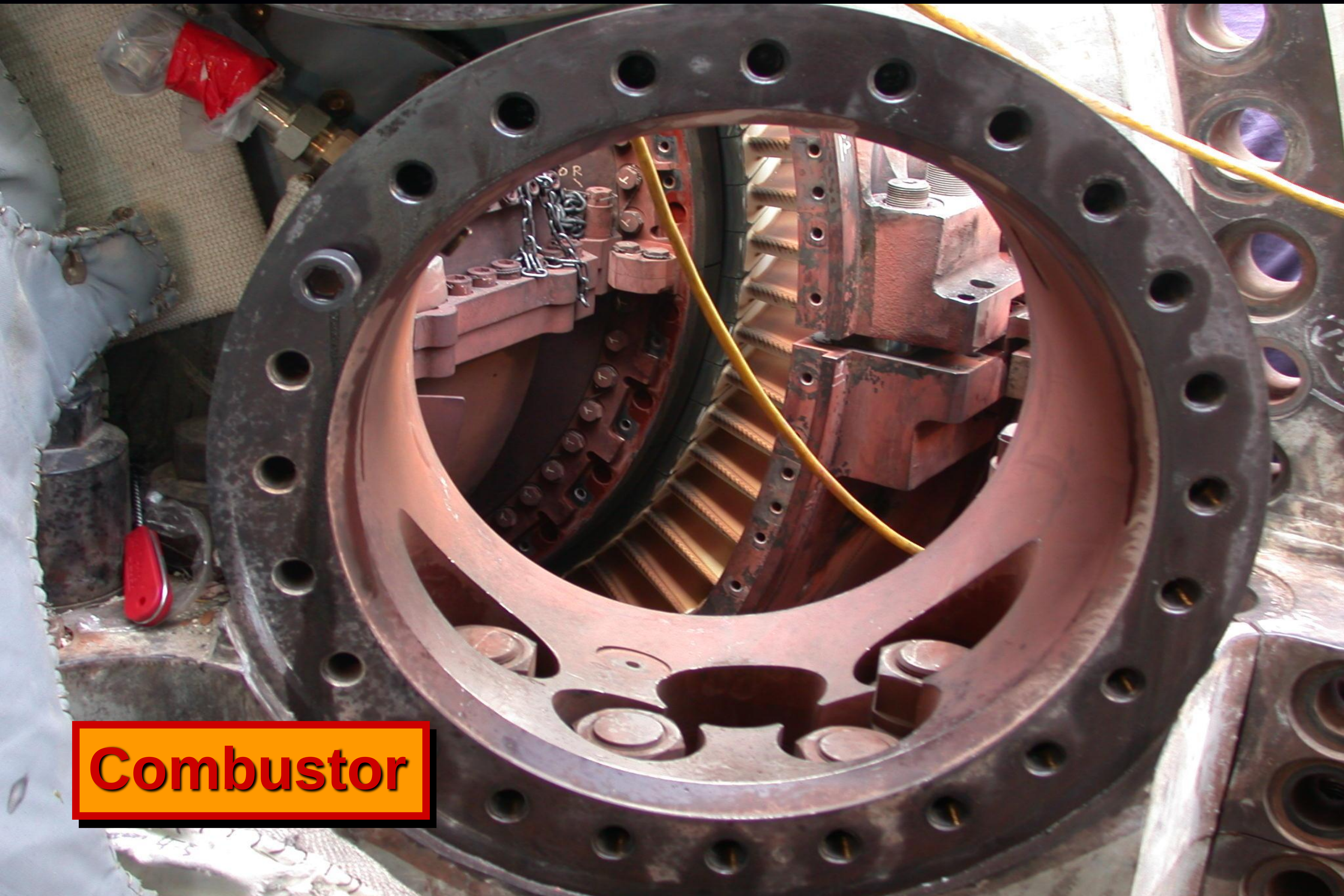

Can-Annular
Combustor

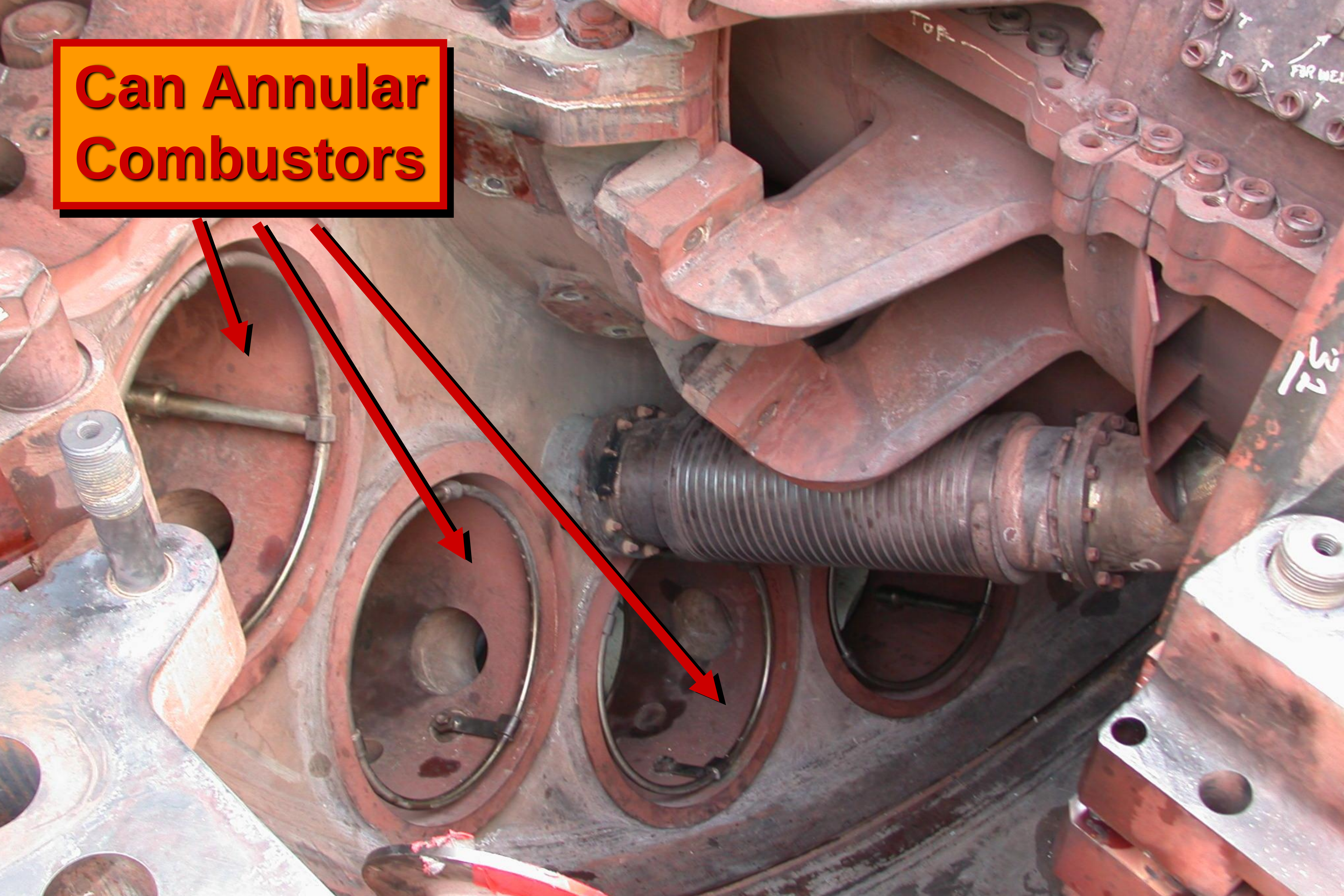

Can-Annular Lean
Premix Burner

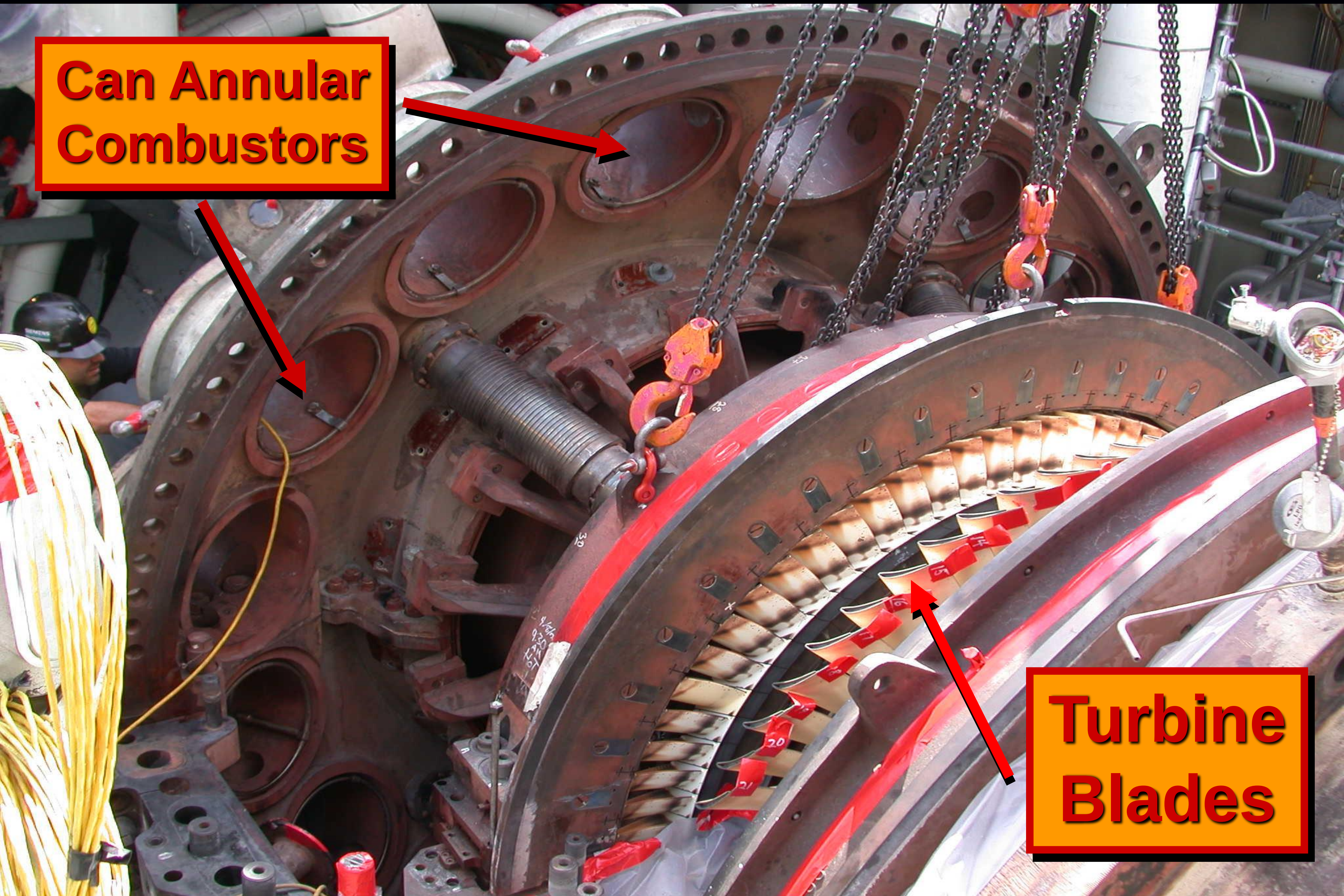
Fuel Nozzles

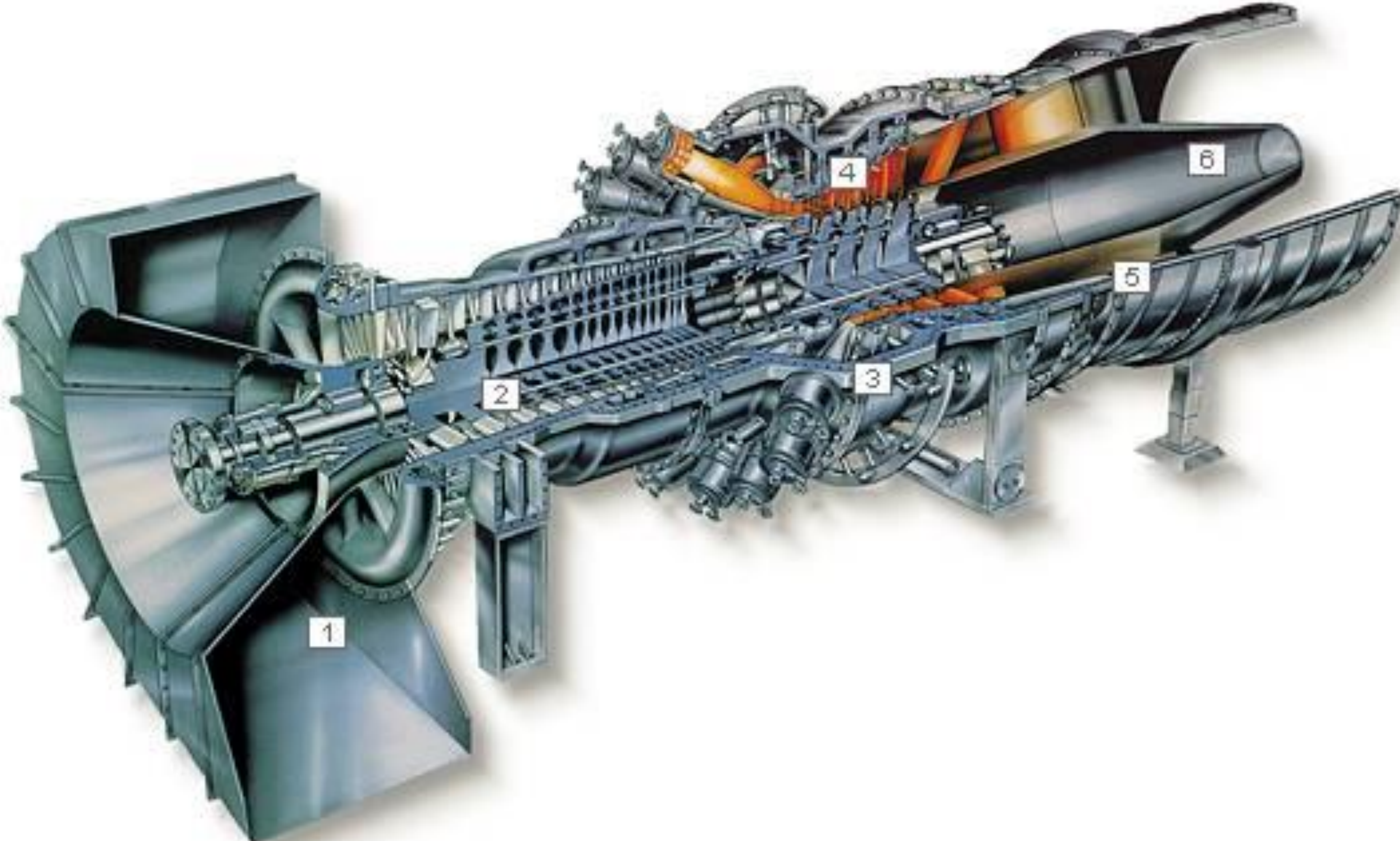

Primary & Secondary Gas Lines
Fuel Nozzles


Combustors


Combustor


Can Annular
Combustors

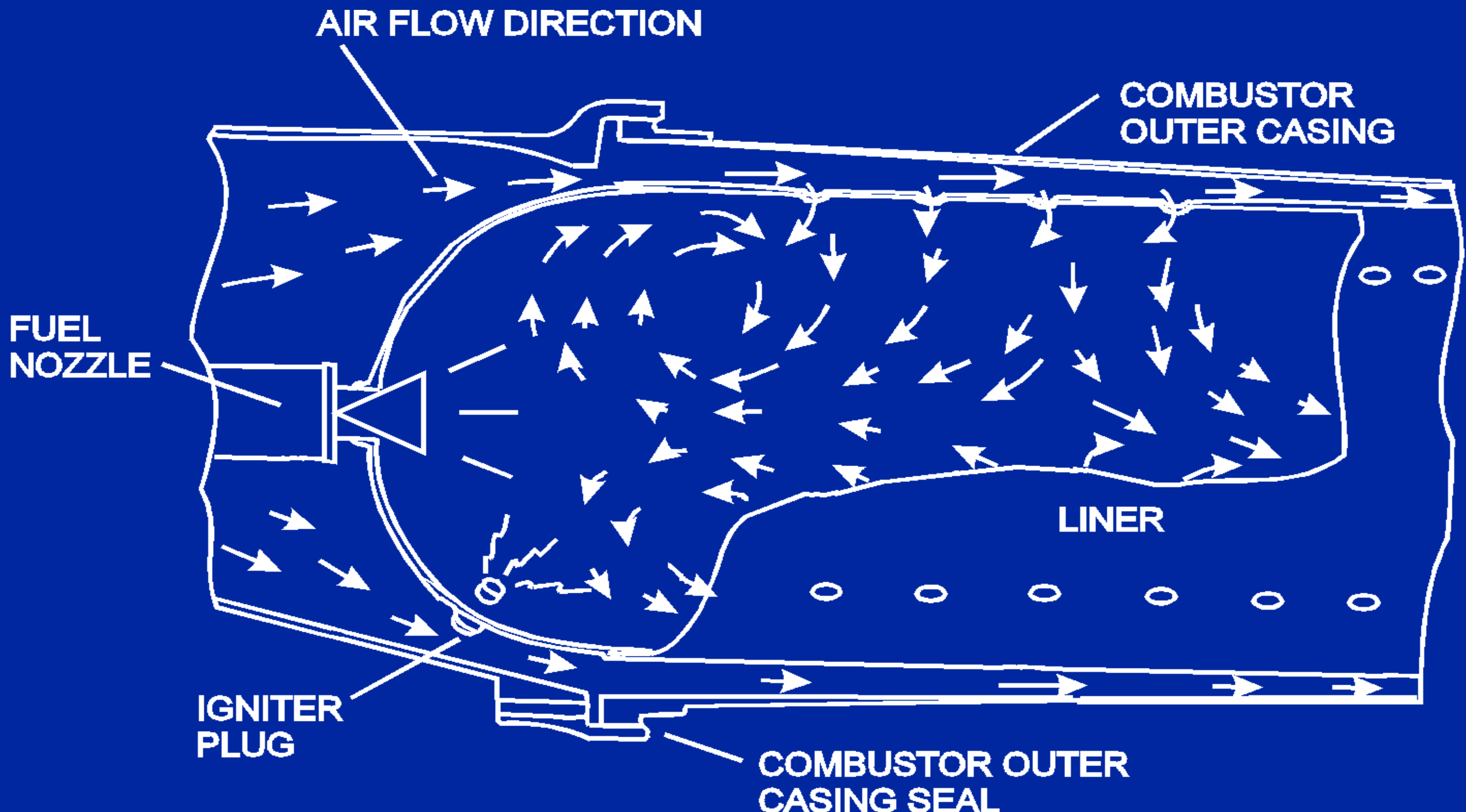

Can Annular Combustors
Turbine Blades

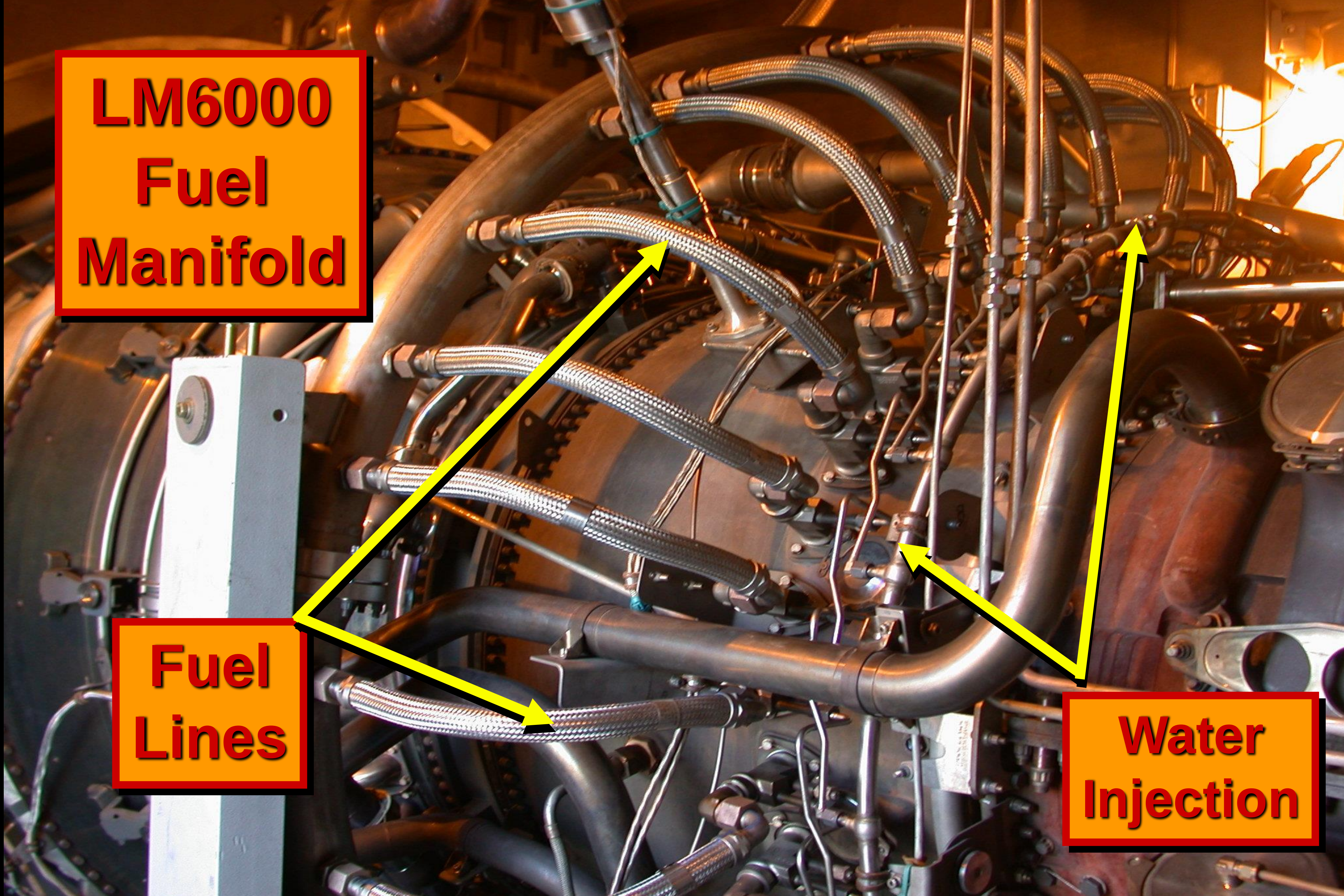


1
2
3
4
5
6

Let’s Discuss Gas Turbine Air & Gas Flows

Combustor Liner and Air Flow

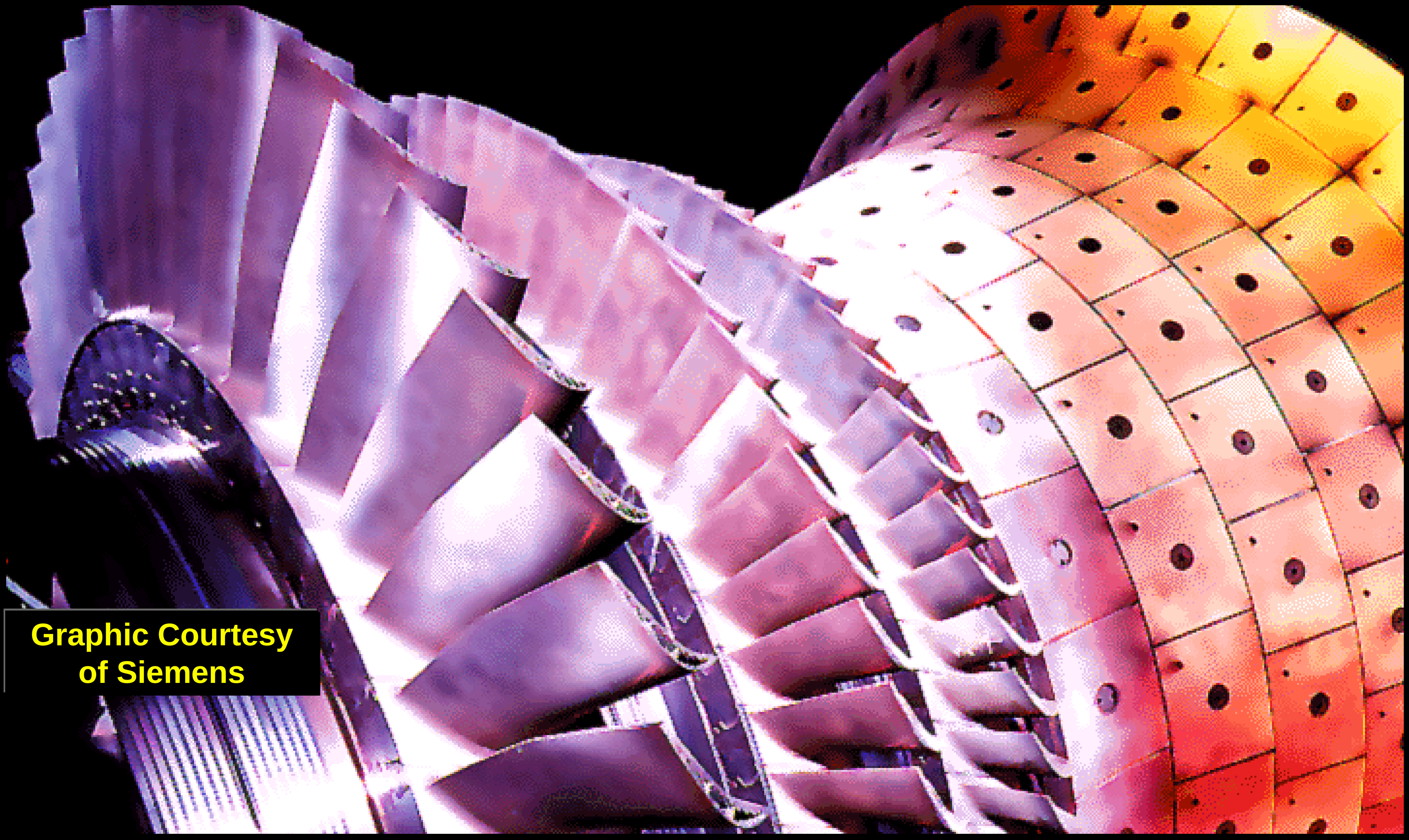



LM6000 Fuel Manifold
Fuel Lines
Water Injection

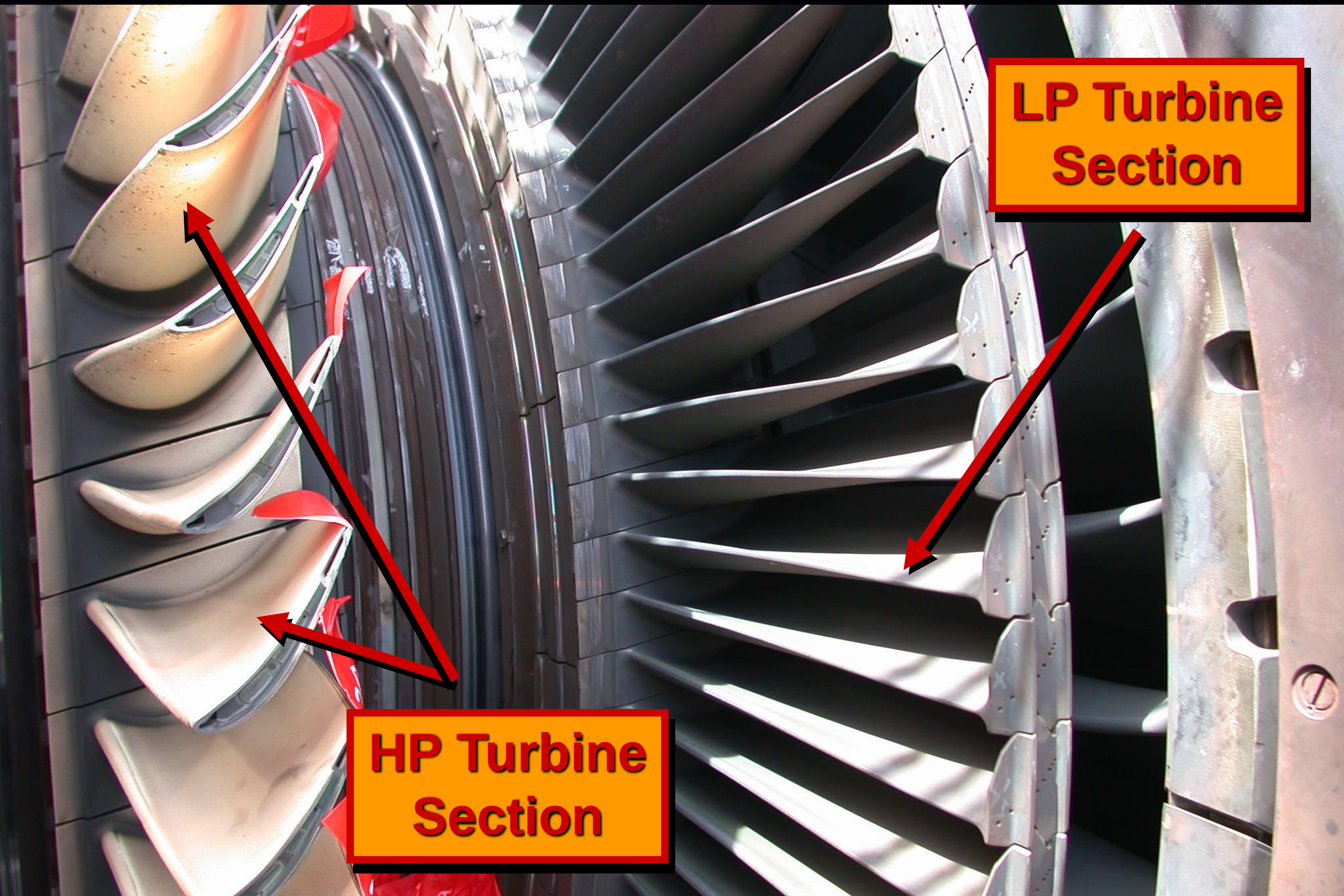

Fuel
Manifold
C
A
B


Let's Discuss Turbine Sections

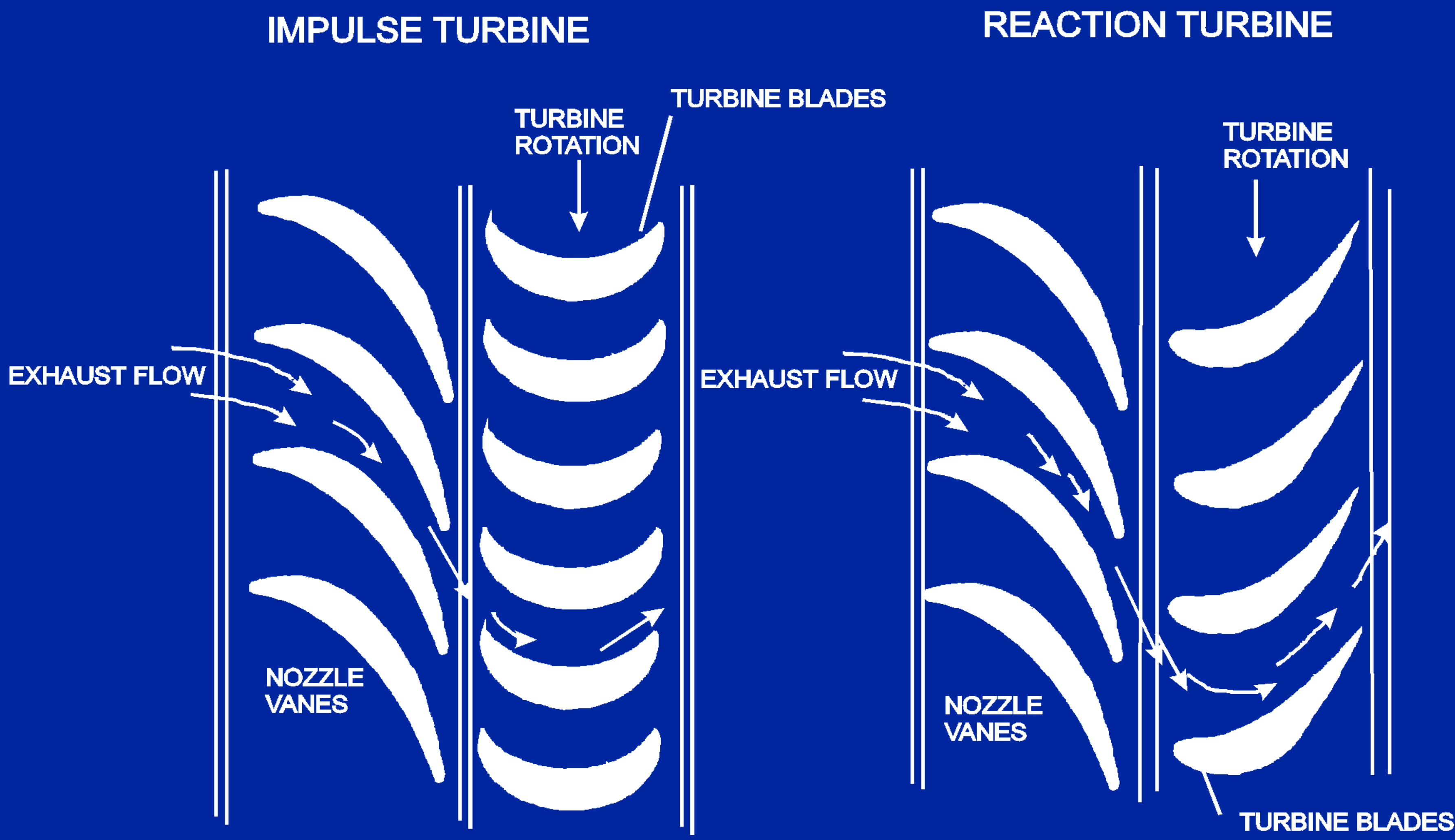
Siemens Hybrid Combustor & Turbine Blades

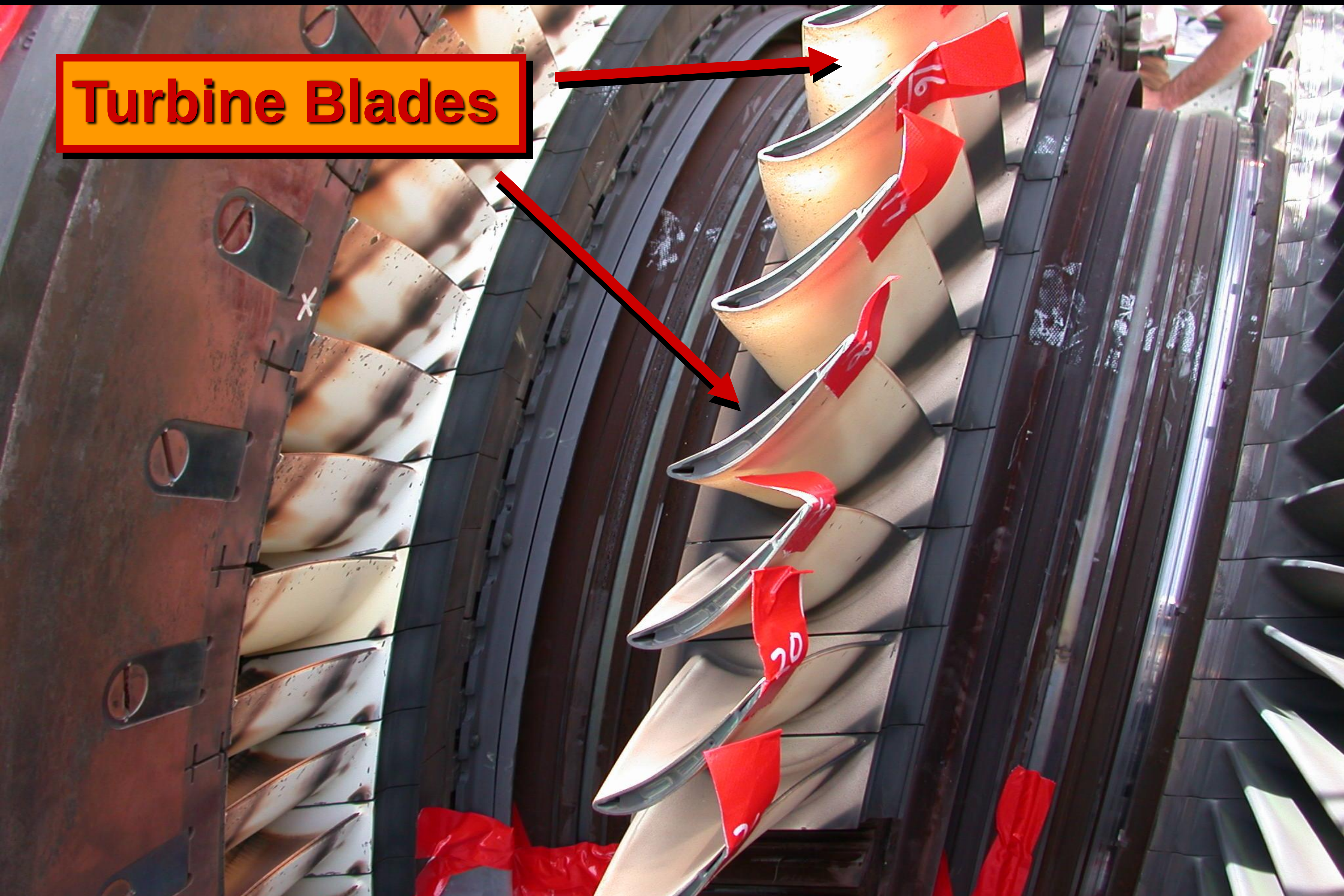


Graphic Courtesy of Siemens


LP Turbine Section
HP Turbine Section

Turbine Blades




Turbine Blades
16
17
20


Turbine
Discs

Turbine Blades


Turbine Disc


Let’s Discuss Turbine Air Cooling


Inlet Air Cooling


Turbine Lube
Oil System

Lube Oil Pump


Lube Oil Pump
to Turbine

Lube Oil Air Cooling

Air-Oil Separator Exhaust

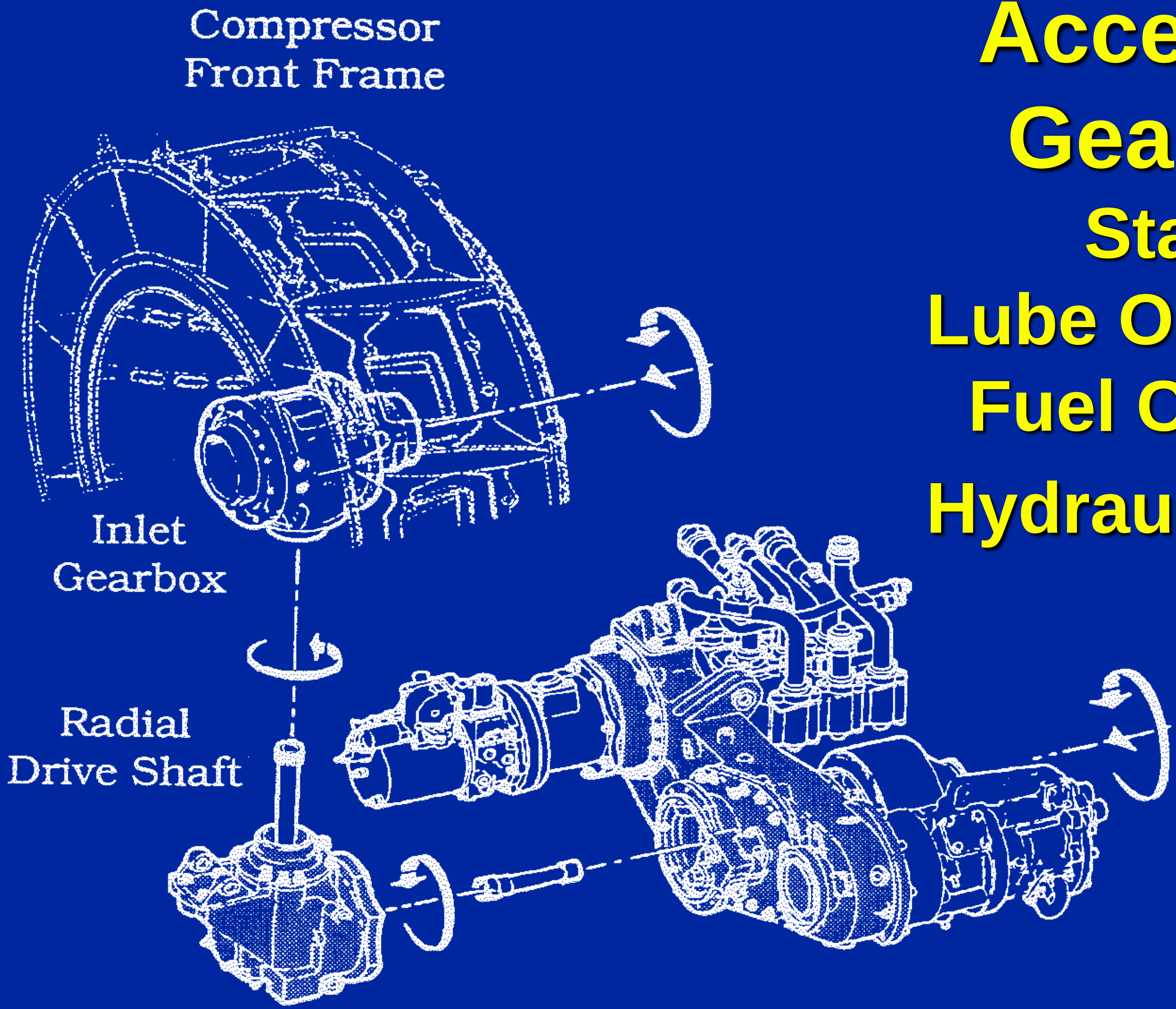
Accessory Gearbox:

Starter

Lube Oil Pumps

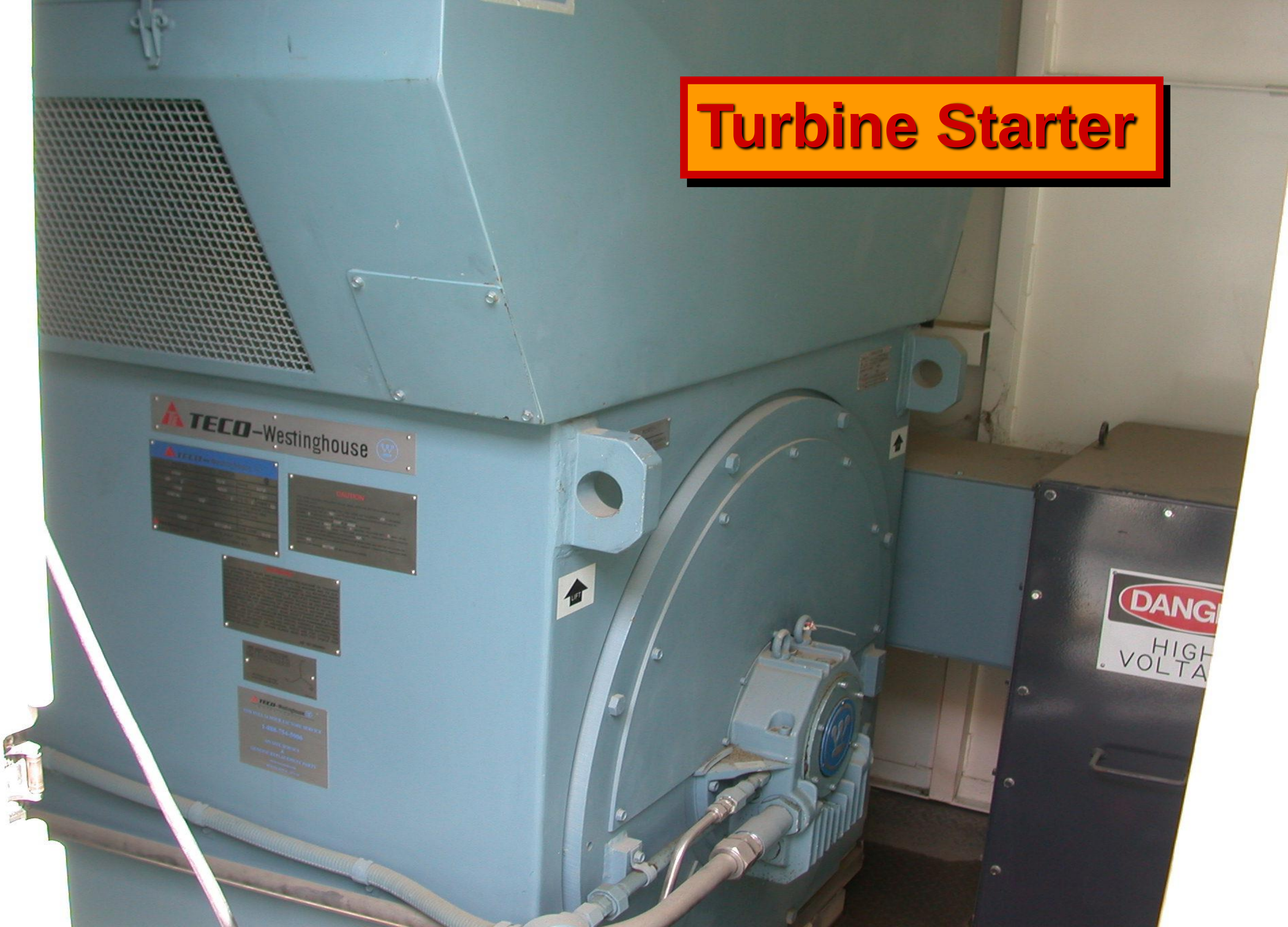
Fuel Controls

Hydraulic Pump



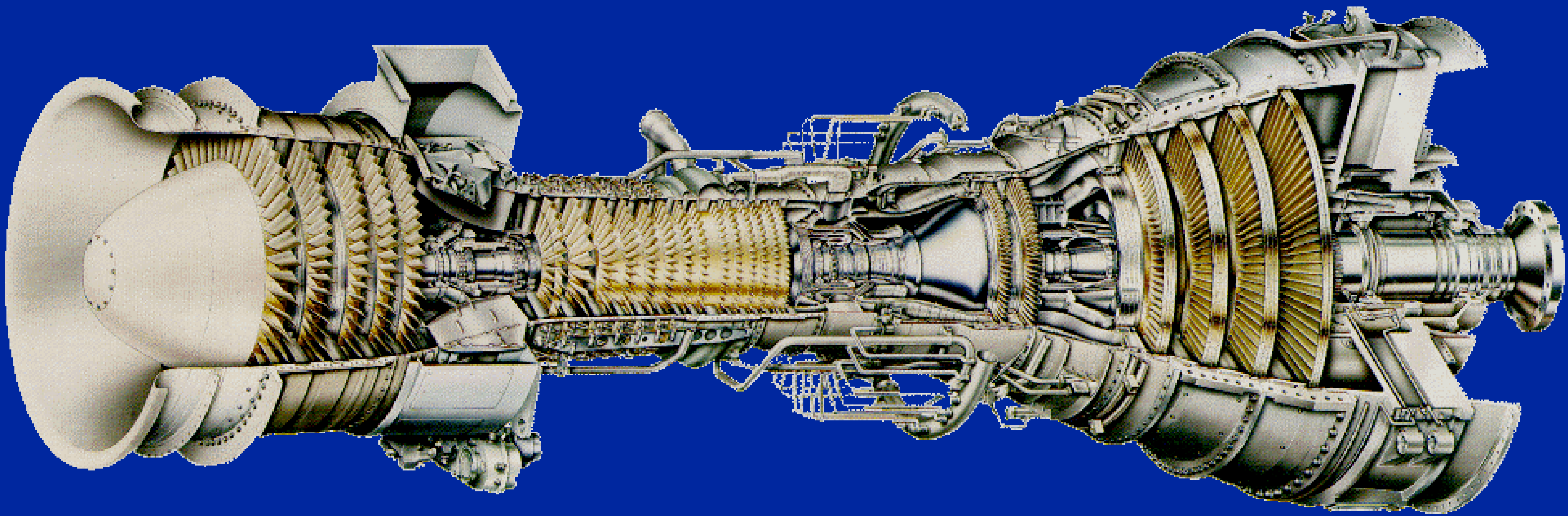

Gear Box

Turbine Starter



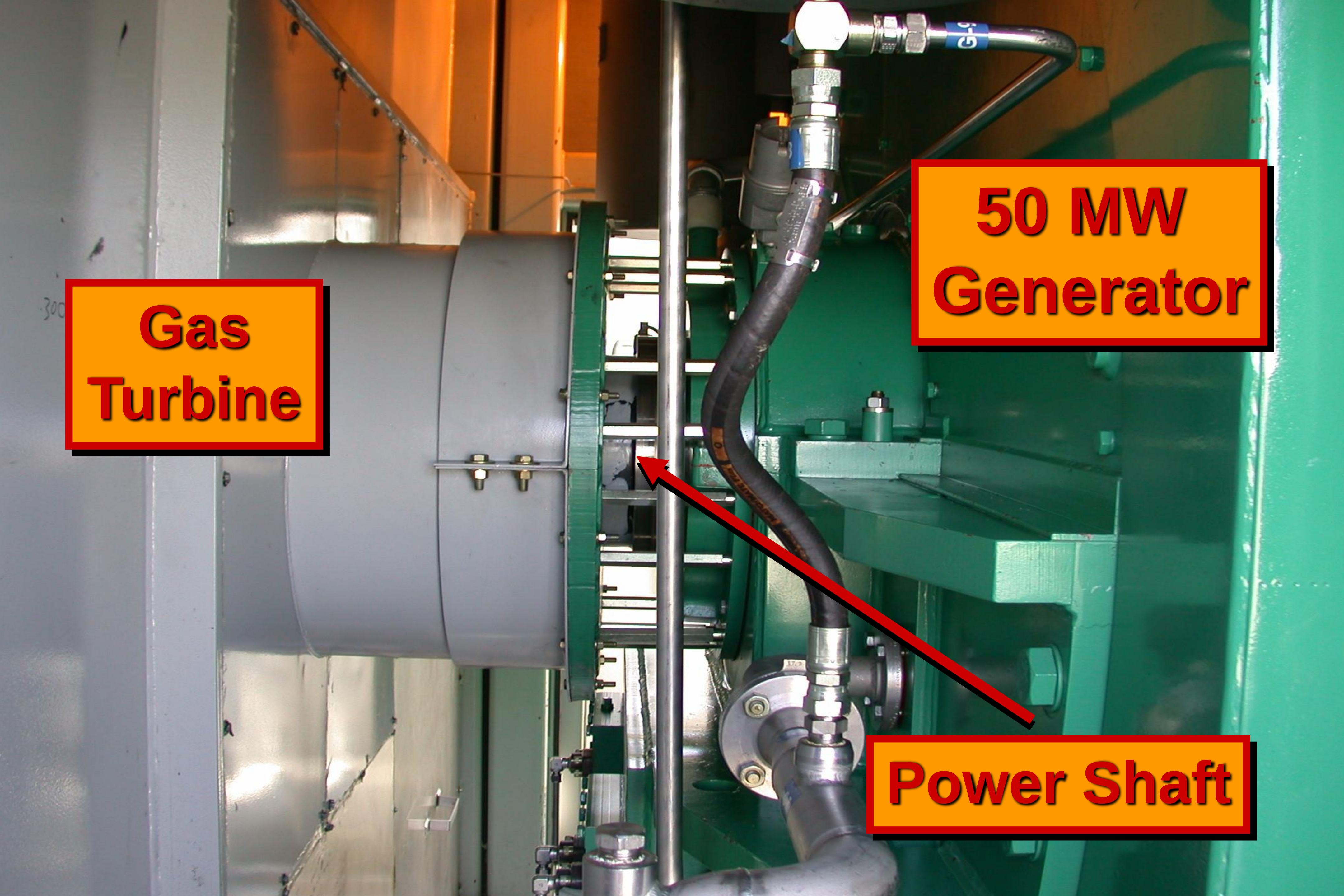

Let's have some fun!!

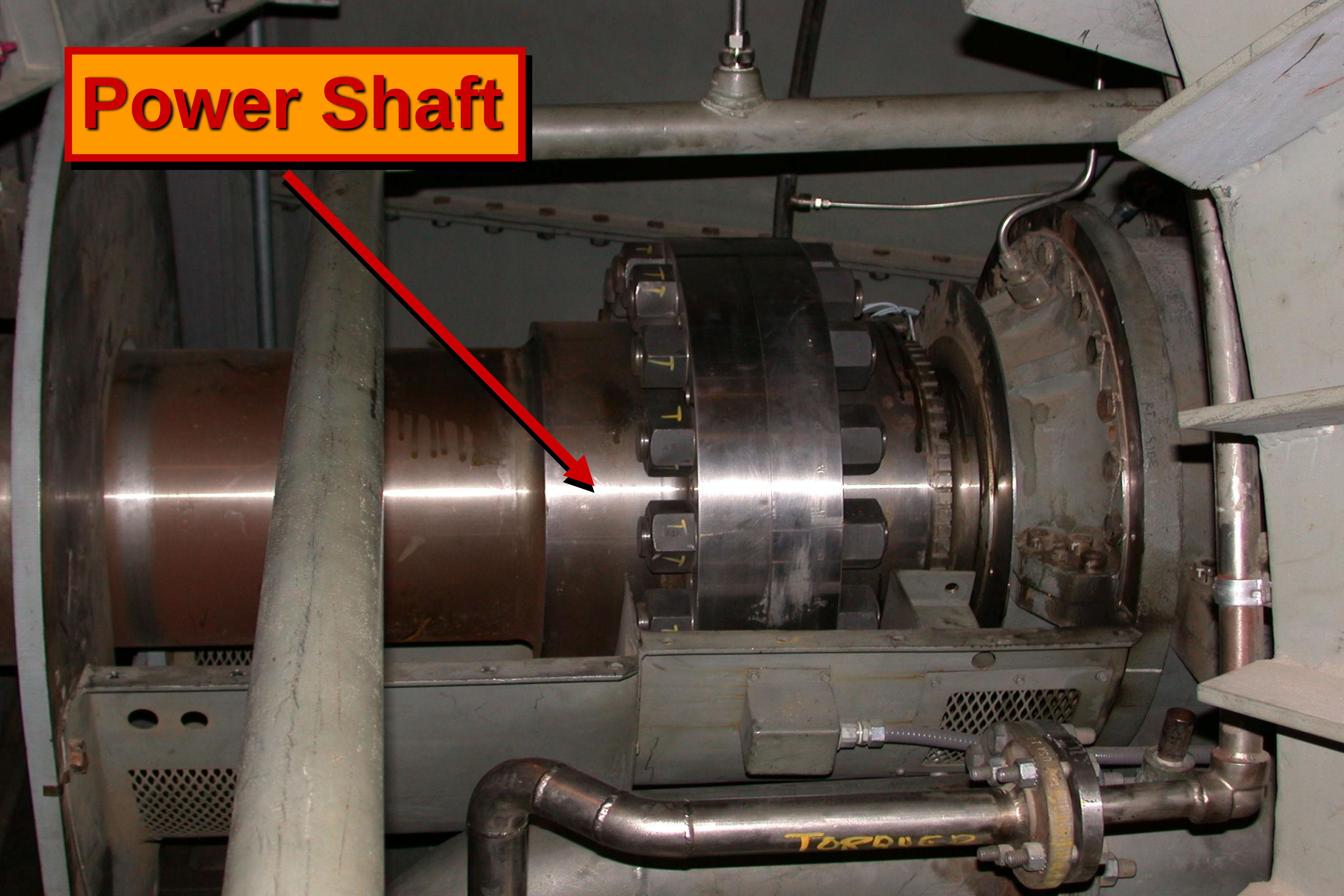
GE LM6000 Gas Turbine



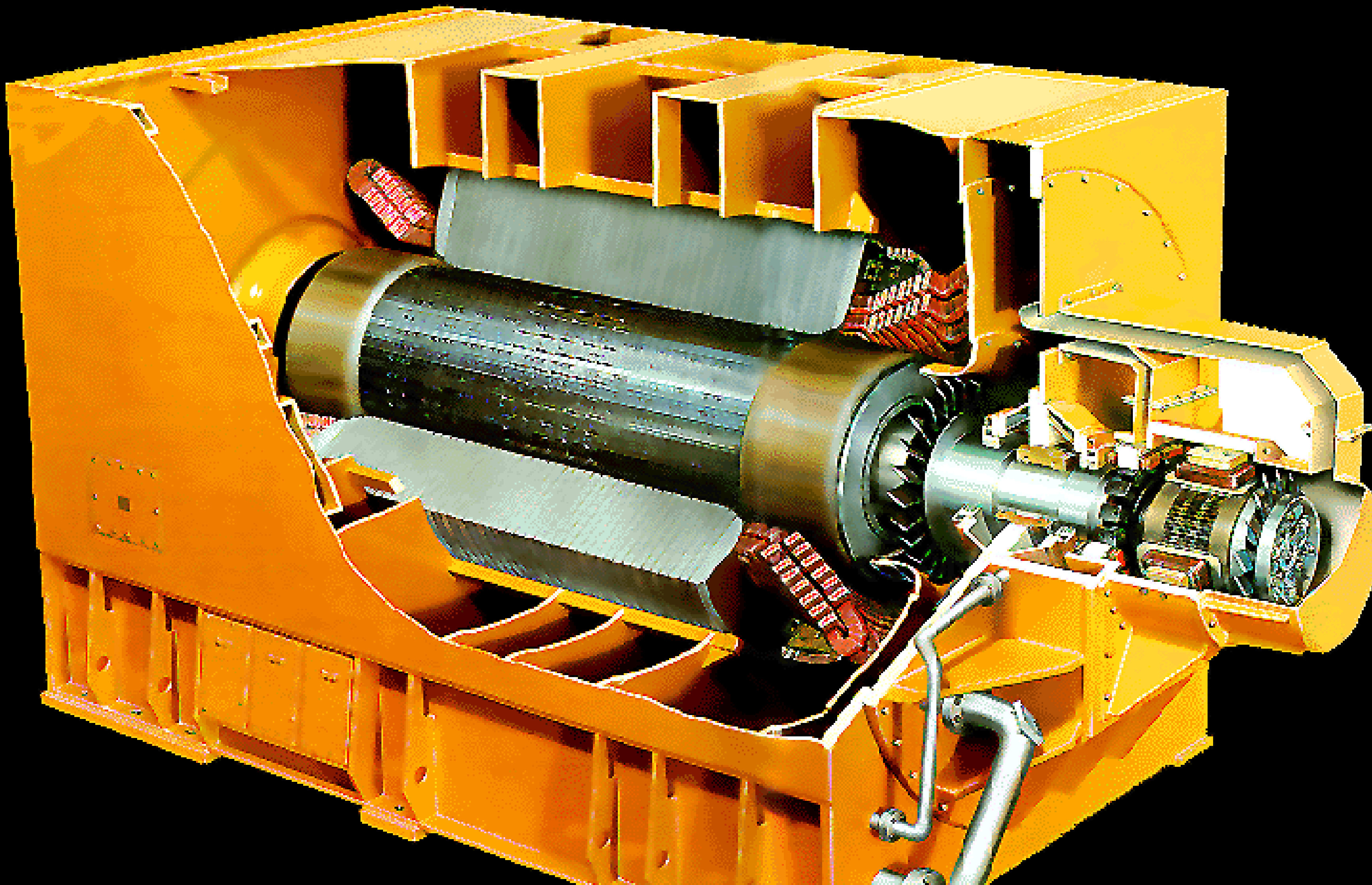
Exercise

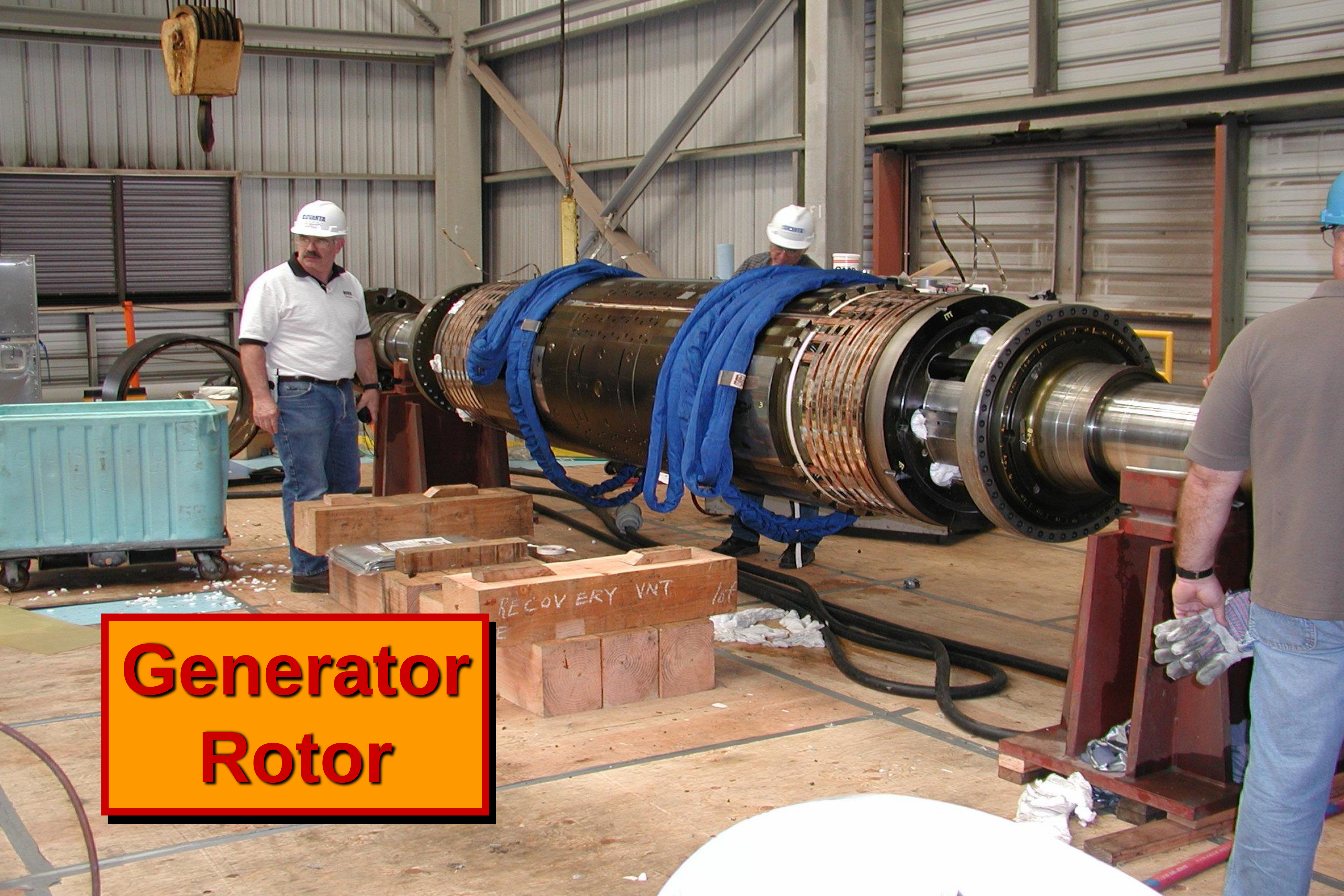

Power
Generation

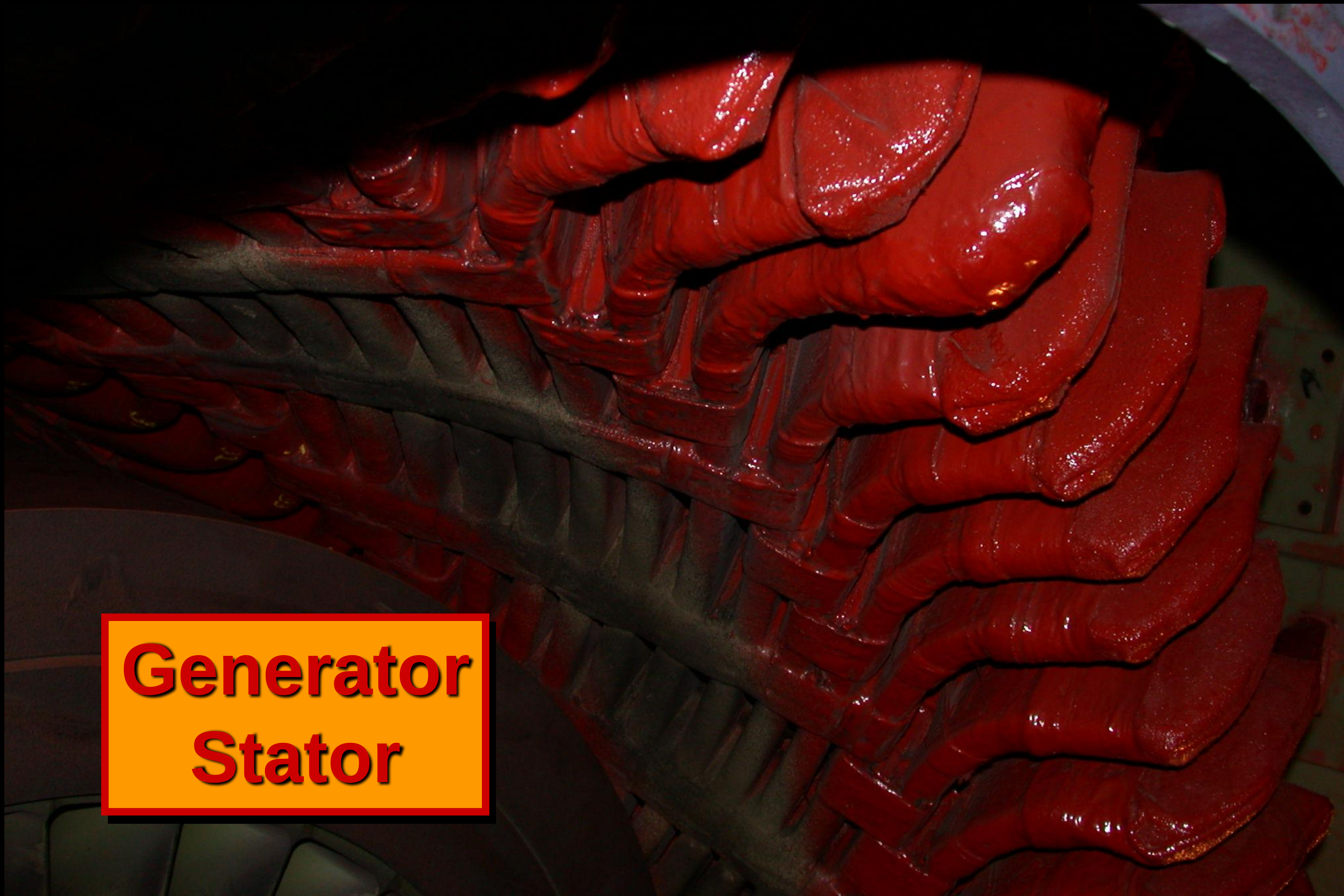

Gas Turbine
50 MW Generator
Power Shaft


Power Shaft

Brush DAX Turbogenerator




Generator Rotor
RECOVERY VNT


Generator
Stator

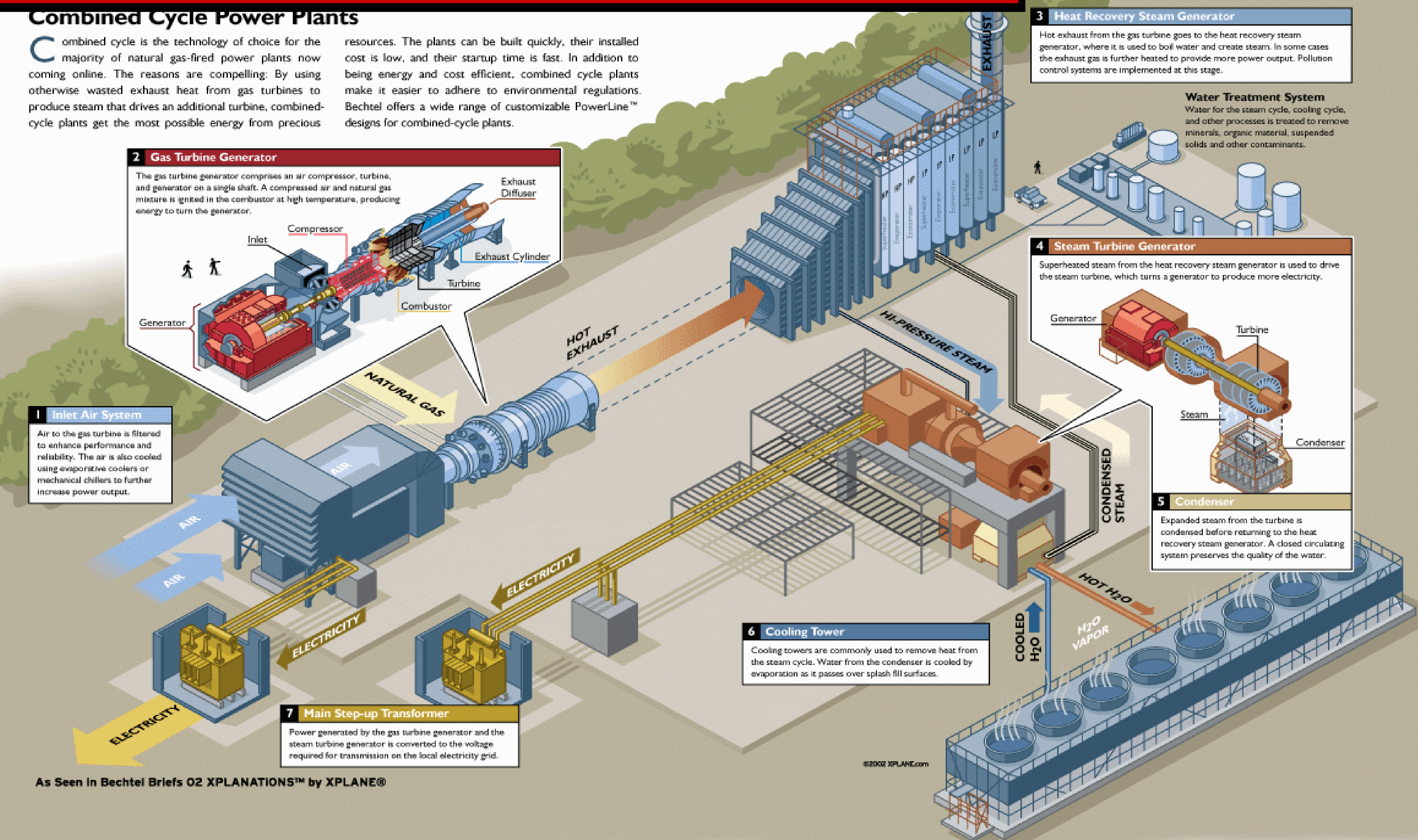

Step-up Transformers


Let’s Discuss
Steam Generation

Combined Cycle Power Plants

Combined Cycle Power Plants

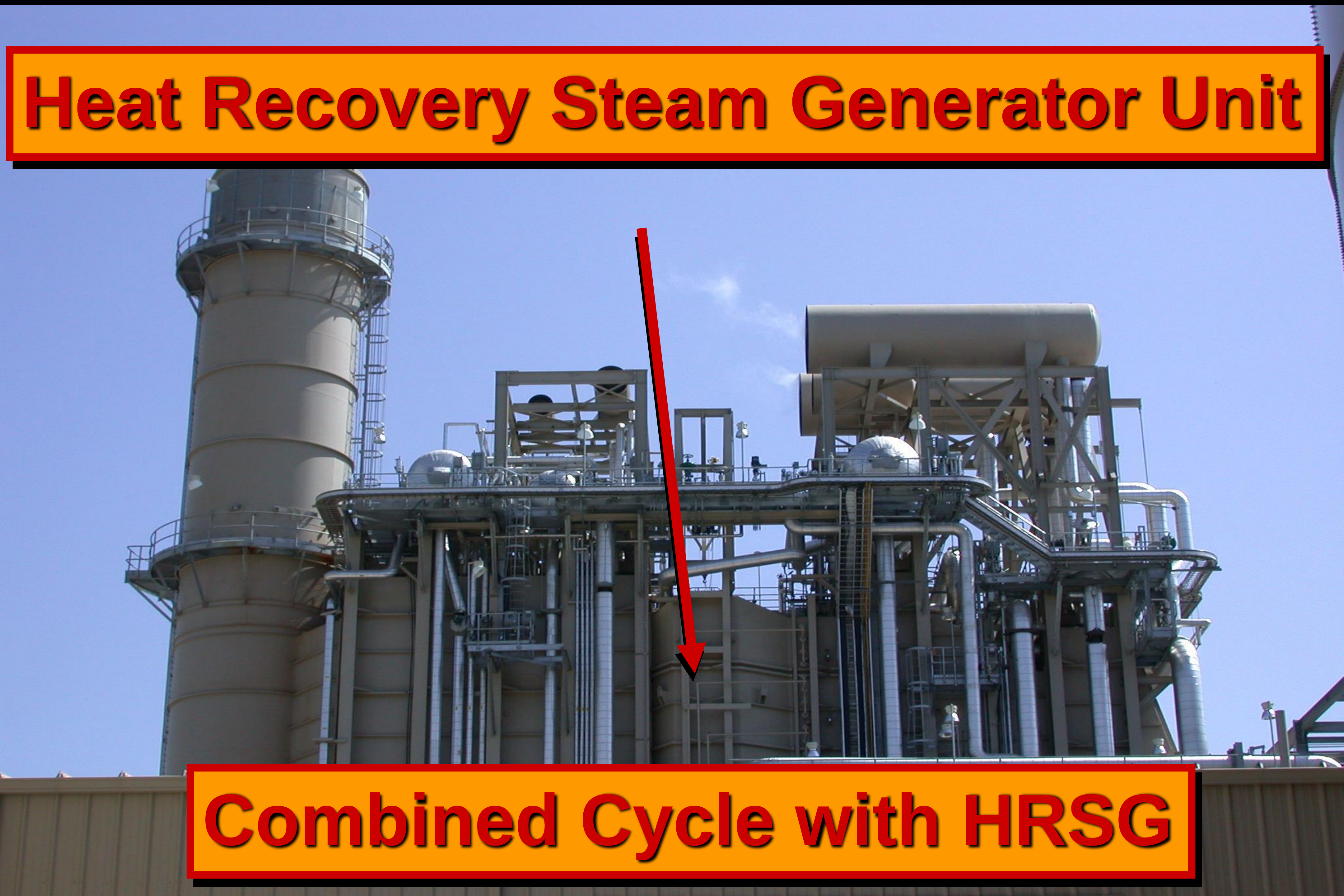
Combined cycle is the technology of choice for the majority of natural gas-fired power plants now coming online. The reasons are compelling: By using otherwise wasted exhaust heat from gas turbines to produce steam that drives an additional turbine, combined-cycle plants get the most possible energy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



As Seen in Bechtel Briefs 02 XPLANATIONS™ by XPLANE®

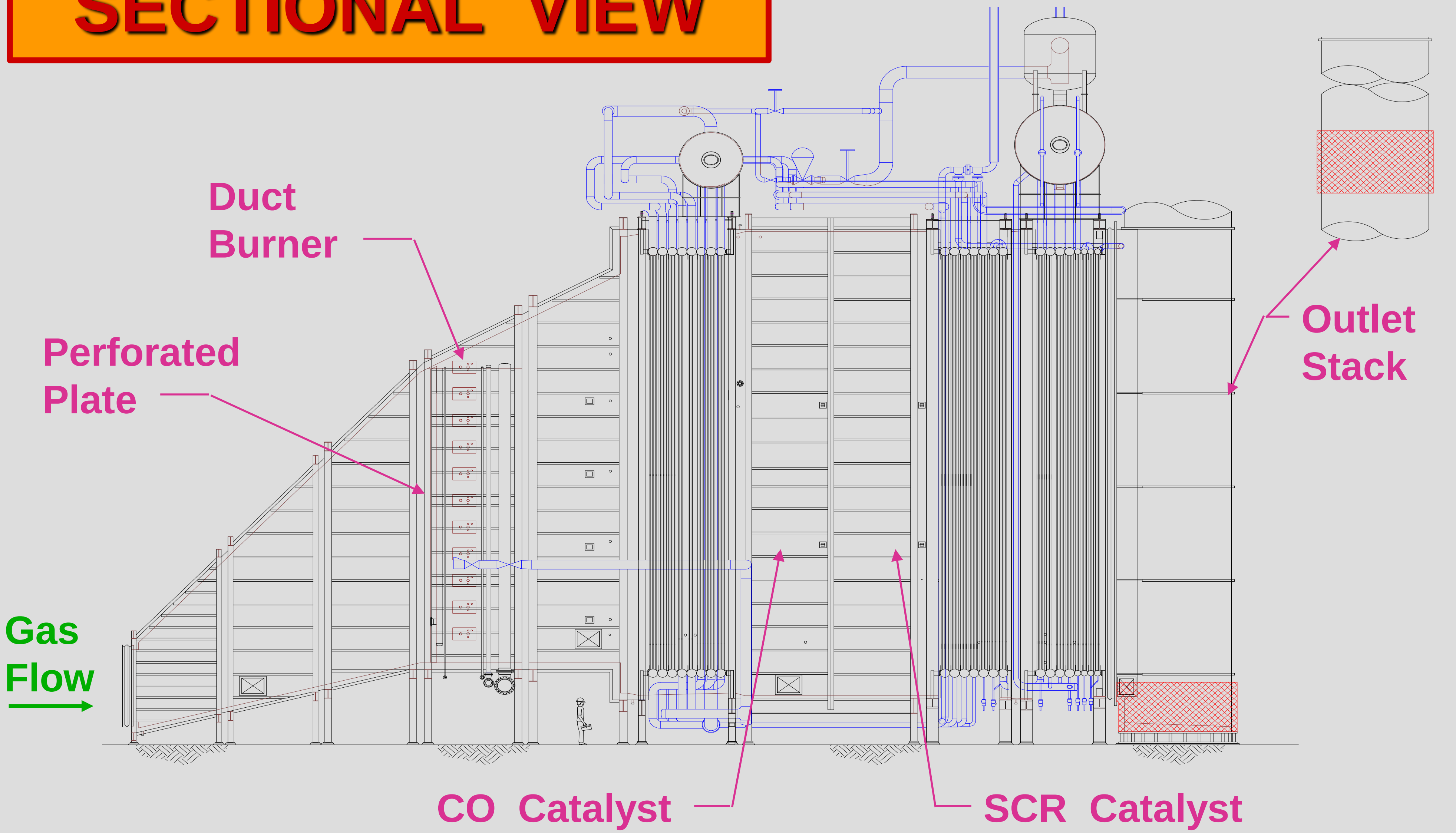
Combined Cycle Power Plant

Heat Recovery Steam Generator Unit

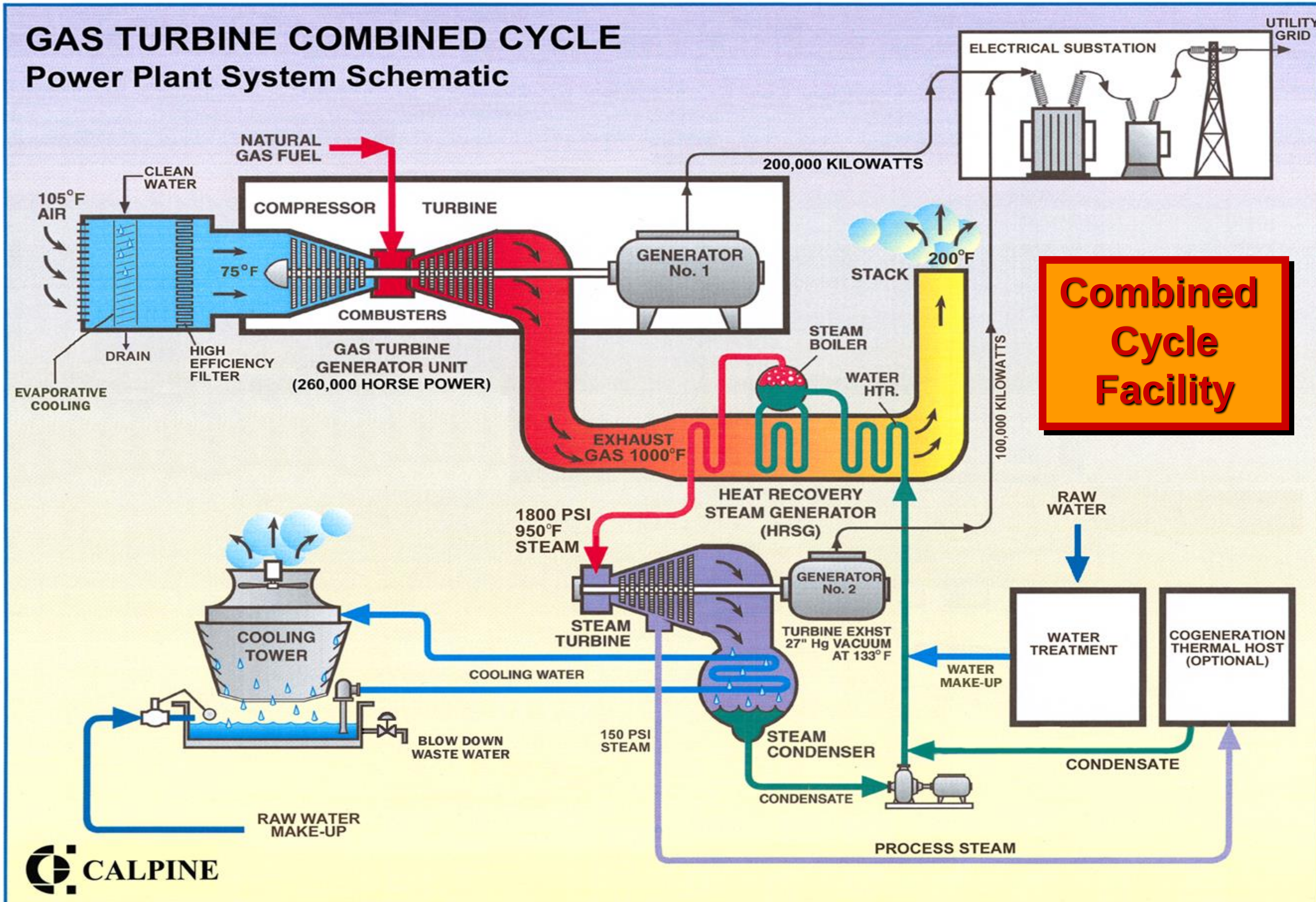


Combined Cycle with HRSG

SECTIONAL VIEW

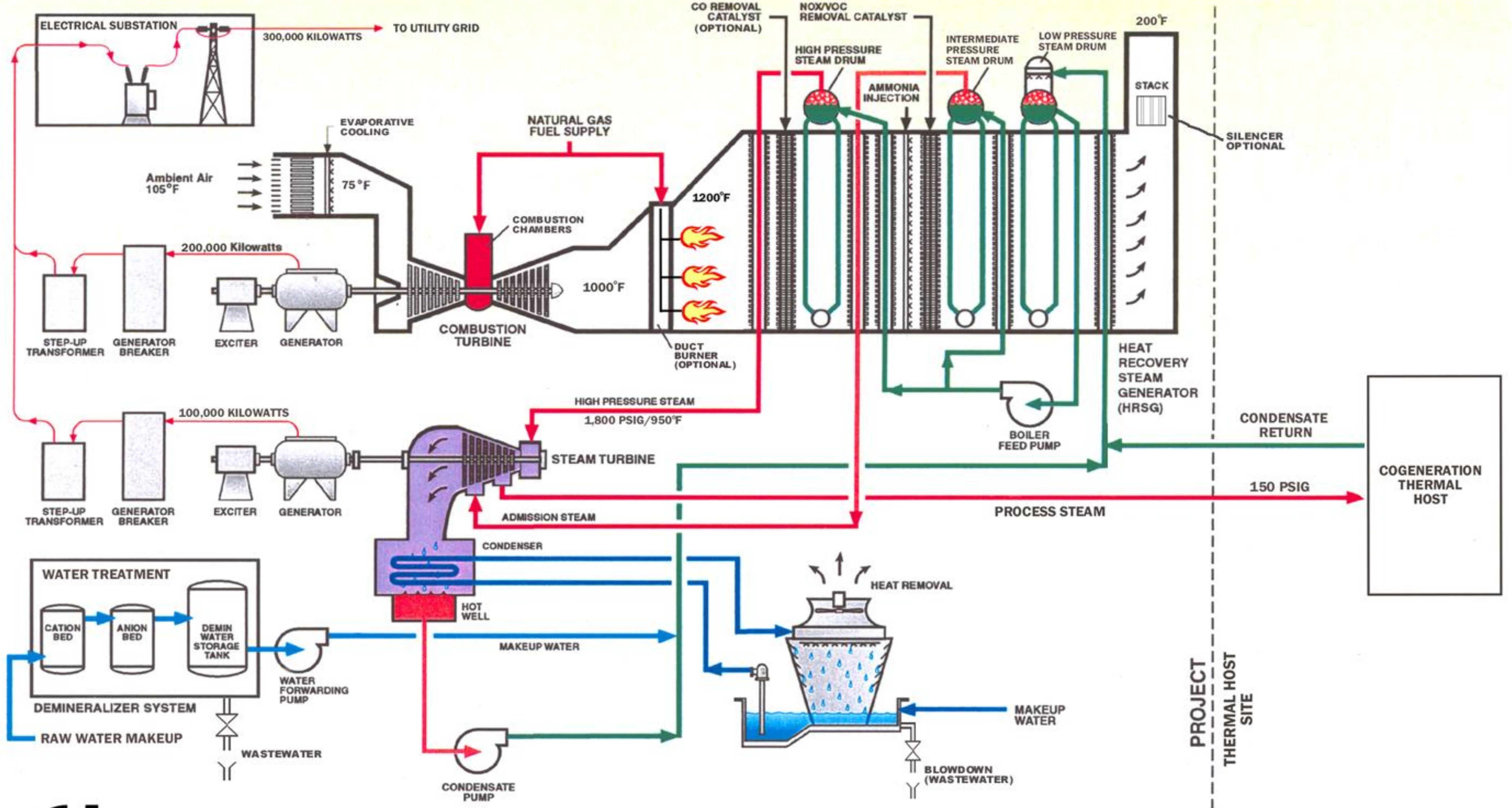


LM6000 Peaking Plant


GAS TURBINE COMBINED CYCLE
Power Plant System Schematic
Combined Cycle Facility
NATURAL GAS FUEL
CLEAN WATER
105°F AIR
75°F
COMPRESSOR
TURBINE
COMBUSTERS
GENERATOR No. 1
200,000 KILOWATTS
ELECTRICAL SUBSTATION
UTILITY GRID
DRAIN
HIGH EFFICIENCY FILTER
EVAPORATIVE COOLING
GAS TURBINE GENERATOR UNIT (260,000 HORSE POWER)
STACK
200°F
STEAM BOILER
WATER HTR.
EXHAUST GAS 1000°F
HEAT RECOVERY STEAM GENERATOR (HRSG)
100,000 KILOWATTS
1800 PSI 950°F STEAM
RAW WATER
STEAM TURBINE
GENERATOR No. 2
TURBINE EXHST 27" Hg VACUUM AT 133°F
WATER TREATMENT
COGENERATION THERMAL HOST (OPTIONAL)
COOLING TOWER
COOLING WATER
WATER MAKE-UP
BLOW DOWN WASTE WATER
150 PSI STEAM
STEAM CONDENSER
CONDENSATE
CONDENSATE
RAW WATER MAKE-UP
PROCESS STEAM
CALPINE

GAS TURBINE COMBINED CYCLE COGENERATION PROJECT

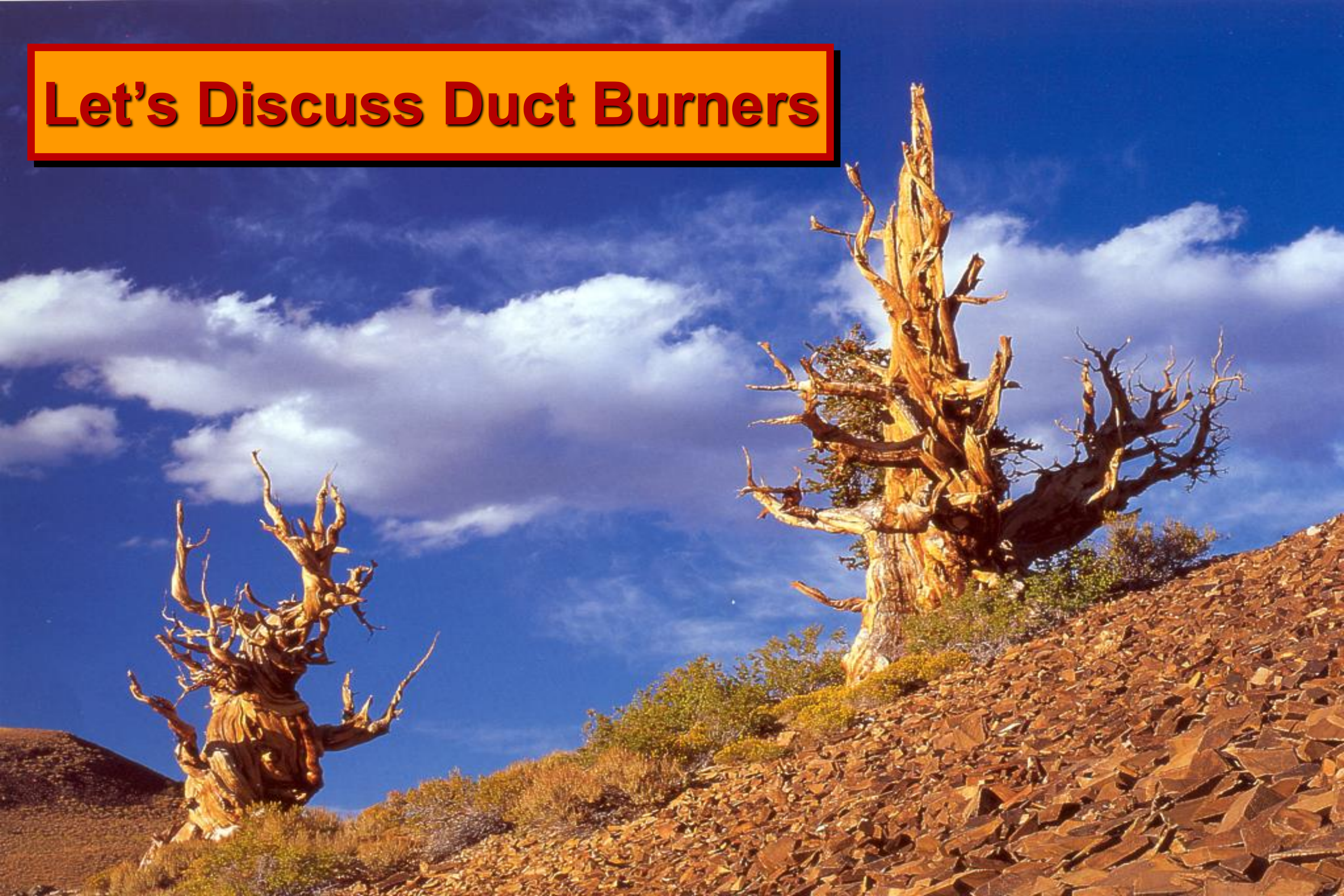
Cogeneration System Schematic

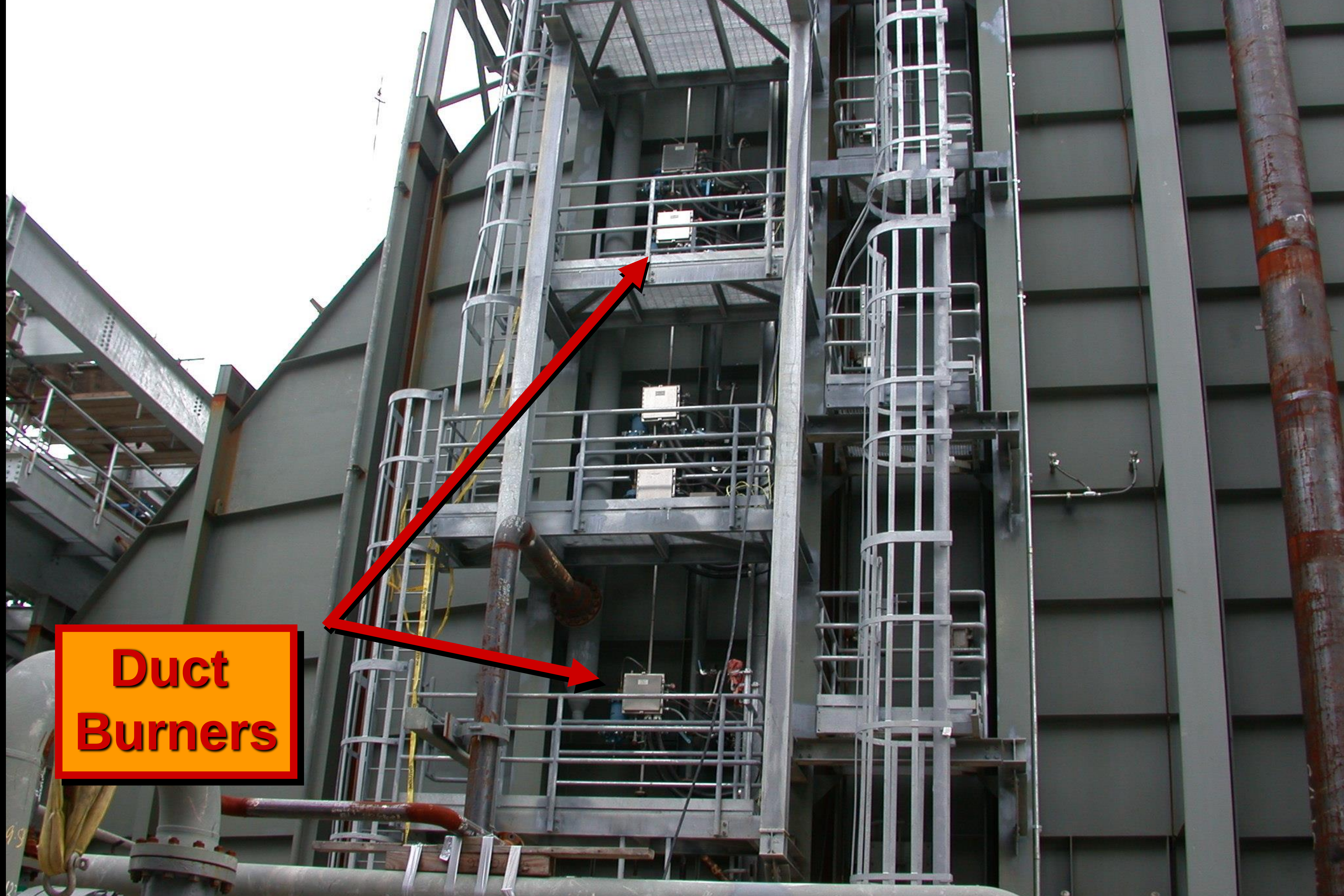


CALPINE

Combined Cycle w/By-pass

Let's Discuss Duct Burners

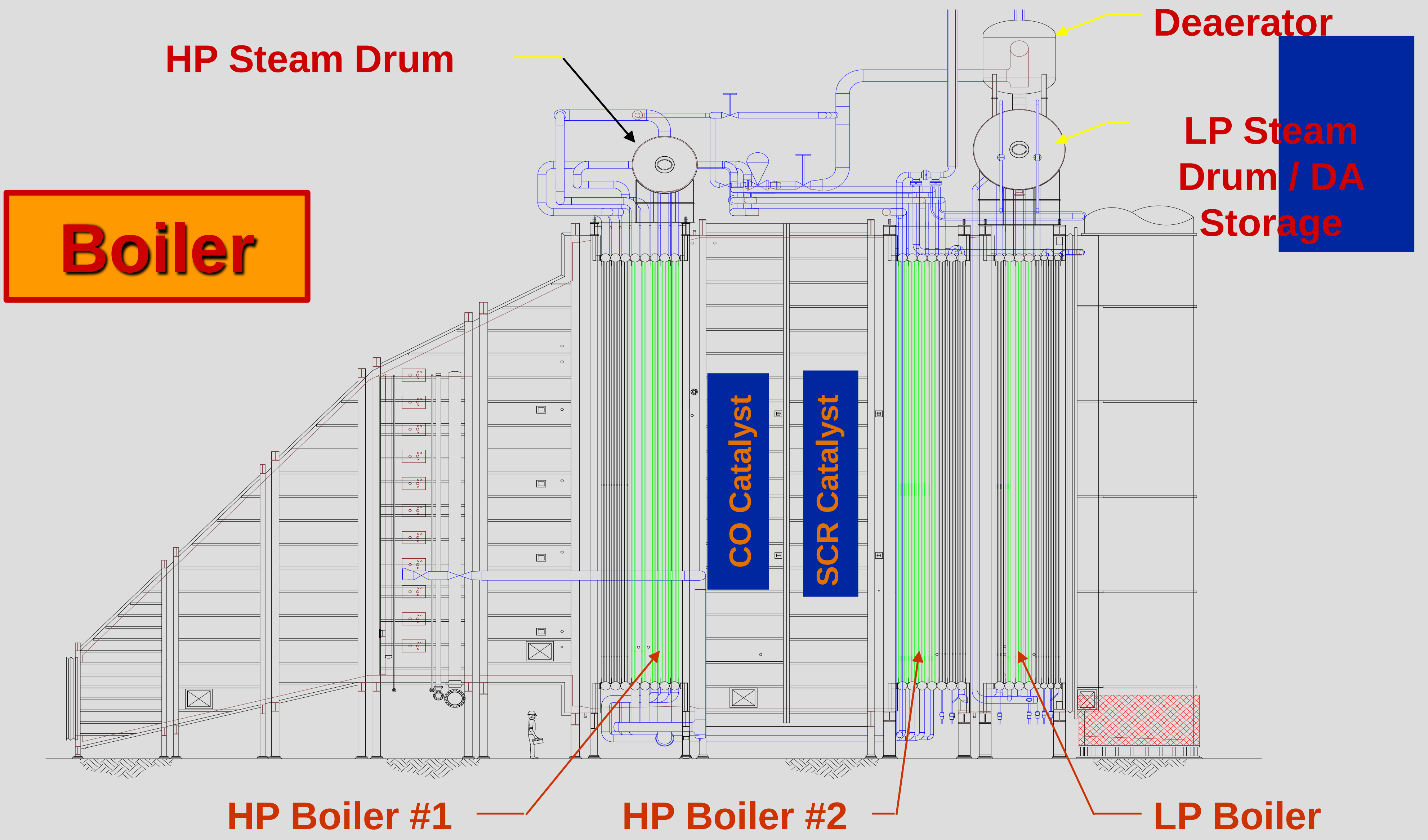



Duct
Burners

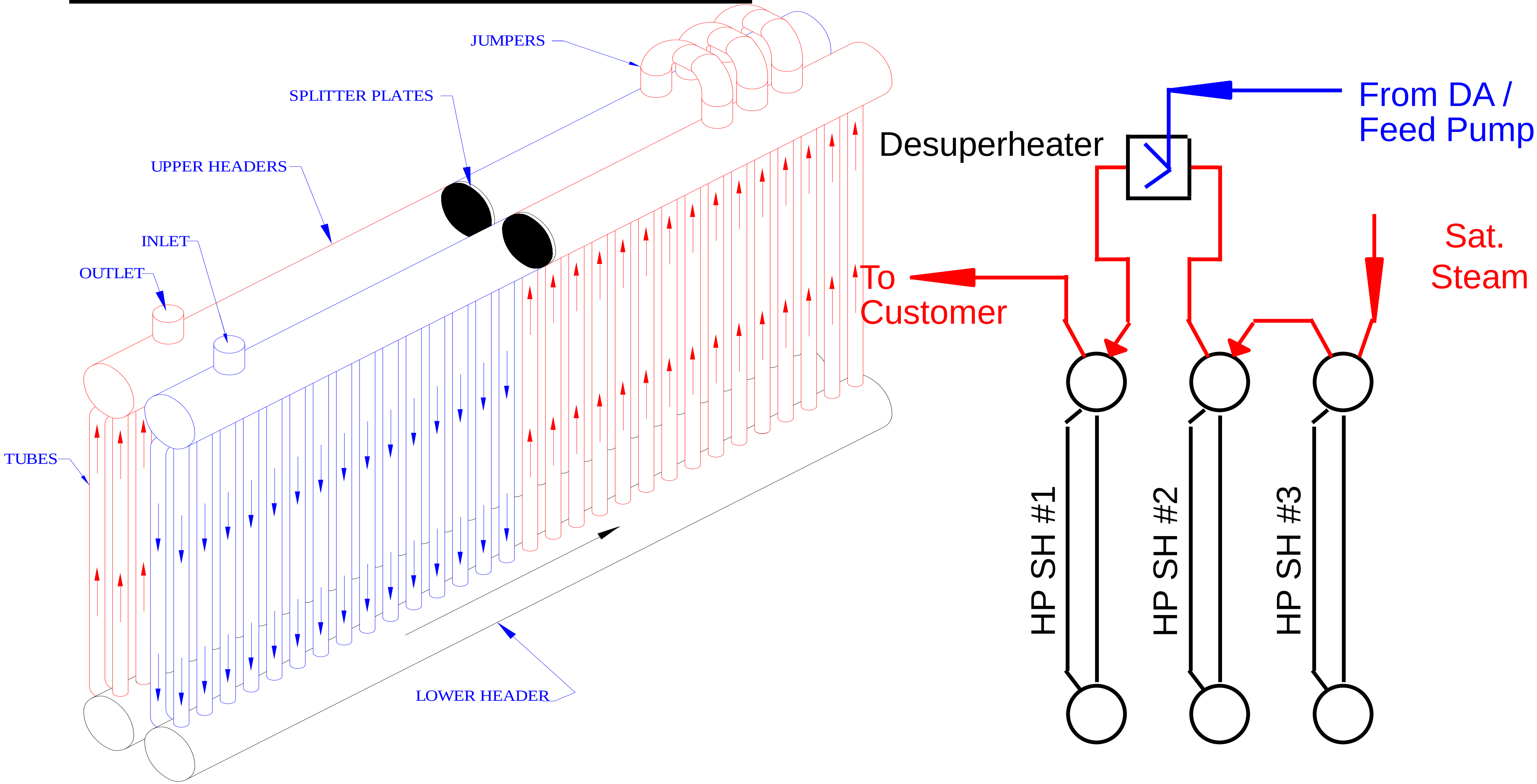

Boiler
Installation
LIEBHERR

HRSG Overview

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


Boiler
HP Steam Drum
Deaerator
LP Steam Drum / DA Storage
CO Catalyst
SCR Catalyst
HP Boiler #1
HP Boiler #2
LP Boiler

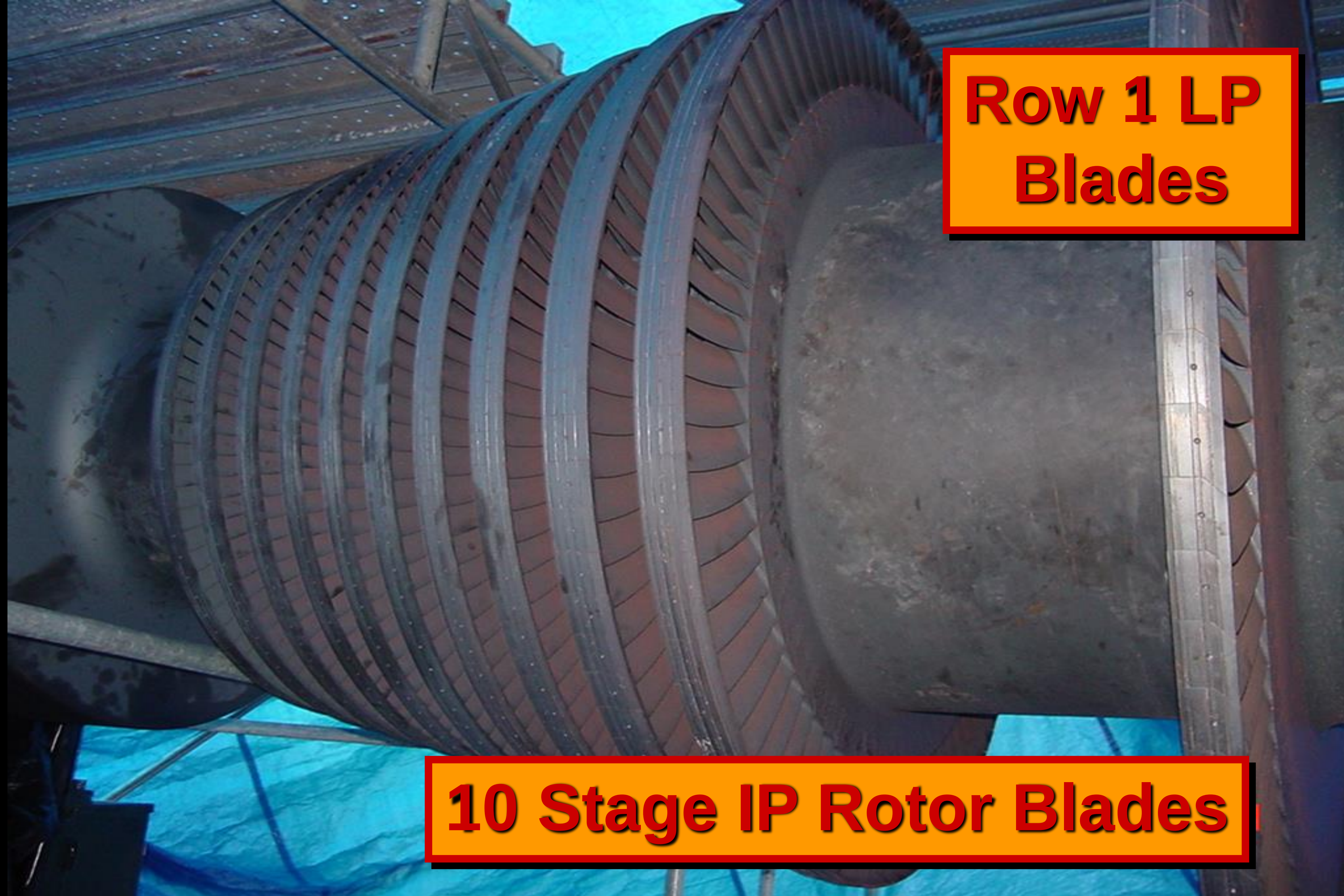
TYPICAL STEAM FLOW




Steam Lines to Steam Turbine


Steam Turbine


LP Steam
Turbine


Row 1 LP Blades
10 Stage IP Rotor Blades

LP Steam Turbine: Row 3 & 4


Steam Turbine


Cooling Towers

Let’s Discuss Dry Air-Cooling


Steam Turbine to
Dry Air Cooling


Dry Air-Cooled Condenser


Dry Air-Cooled Condenser Fans

Dry Air-Cooled Condenser Fans

Let’s Discuss Combustion Emissions

Prometheus Tree – 4,844 years old

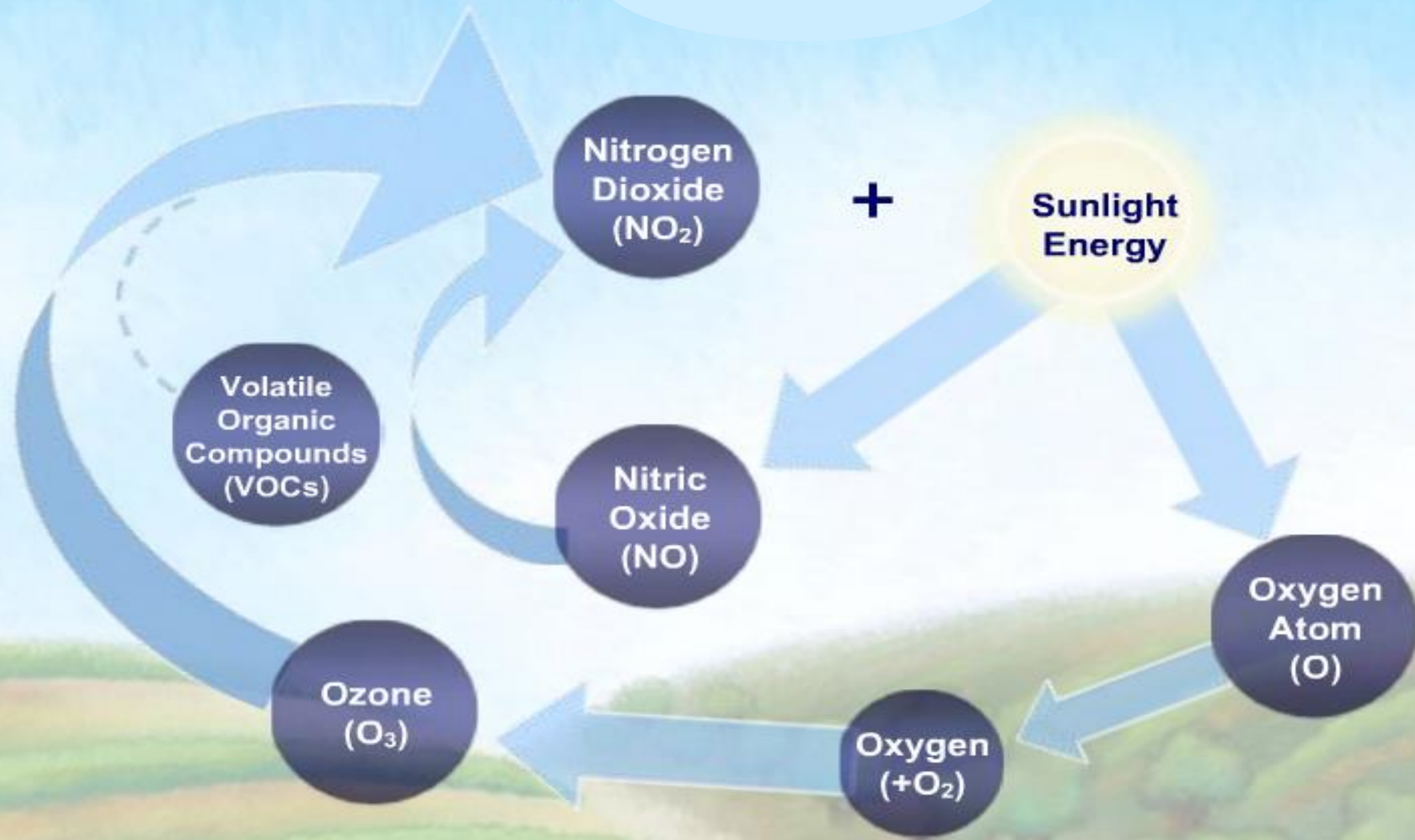
Emissions From Gas Turbines

Fuel
+
Air
(N_2, O_2)

→

- H_2O
- CO_2
- CO
- VOC
- NO_X
- SO_X
- PM

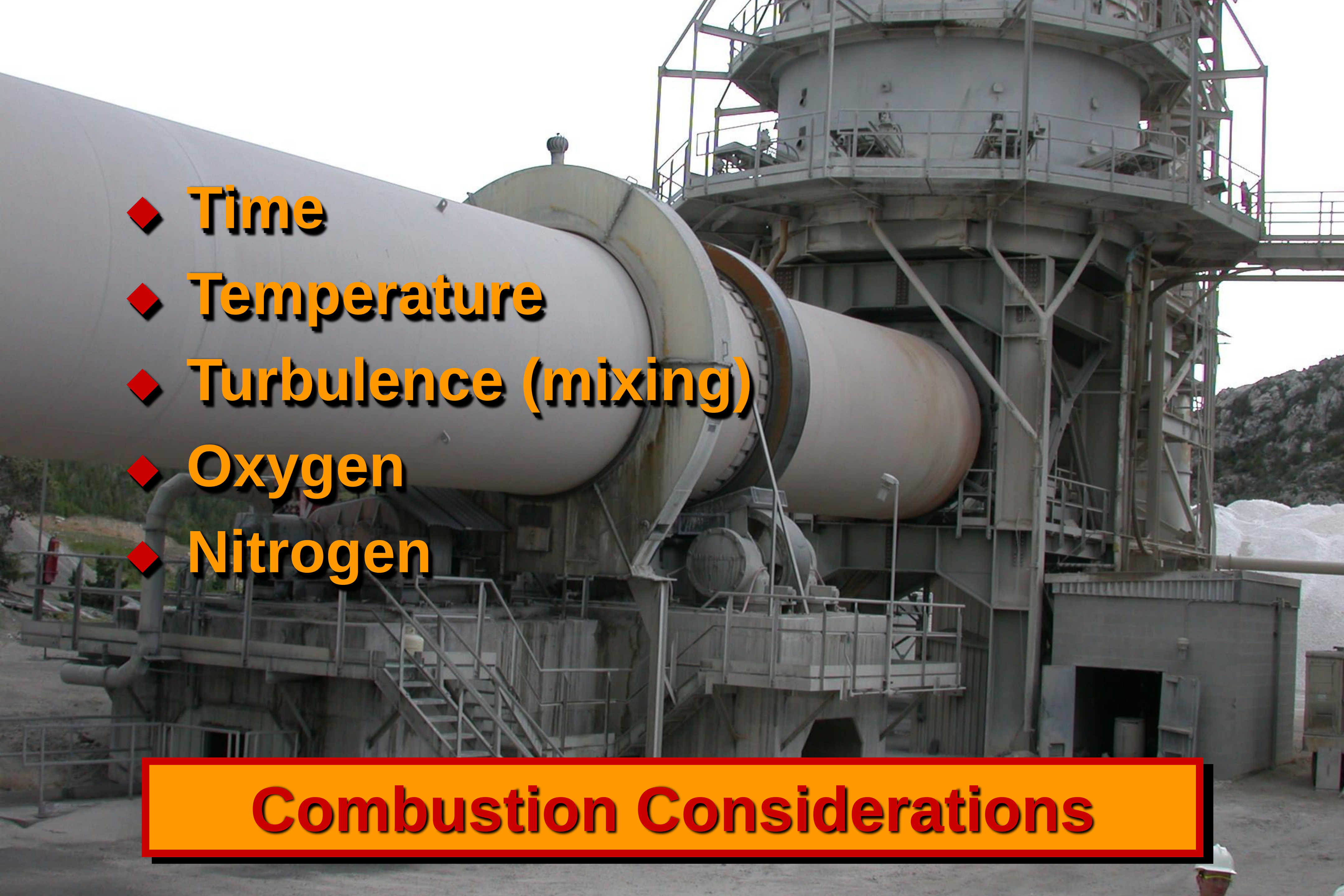
Ozone Photochemistry




Let’s Discuss Emissions Controls

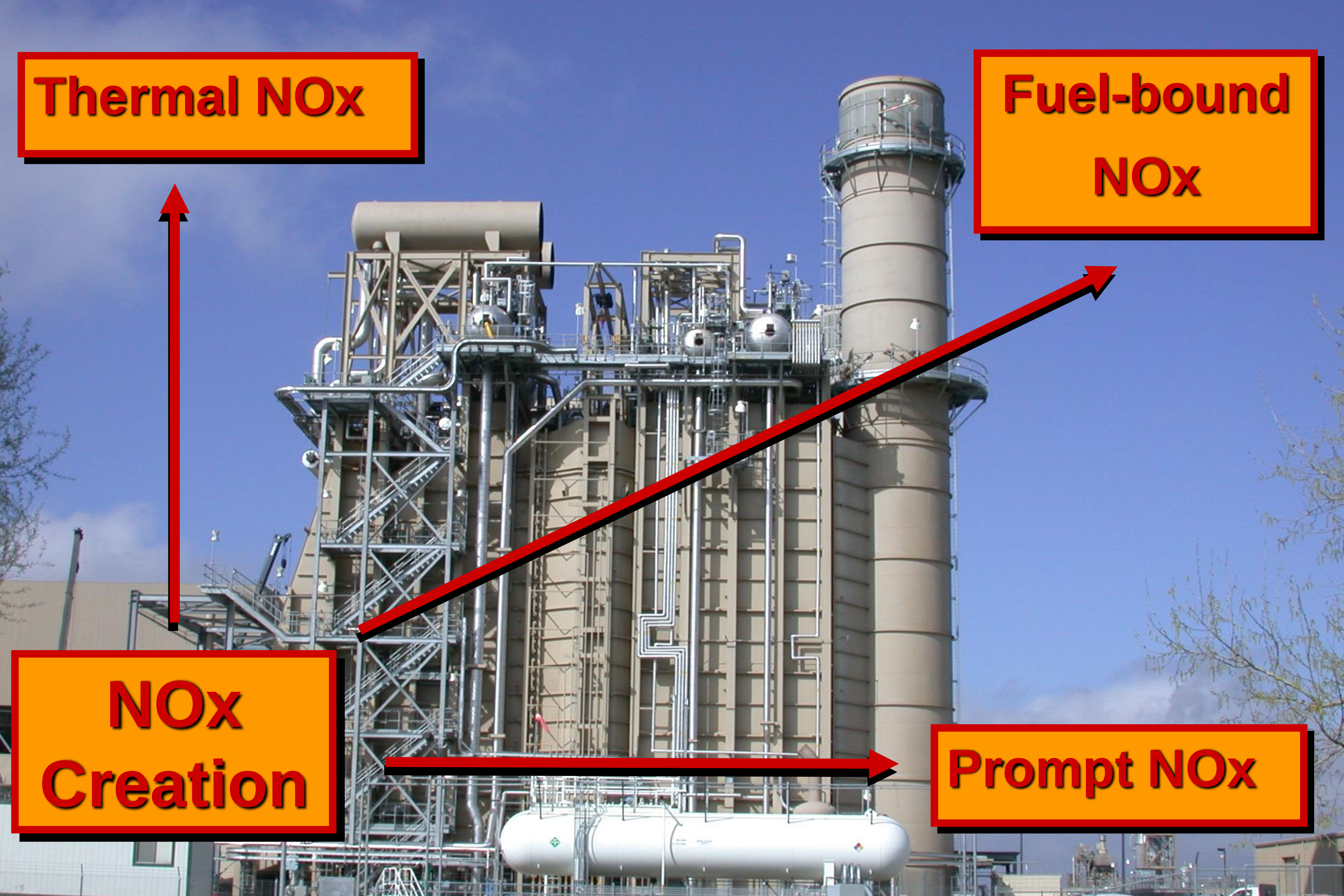
Emissions Control Methods

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

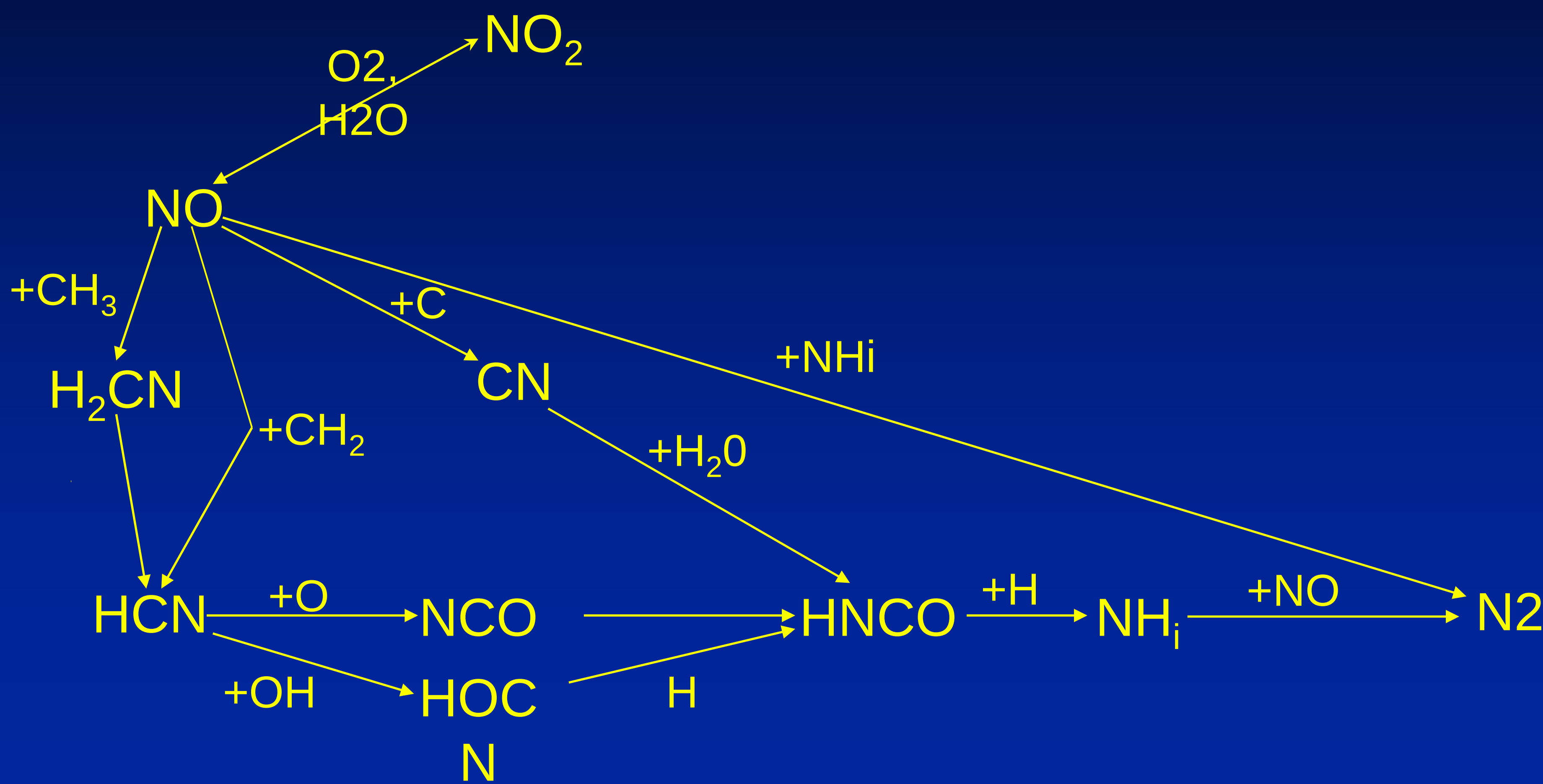


Combustion Considerations

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

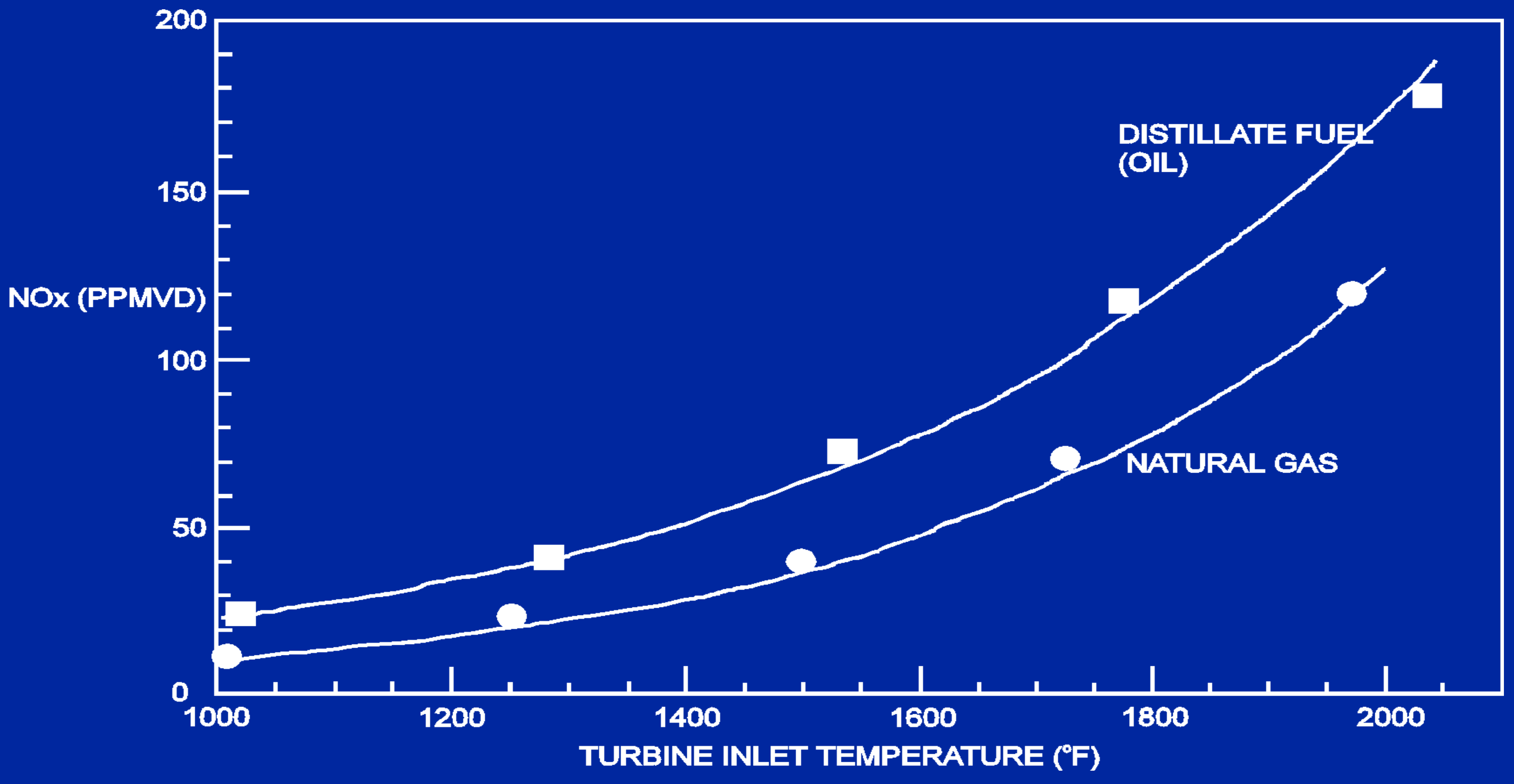

Thermal NOx
Fuel-bound NOx
NOx Creation
Prompt NOx

PROMPT NOx



NO_2
O2,
H2O
NO
$+CH_3$
H_2CN
$+CH_2$
+C
CN
+NHi
$+H_20$
HCN
+O
NCO
+OH
HOC
N
HNCO
H
+H
NH_i
+NO
N2

NOx vs. Turbine Inlet Temperature



Thermal NOx vs. Equivalence Ratio

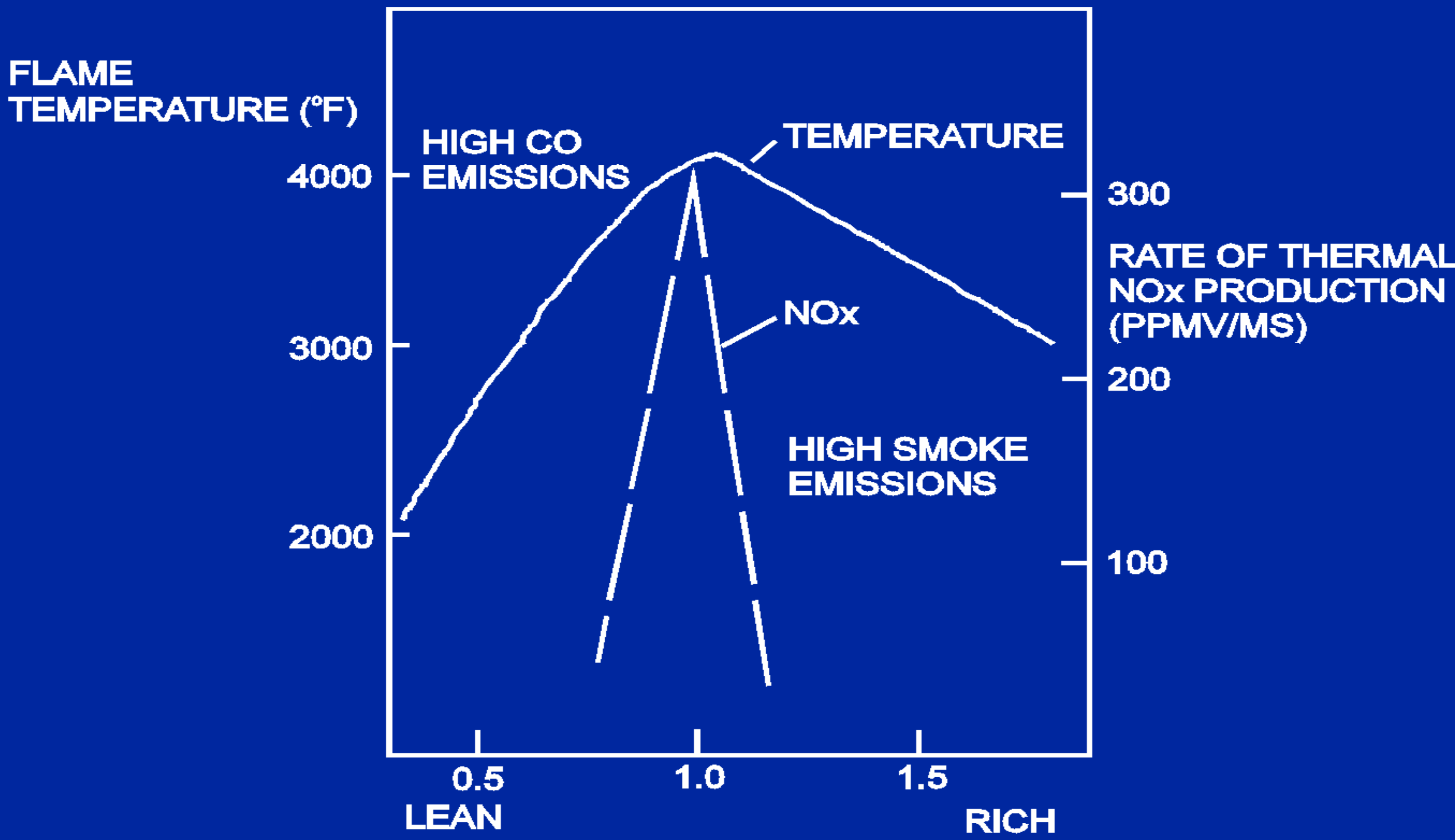
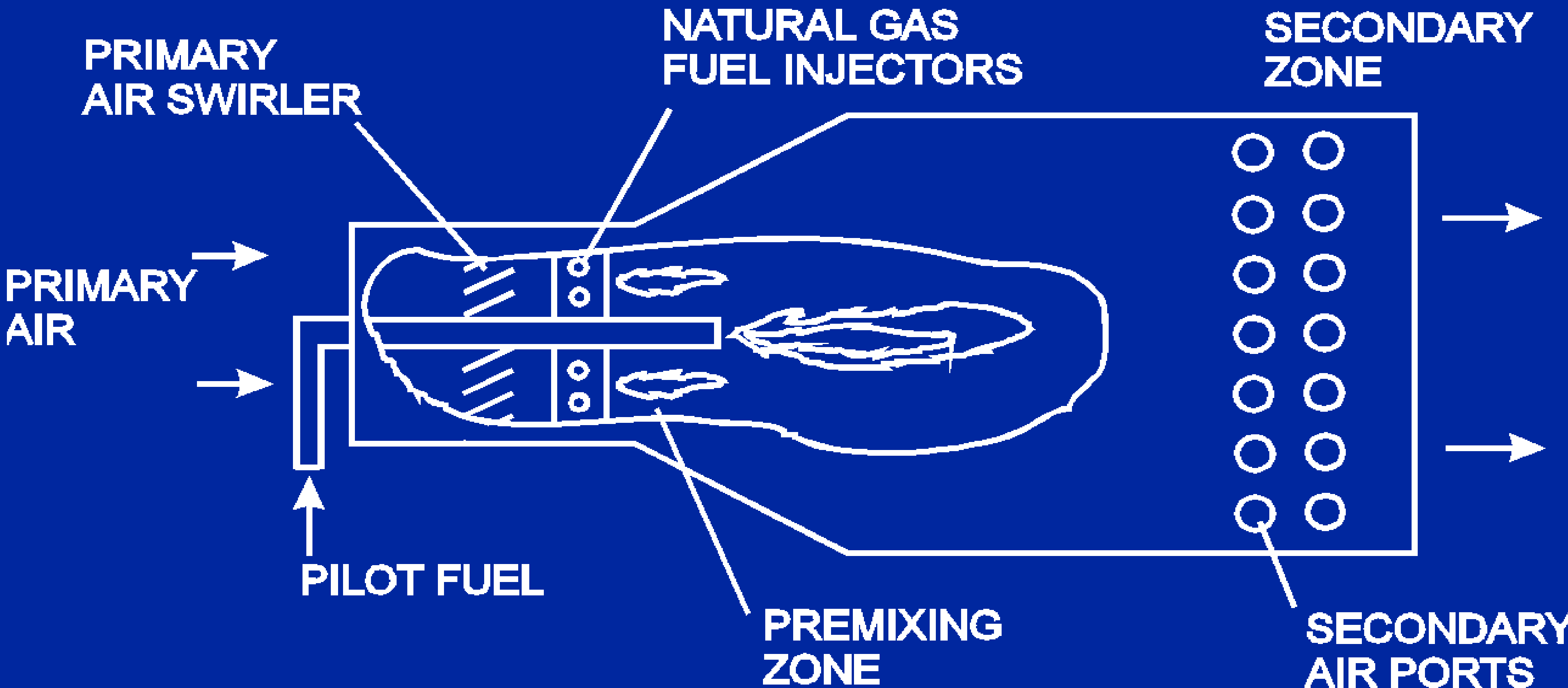
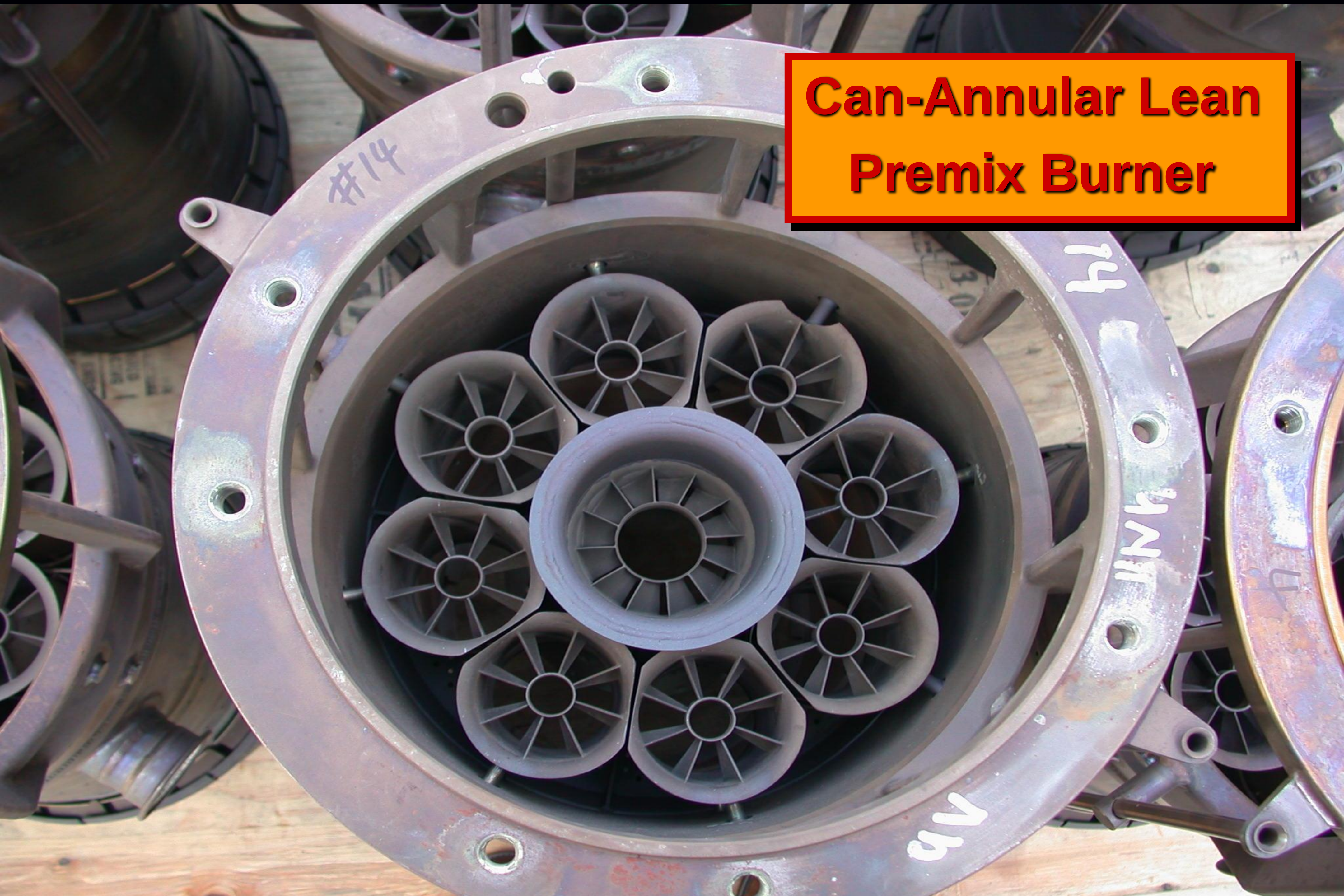
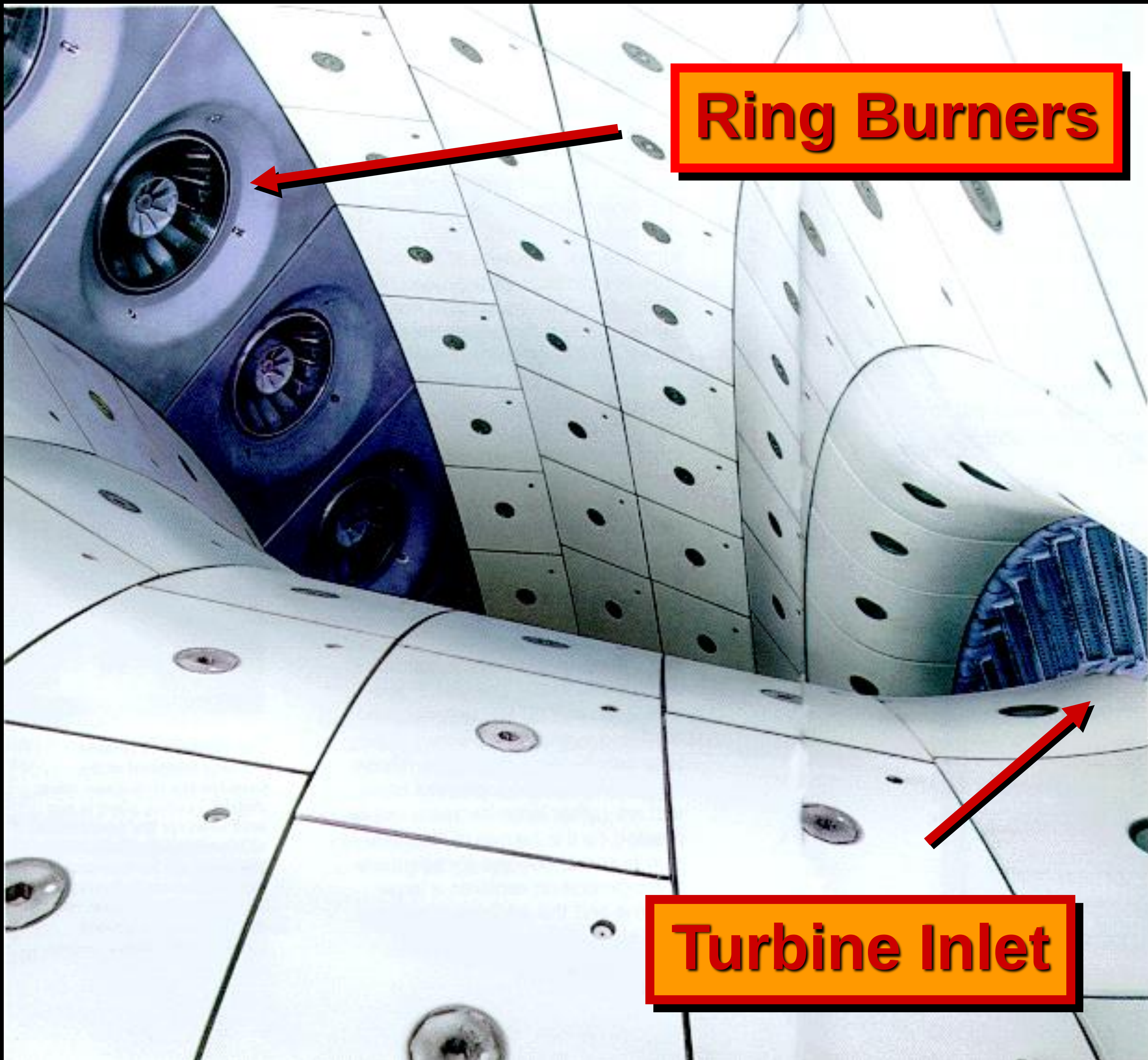


Figure 301.2

Lean Premix Combustor



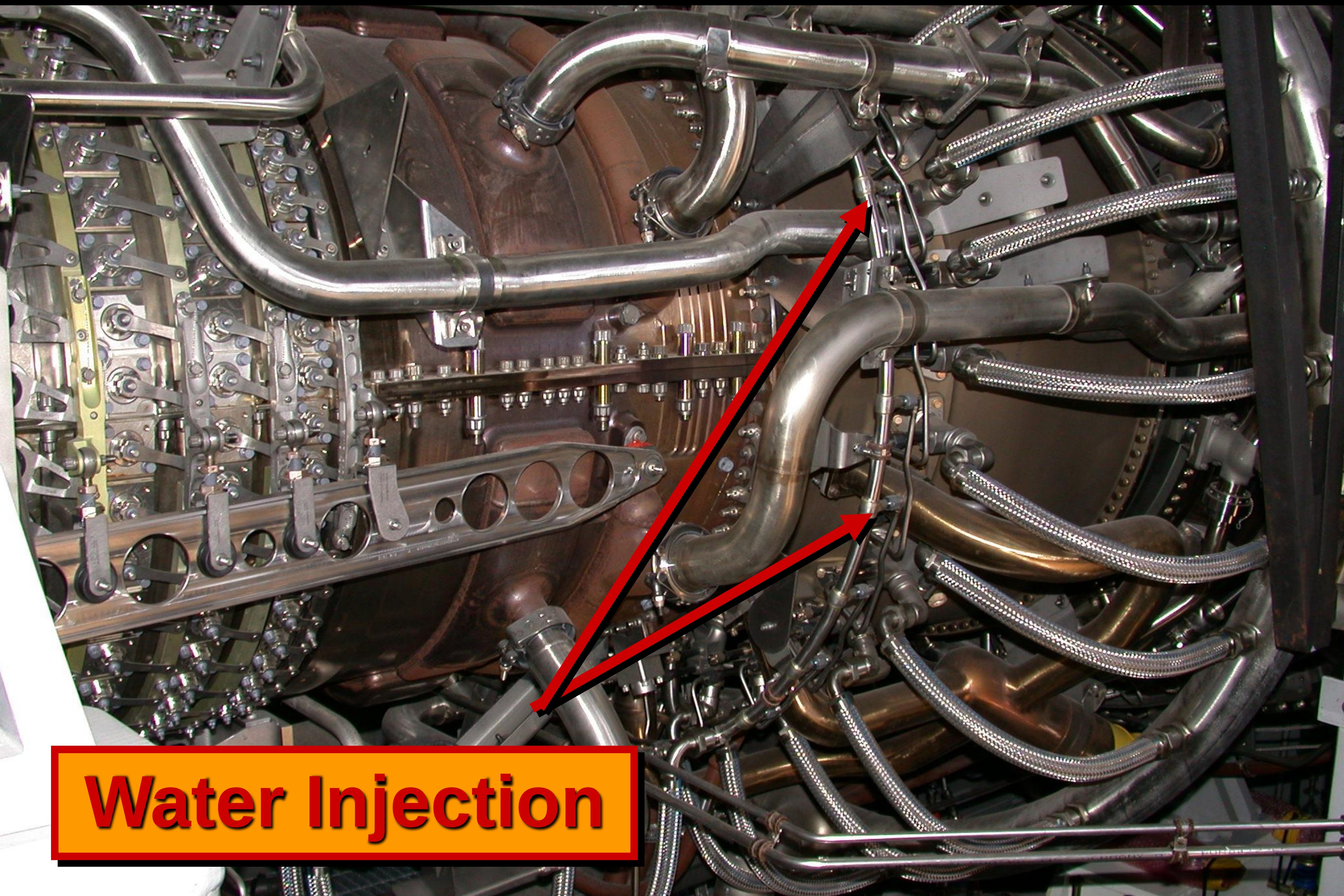

Can-Annular Lean
Premix Burner



Siemens Hybrid Burner Ring Combustor

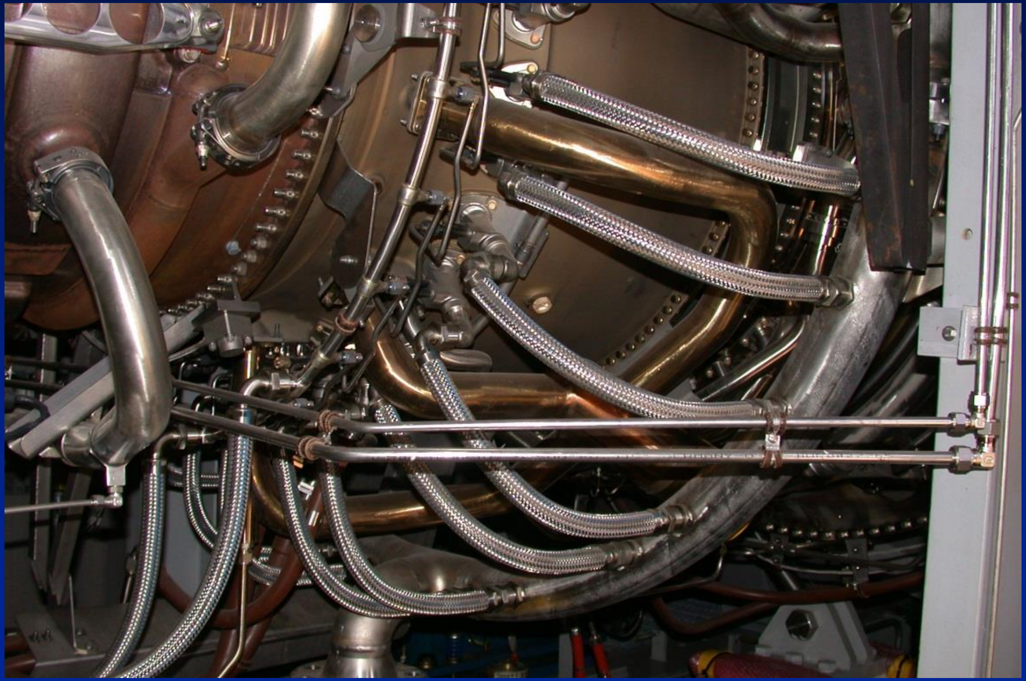
Graphic Courtesy of Siemens

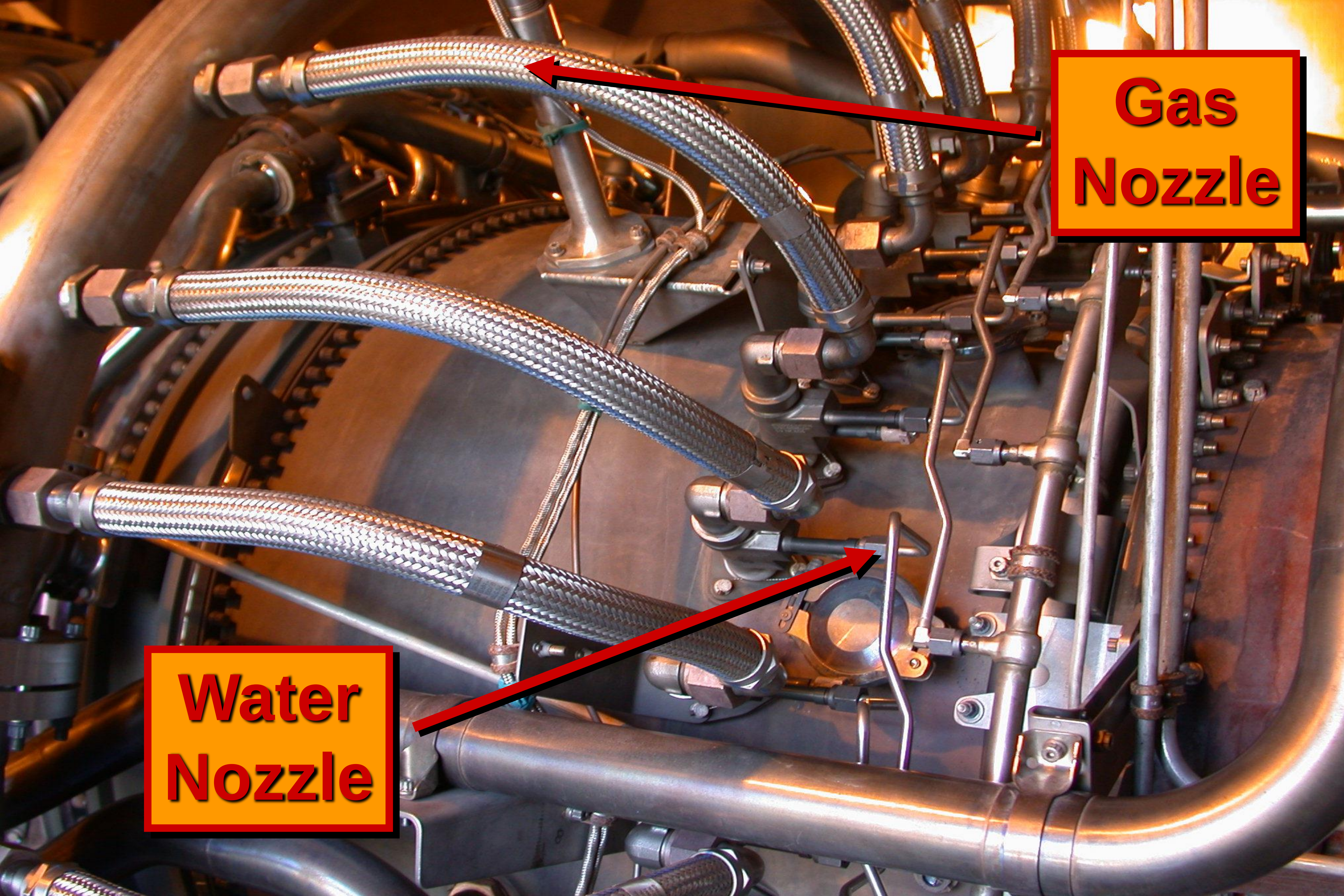
Let's Discuss Steam/Water Injection


Water Injection

Water & Steam Injection NOx Control

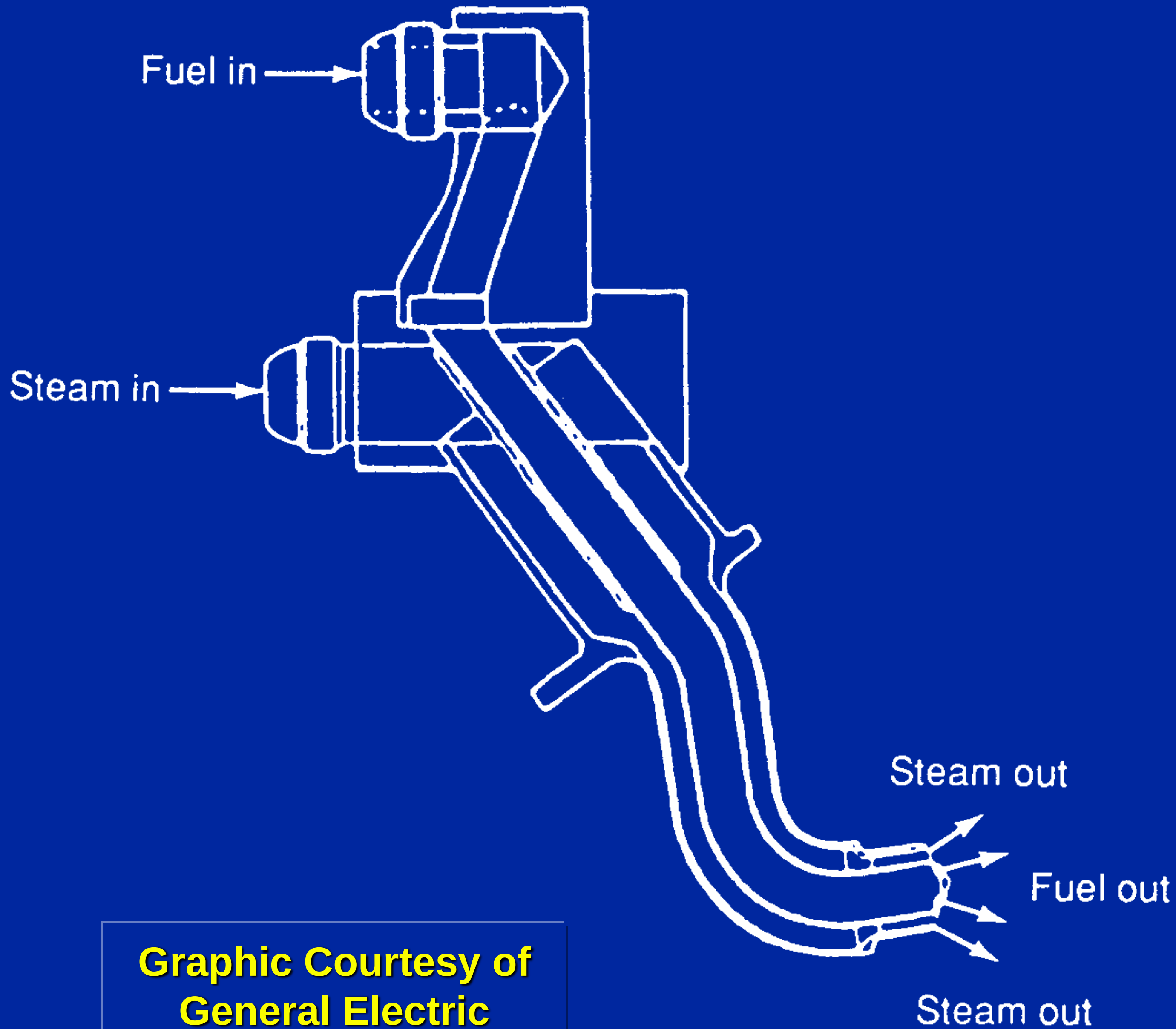
- Advantages
  - Reduces NOx
  - Increases power output
- Disadvantages
  - Water treatment expense
  - Increased fuel use
  - Increases HC
  - Increases CO
  - Increased wear & maintenance




Gas Nozzle
Water Nozzle

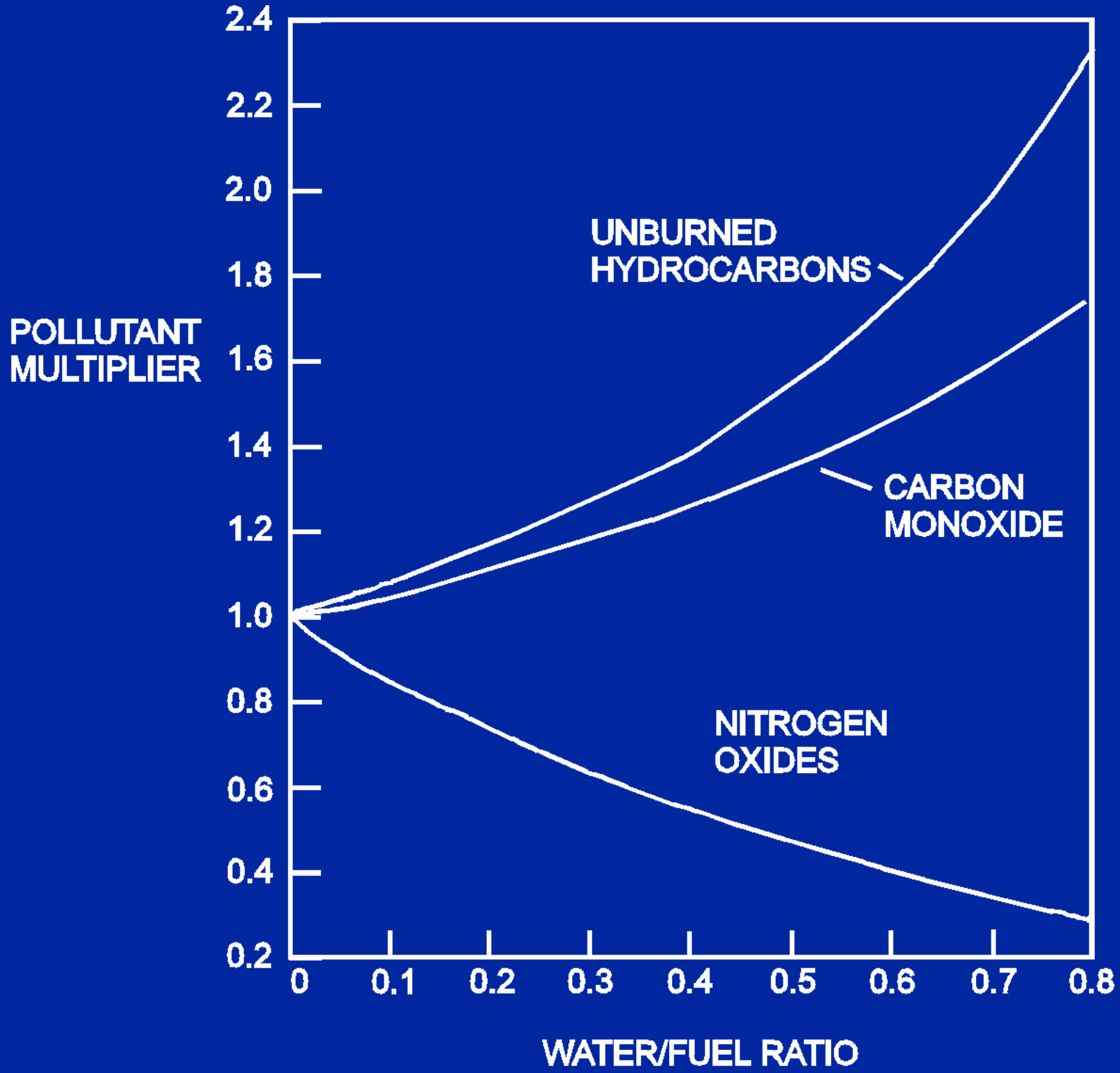

Water Treatment


Water Treatment
De-Min. Process
B4005



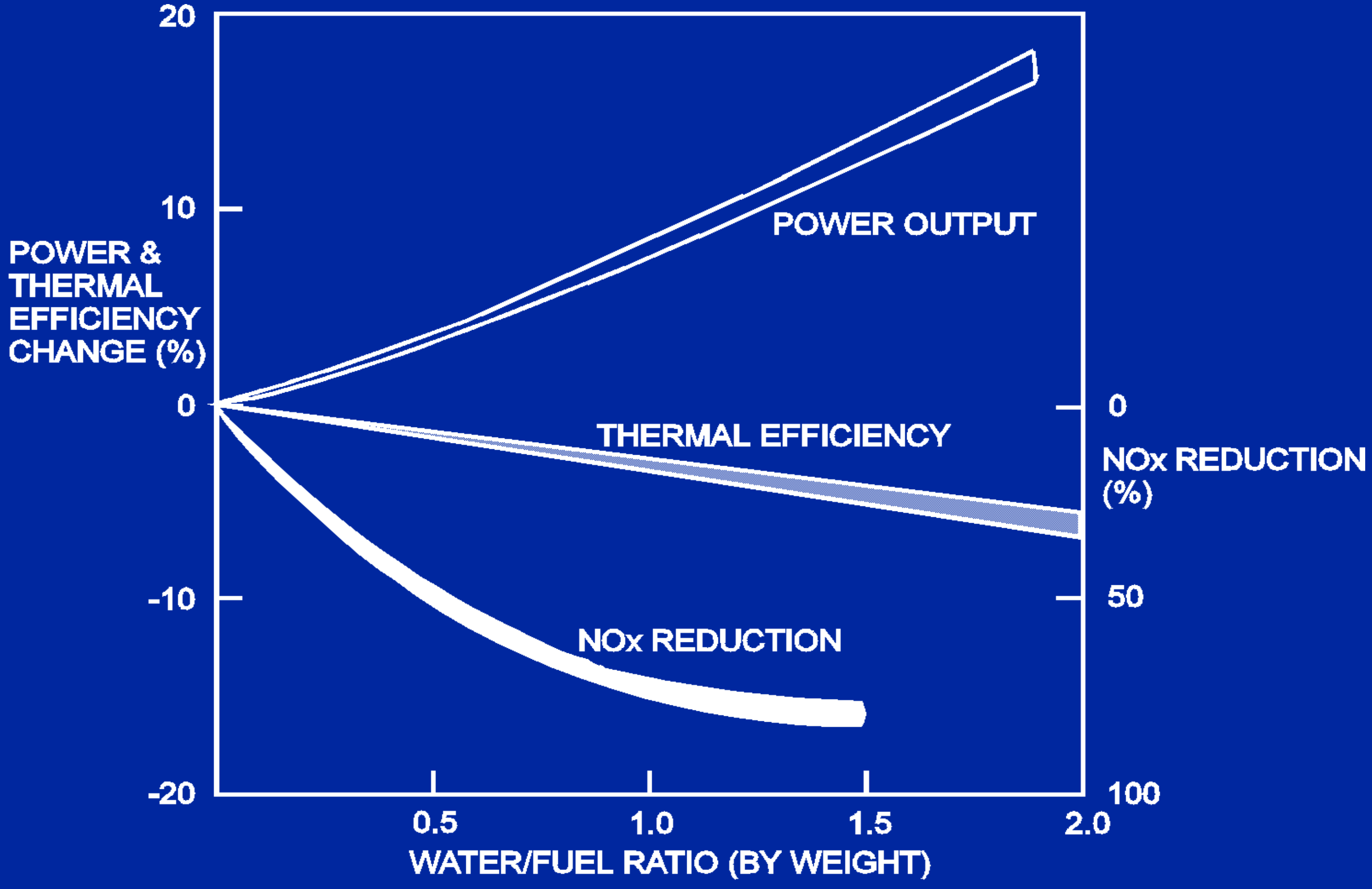
Gas/Steam Fuel Nozzle

Graphic Courtesy of General Electric

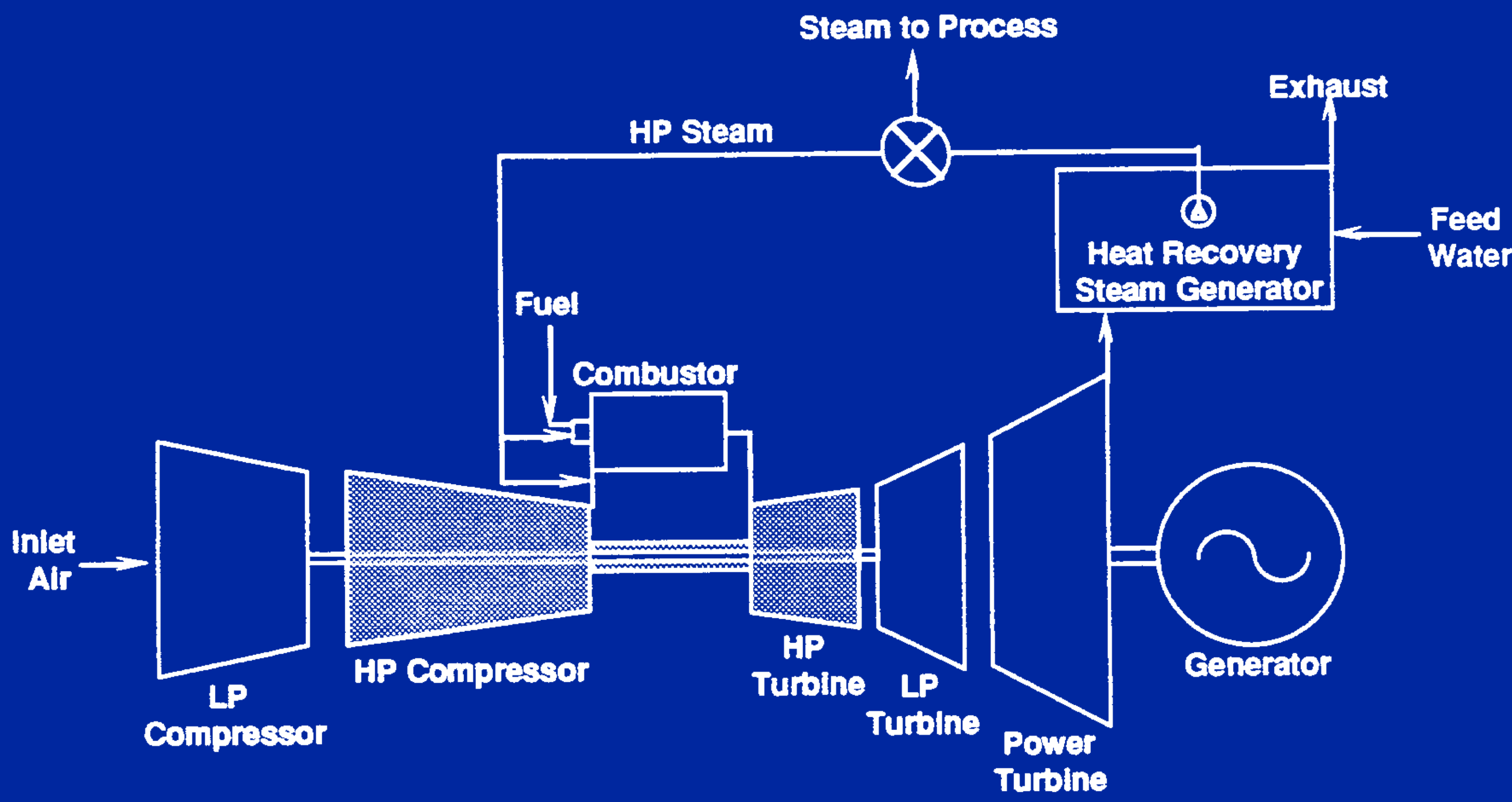


NOx, CO, and Unburned HC vs. Water Injection

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

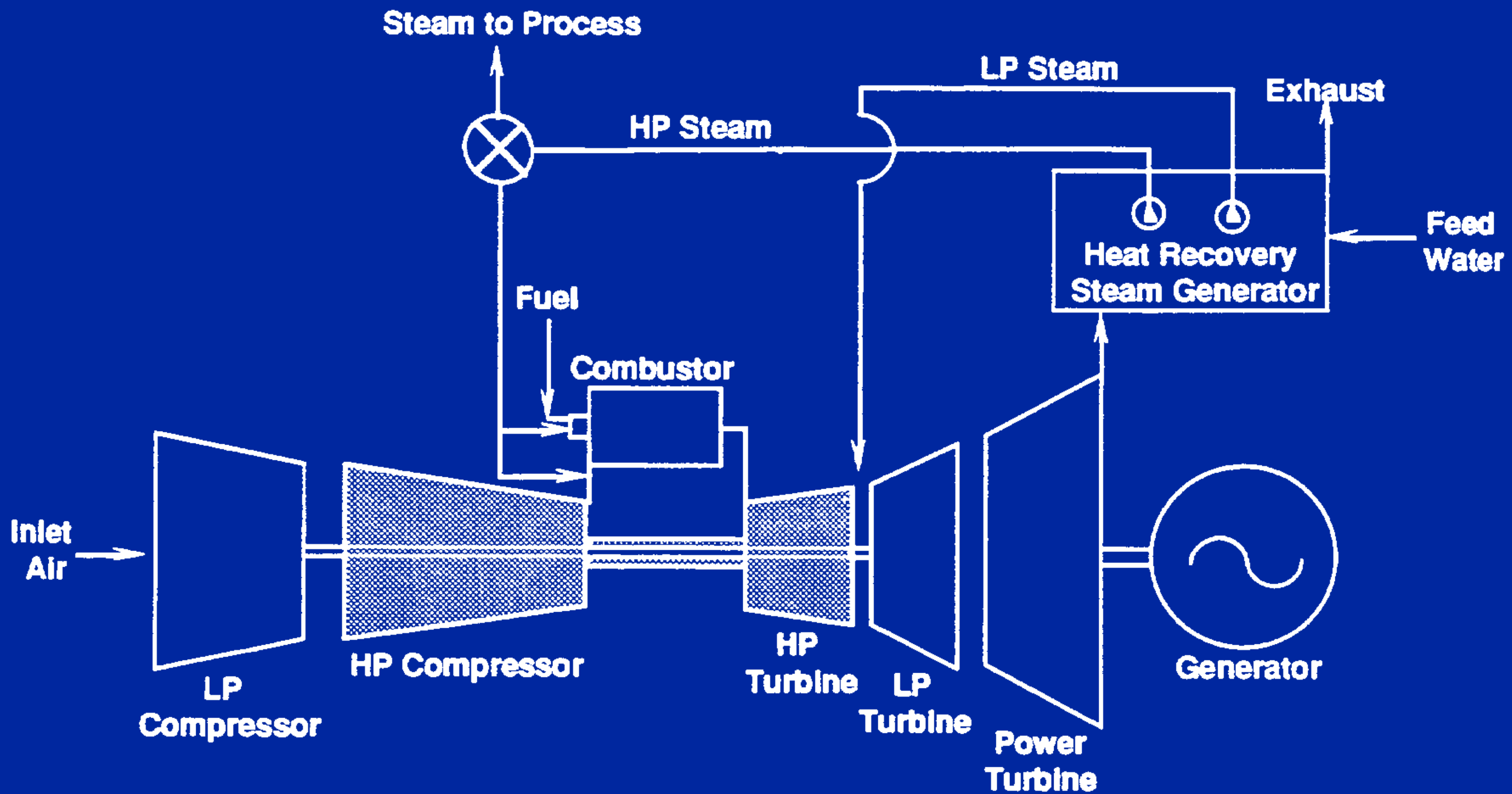


Partial STIG

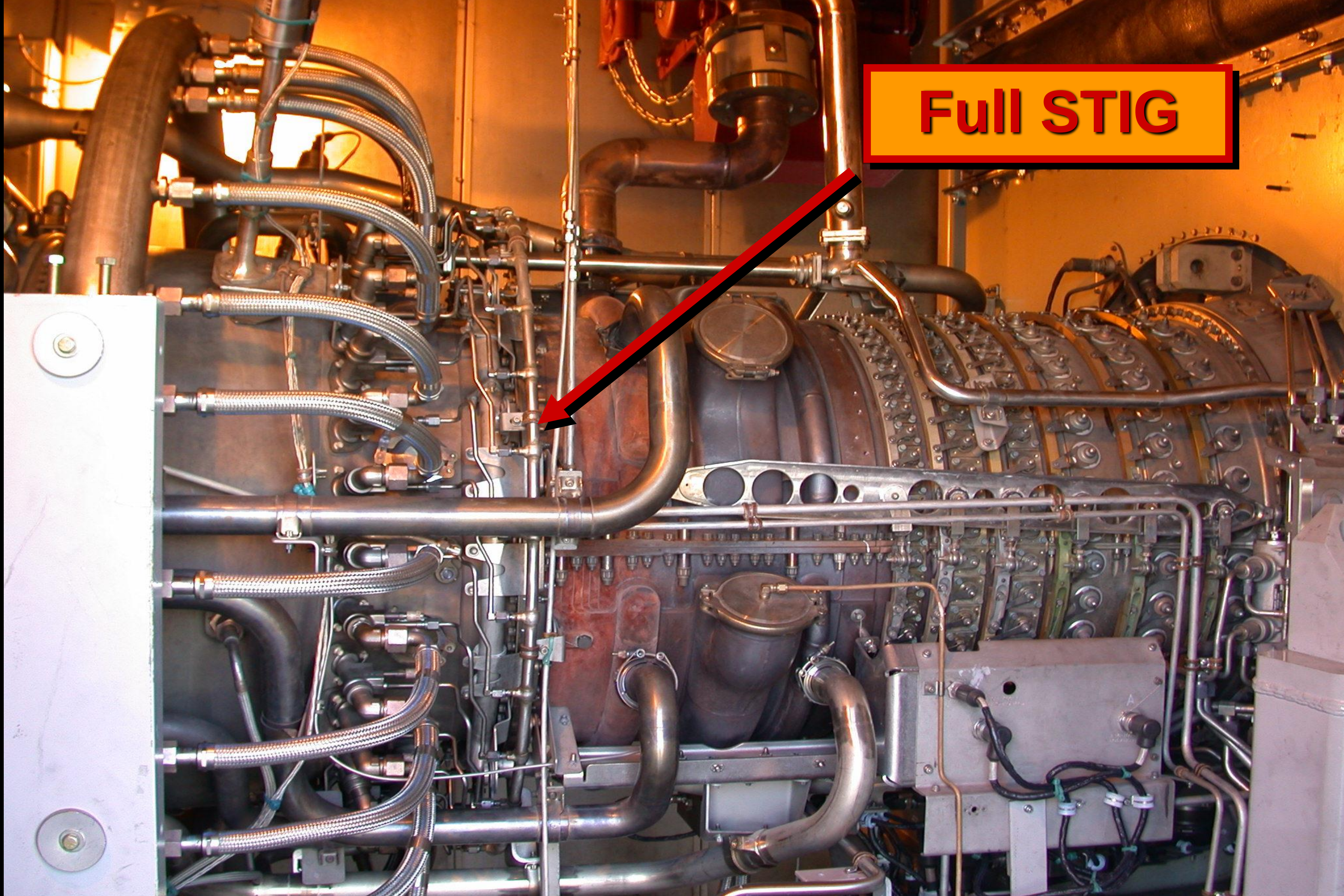


Graphic Courtesy of General Electric

Full STIG



Graphic Courtesy of General Electric


Full STIG

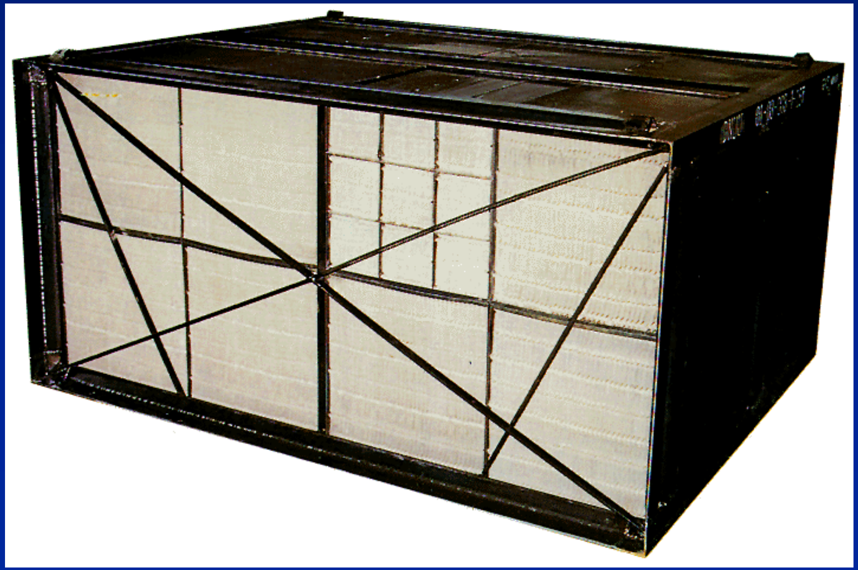
Water and Steam Injection - Summary

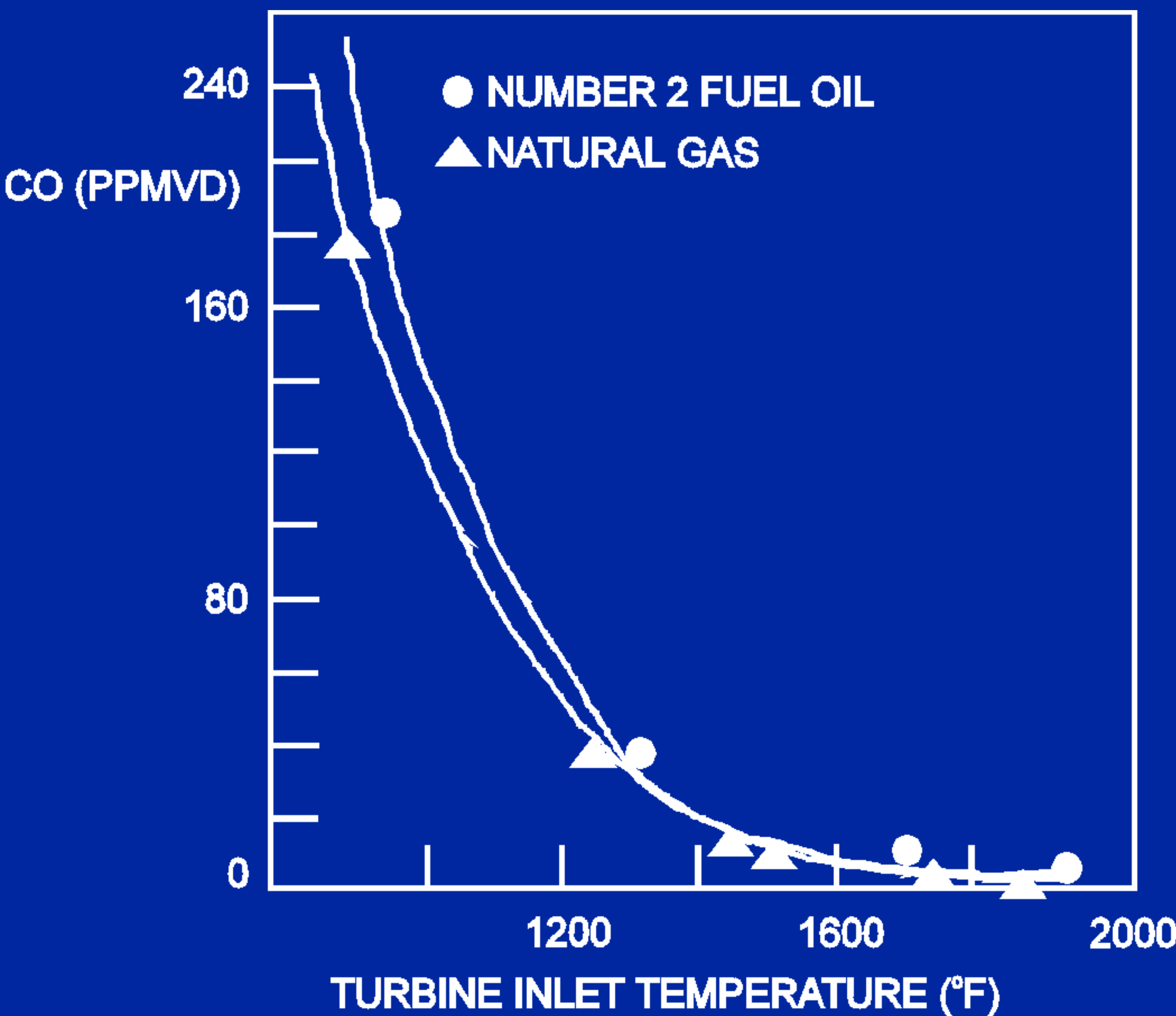
- NOx reduced
- Power output increased
- Thermal efficiency decreased
- Fuel flow rate increased
- Maintenance frequency increased

Let’s Discuss Catalytic Conversion

Catalytic Conversion

- CO is oxidized ➡ CO_2 Oxidation catalyst
- NOx is reduced ➡ N_2 Reduction catalyst



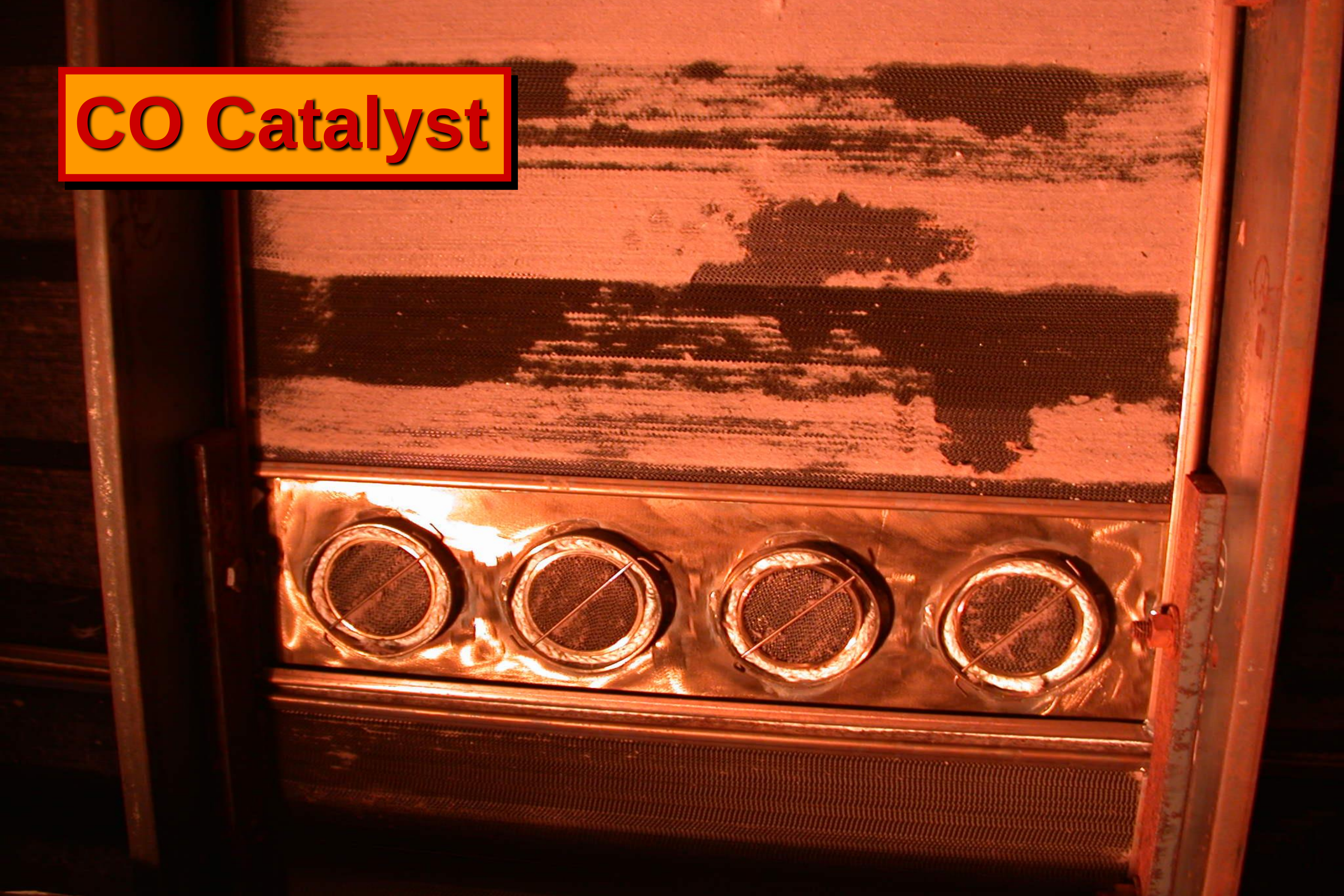


CO vs. Turbine Inlet Temp

CO Catalyst

- $2CO + O_2 \rightarrow 2CO_2$
- 700 to 1000 ºF operating temp
- 90% efficient
- Pressure drop 1-2 in. H_2O
- Problems
  - – Expensive
  - – High maintenance
  - – Catalyst replacement & disposal

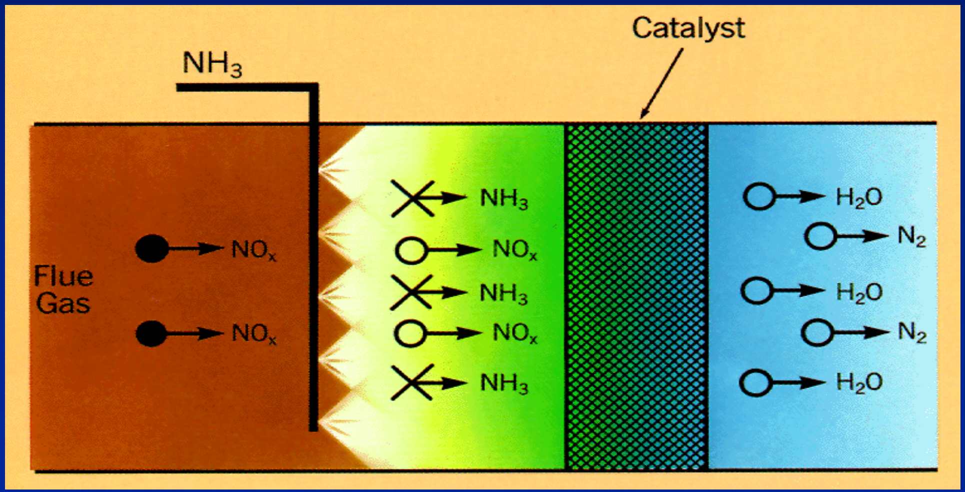
CO Catalyst



Let’s Discuss Selective Catalytic Reduction (SCR)

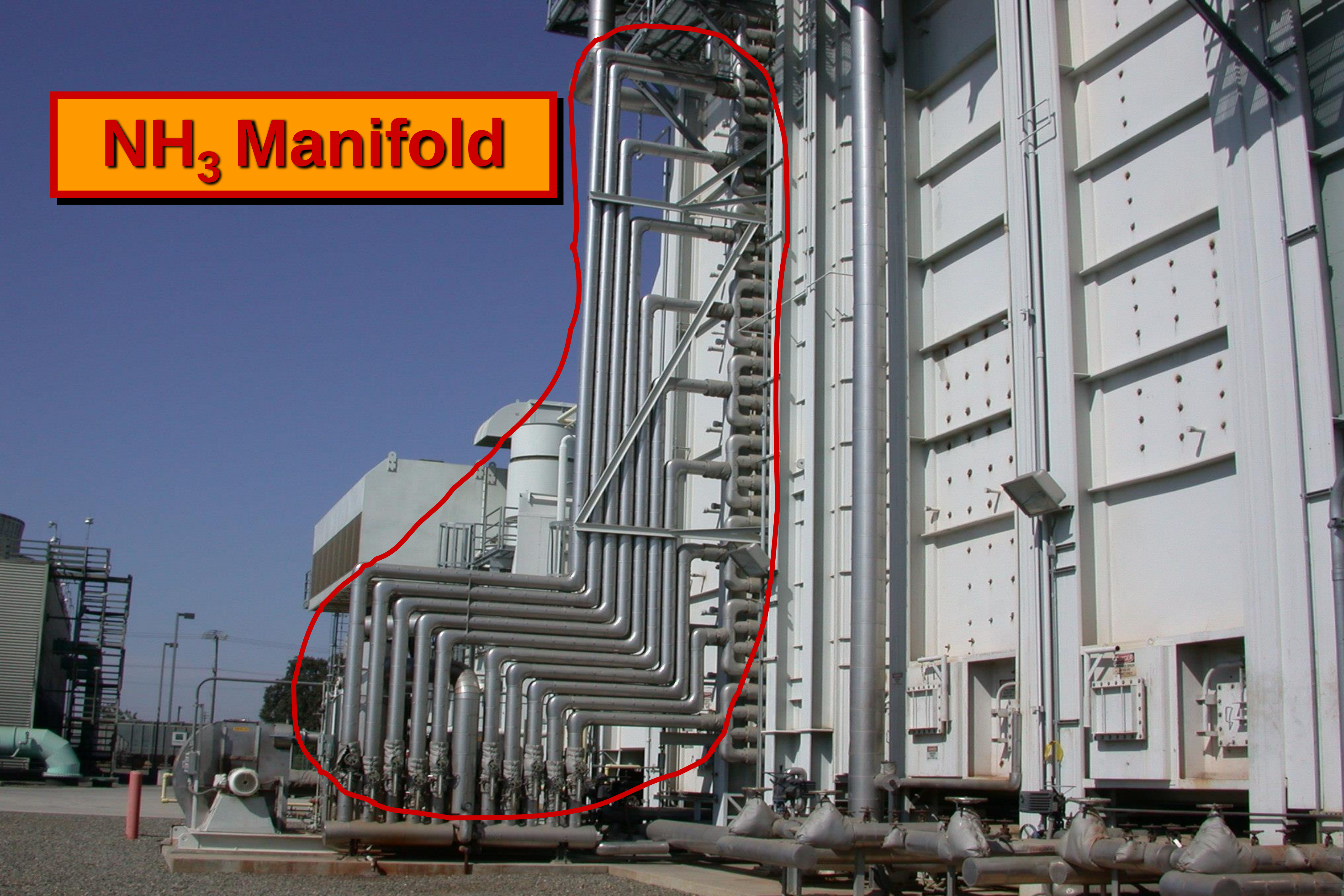
Selective Catalytic Reduction (SCR)

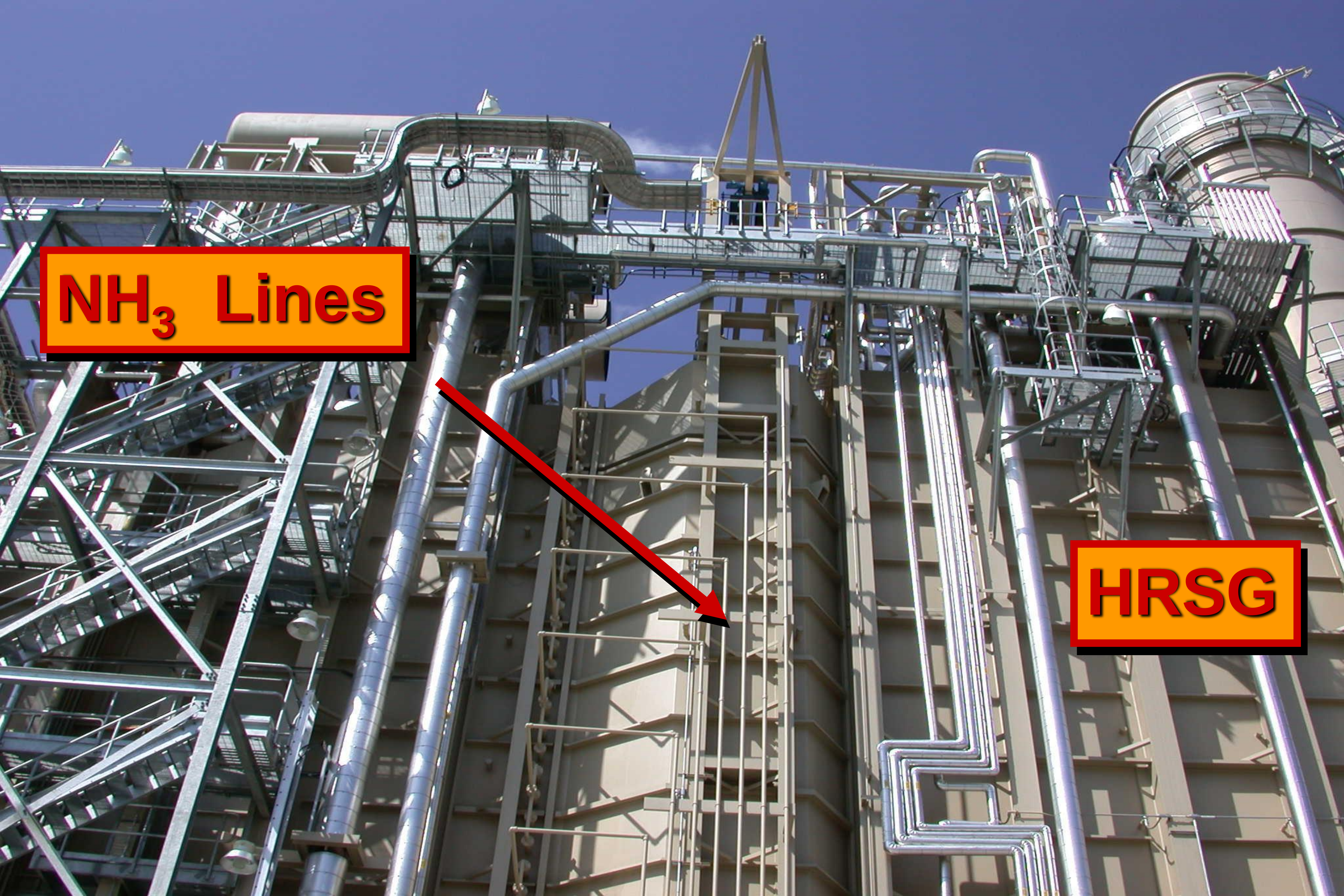
- NOx control thru ammonia (NH_3) injection
- $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$
- $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$
- 90-95% control
- Problems
  - Expensive
  - High maintenance
  - Ammonia "slip"
  - Catalyst replacement & disposal



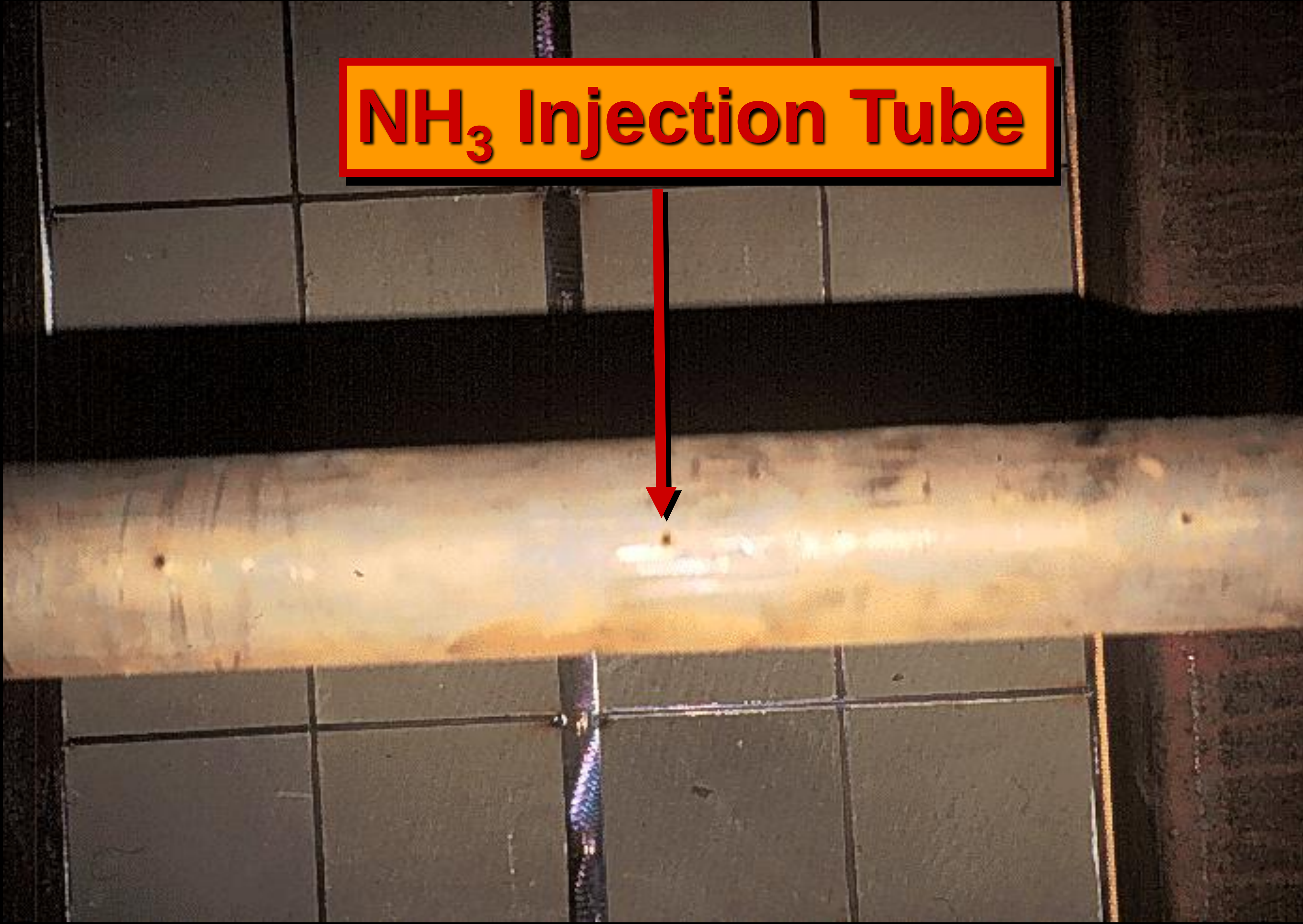
NH_3 Storage Tank


NH$_3$ Lines
AMMONIA
AMMONIA
AMMONIA
AMMONIA
AMMONIA
AMMONIA
AMMONIA
AMMONIA
AMMONIA


NH_3 Manifold



NH_3 Lines
HRSG

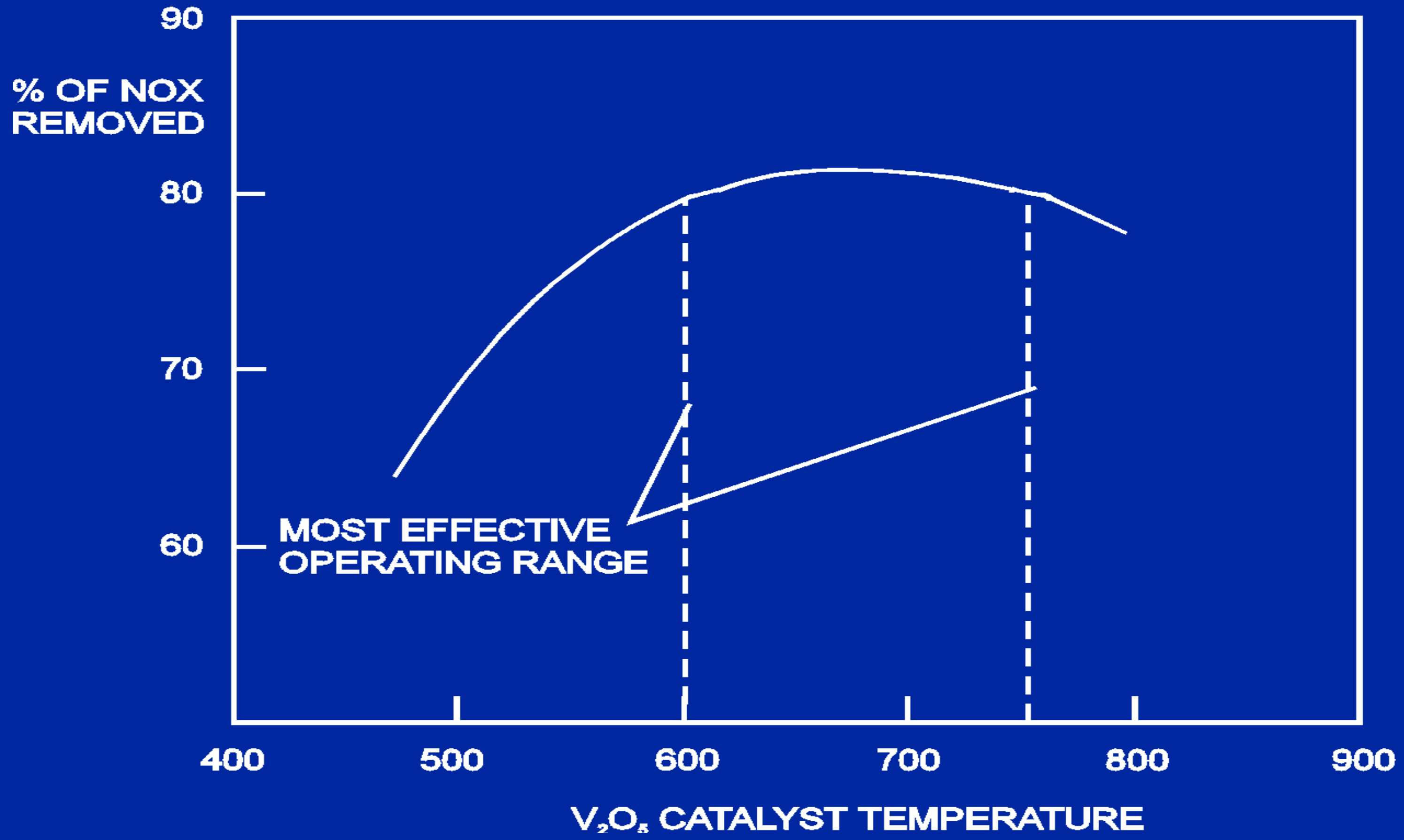

NH_3 Injection Tube

Catalyst System Installation


SCR Catalyst &
NH_3 Tubes


SCR Catalyst

% NOx Removed vs. Vanadium Pentoxide Catalyst Temperature



Regulatory Requirements

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

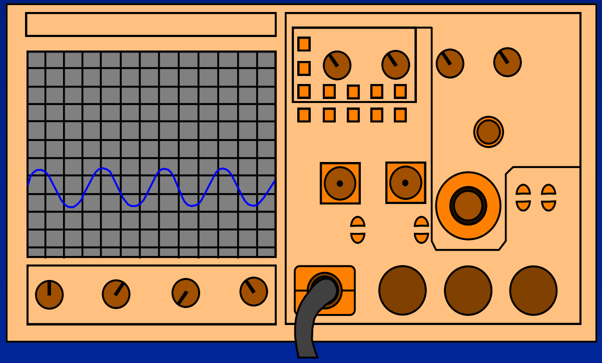
	NO_x	CO	VOC	PM_{10}	SO_x
Simple-Cycle	2.0 ppmvd @ 15%O2	6 ppmvd	2 ppmvd OR 0.0027 lbs/MMBtu (HHV)	Equiv. to natural gas with fuel sulfur < 1 grain/100 scf	Equiv to natural gas with fuel sulfur < 1 grain/100 scf (< 0.55 ppmvd)
Combined-Cycle & Cogen	2.0 ppmvd @ 15% O2	3.0 ppmvd	2 ppmvd OR 0.0027 lbs/MMBtu (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
  - O_2
  - 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

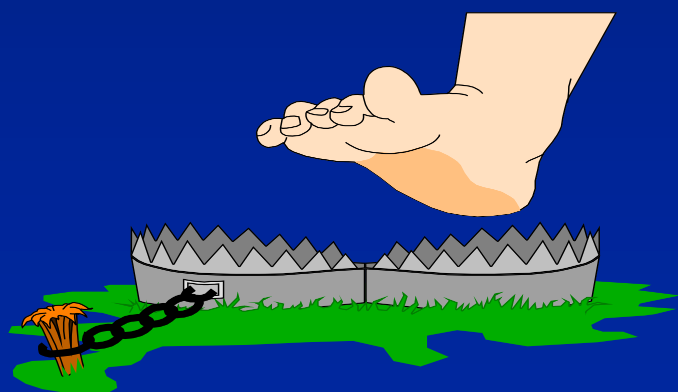
Inspection

- 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
  - https://www.epa.gov/sites/production/files/2016-03/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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