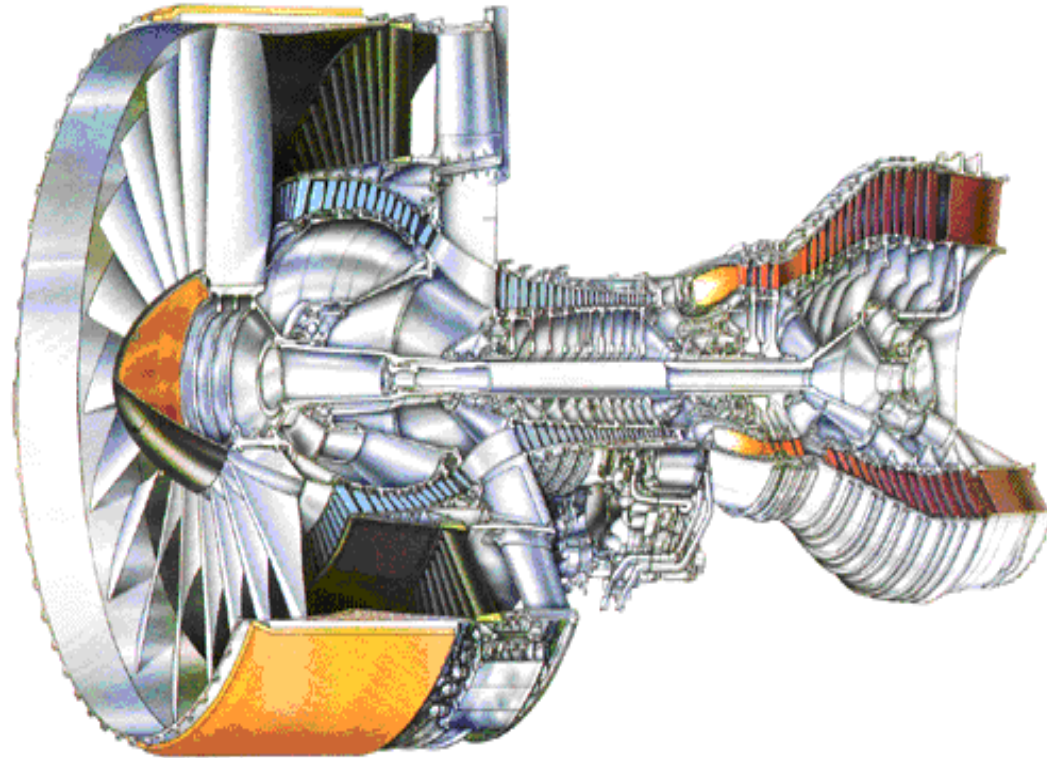


NACT 272



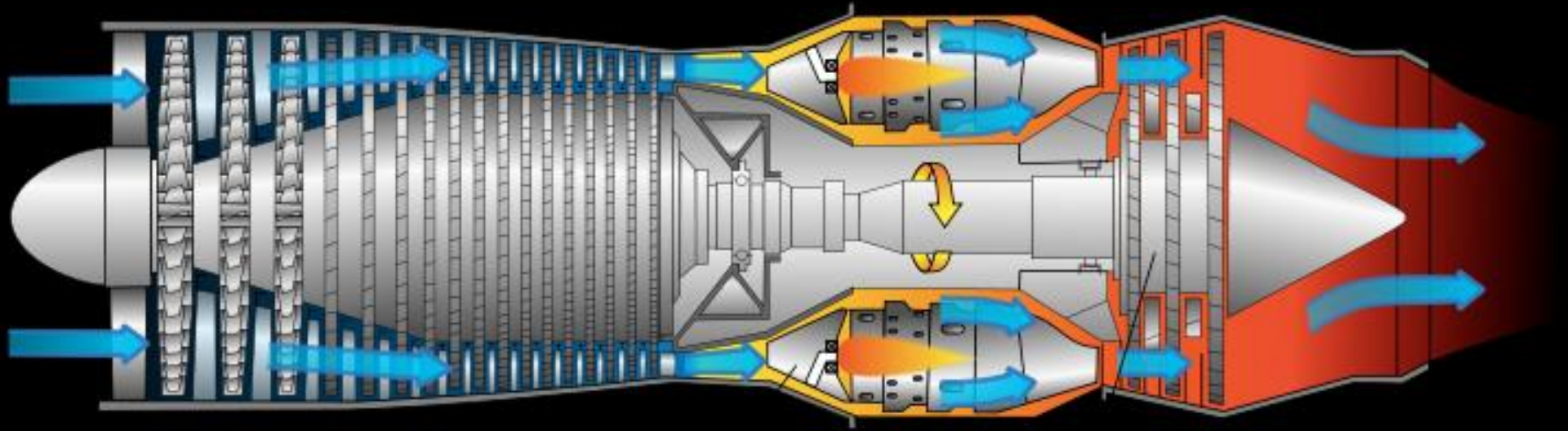
Stationary Gas Turbines

Course Overview

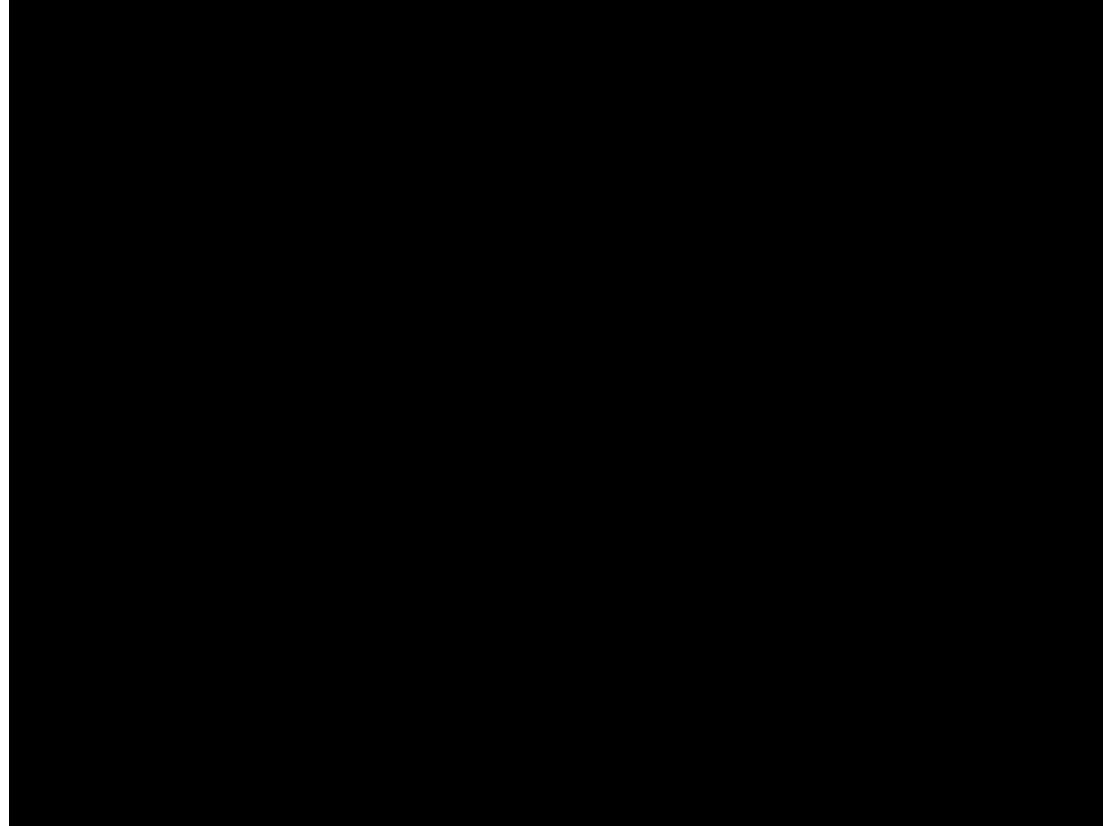
- ◆ Gas turbine theory and operation
- ◆ Gas turbine uses
- ◆ Air pollution control devices
- ◆ Gas turbine regulations
- ◆ Typical permit conditions
- ◆ Inspection procedures
- ◆ Continuous emission monitoring
- ◆ Source testing requirements



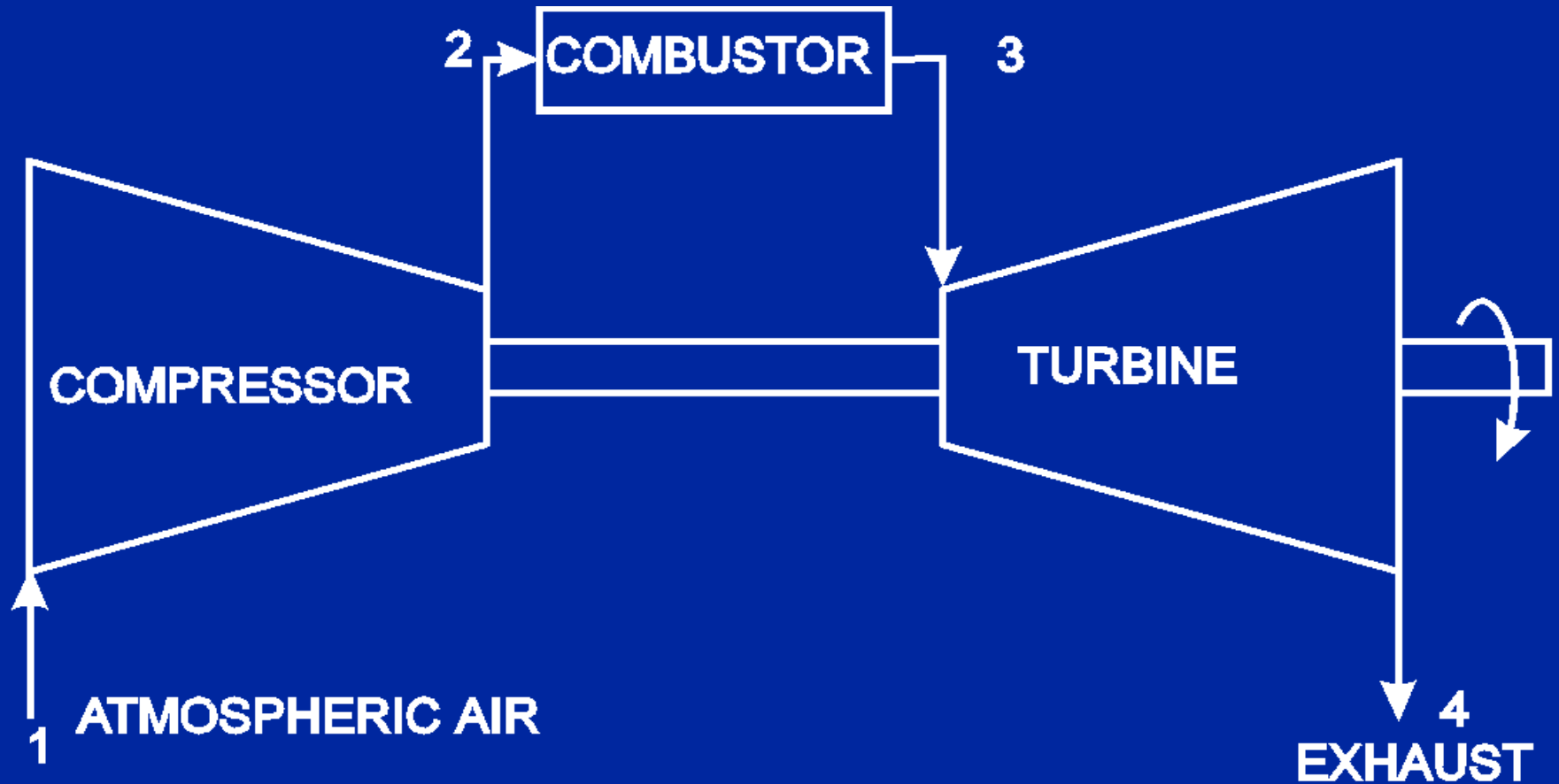
What is a Gas Turbine



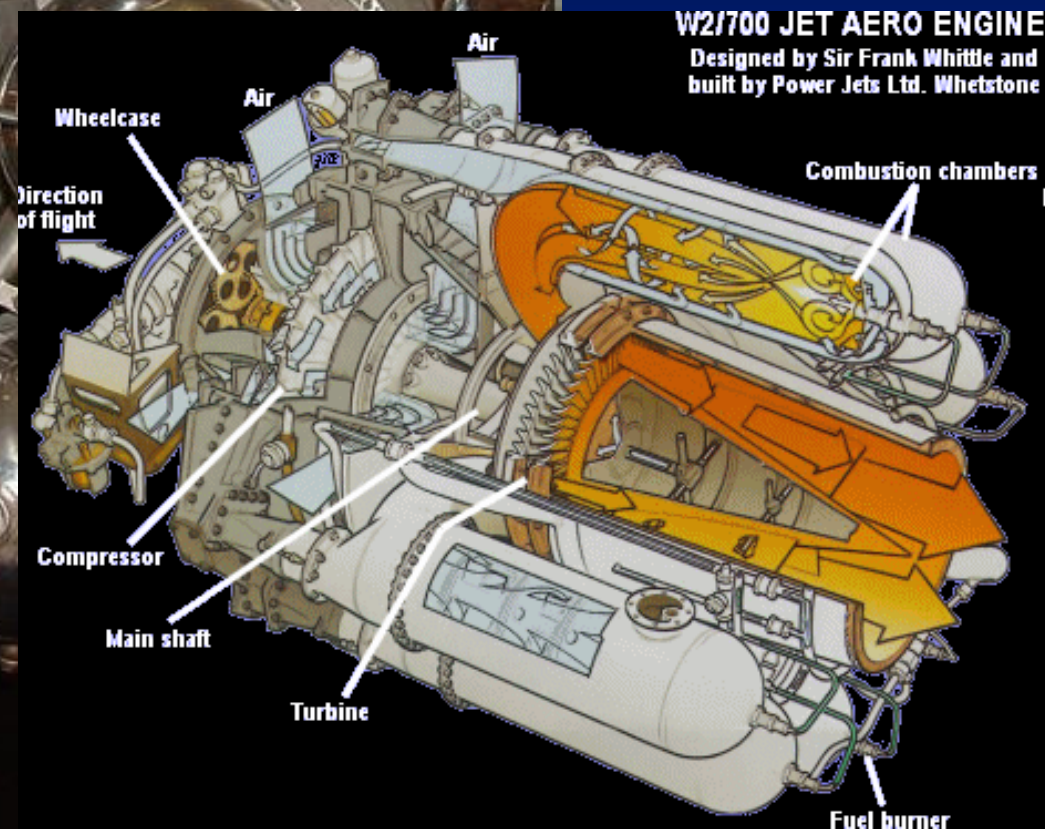
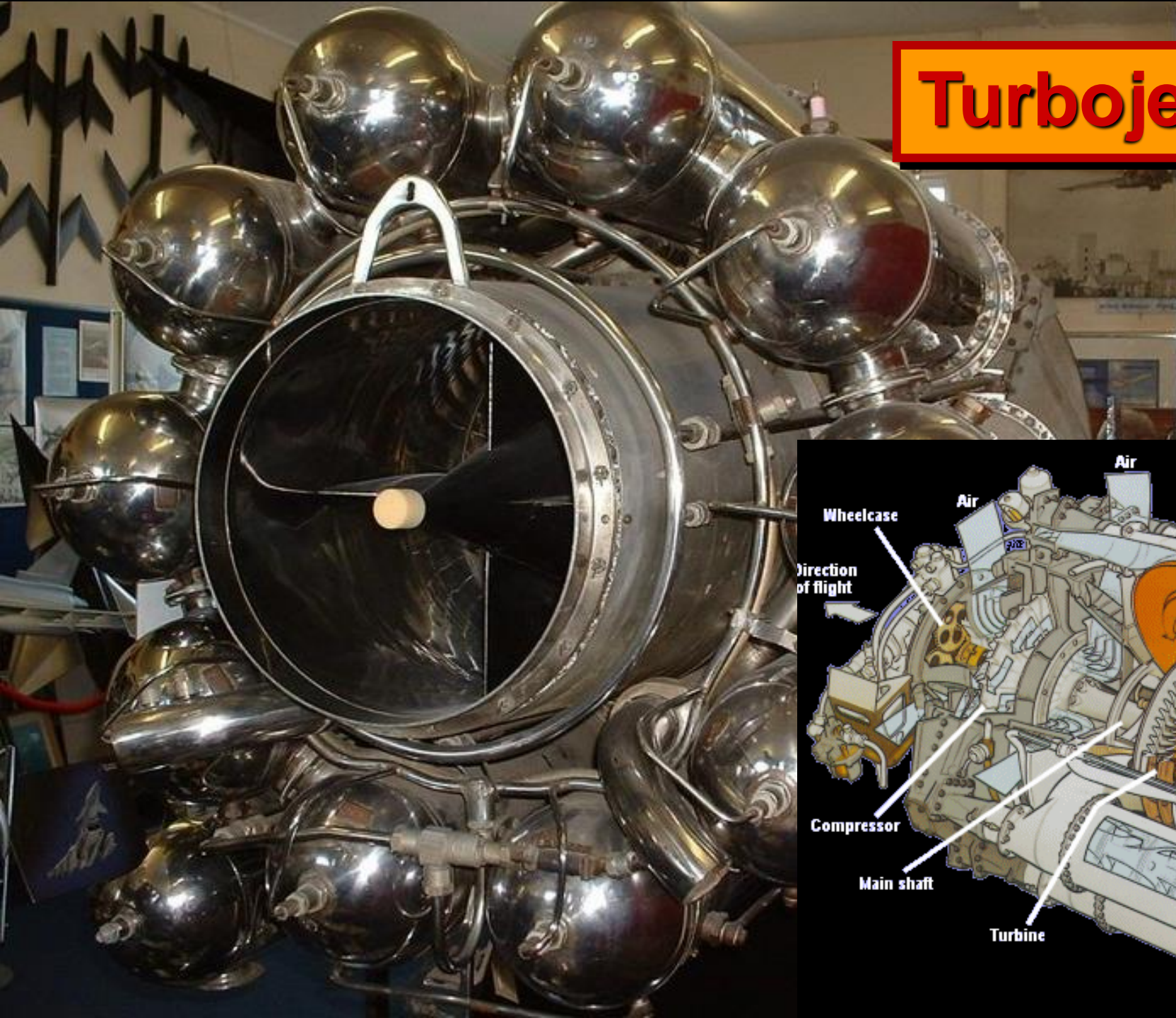
How does a Turbine Work?



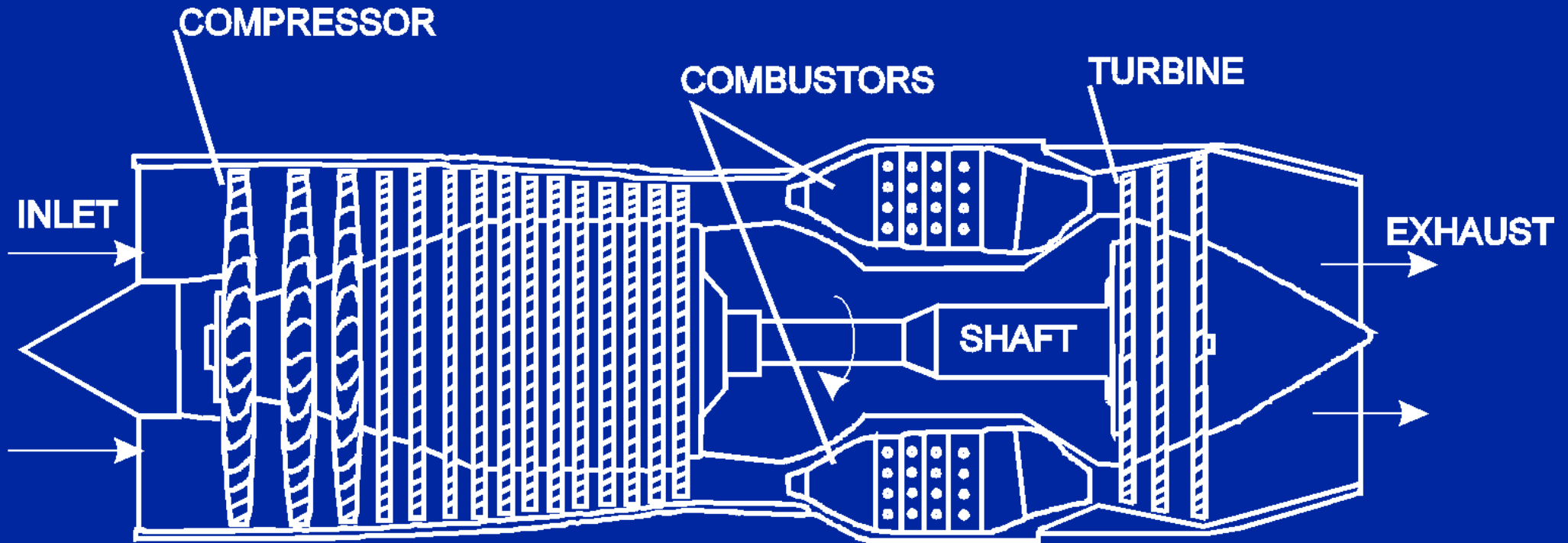
Simple Open Cycle Gas Turbine



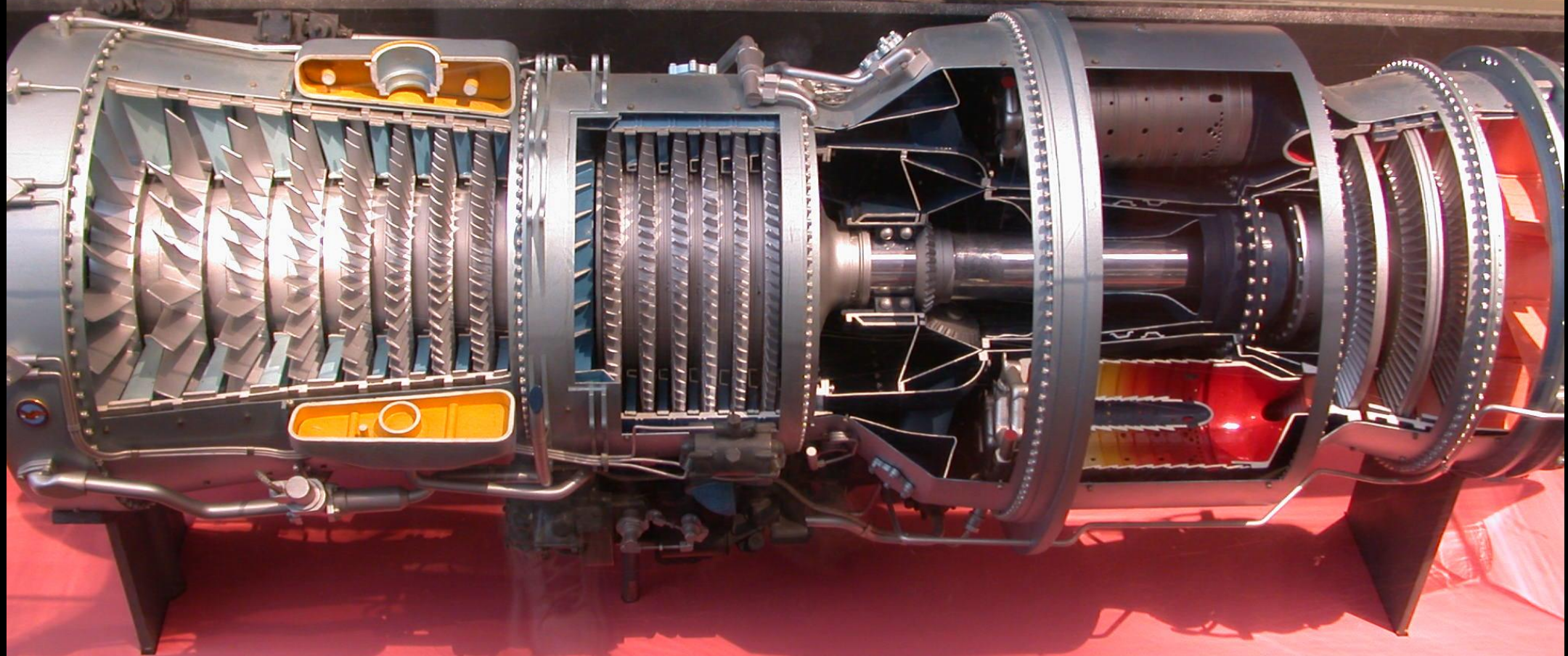
Turbojet Engine



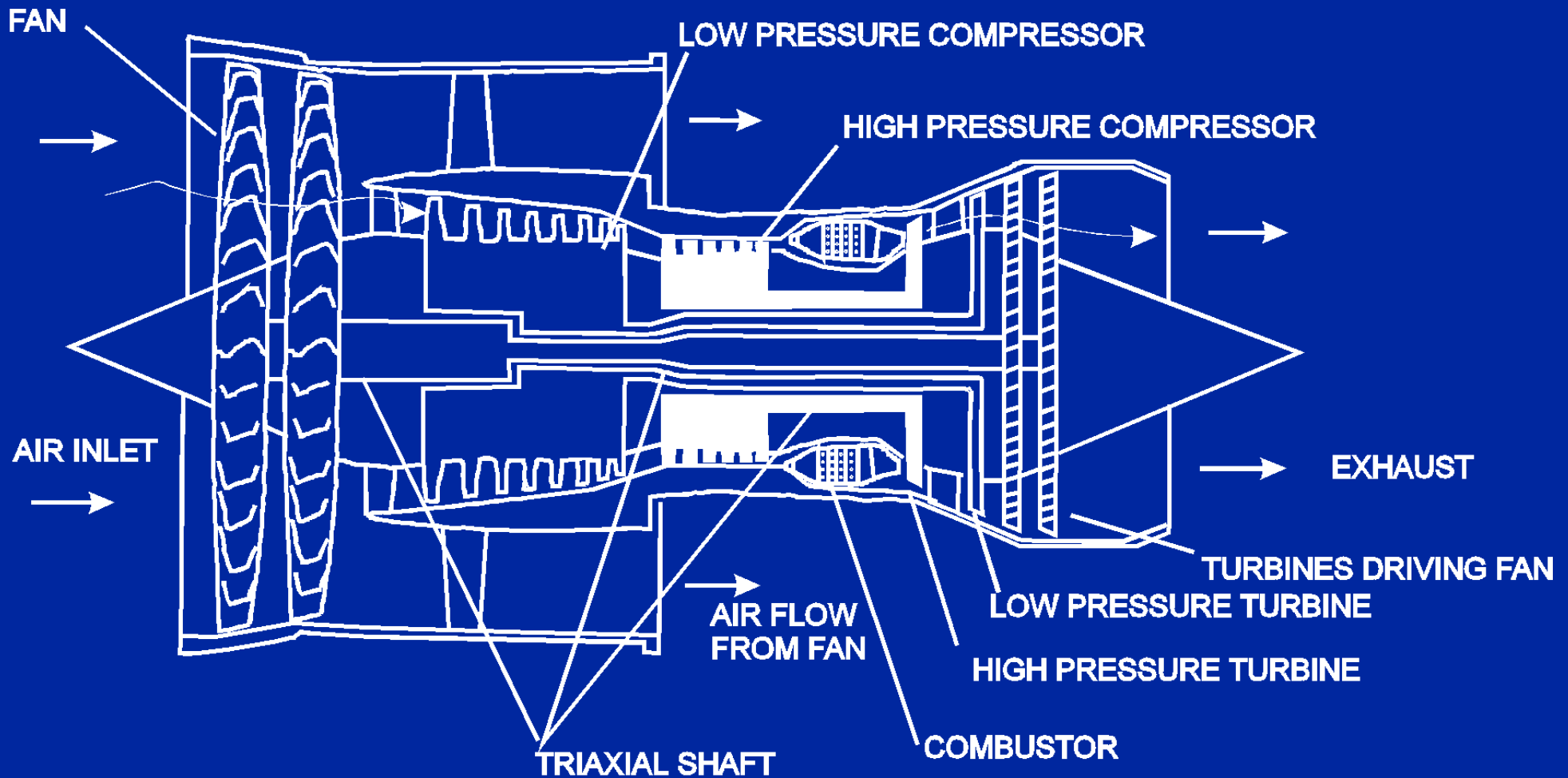
Single Spool Turbojet Engine

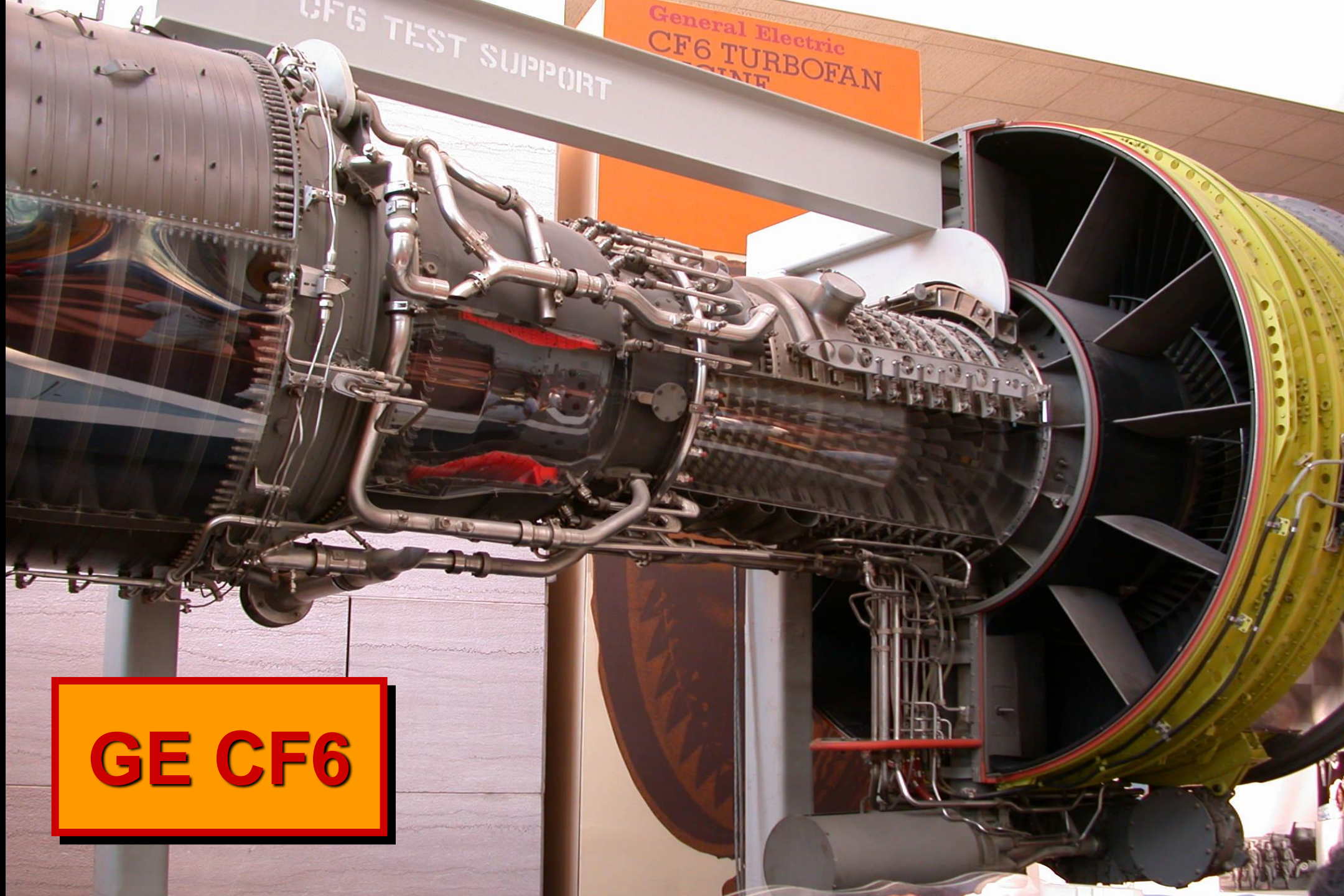


Turbojet Engine



Turbofan Gas Turbine Engine

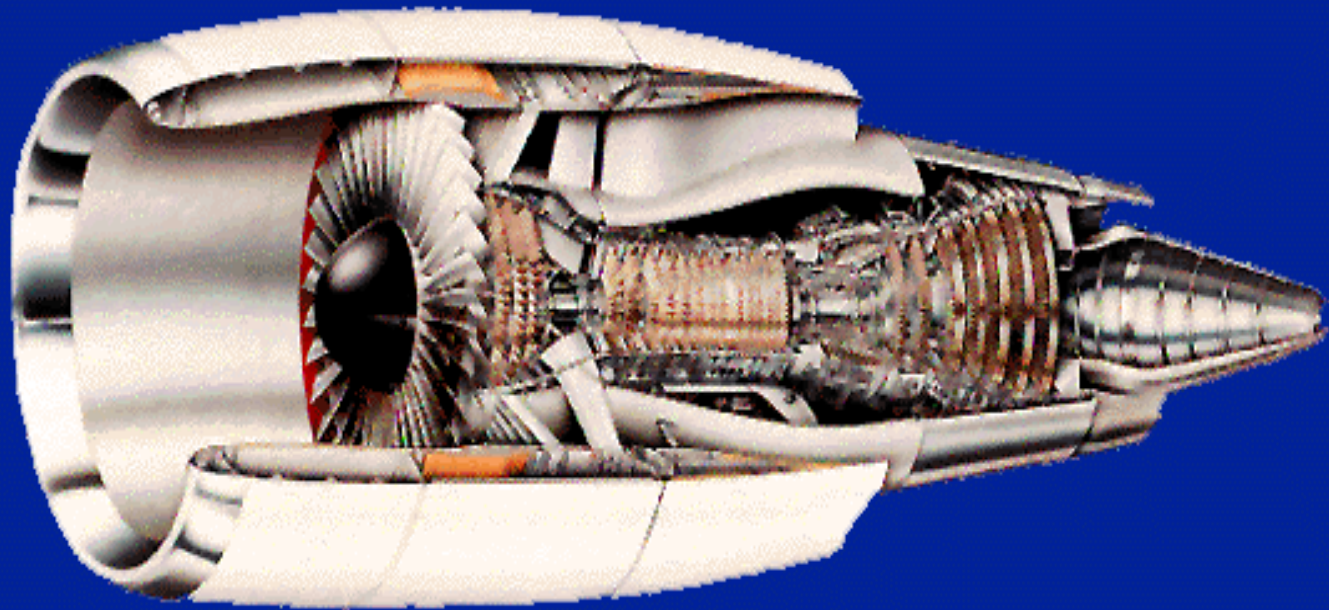




CF6 TEST SUPPORT

General Electric
CF6 TURBOFAN
ENGINE

GE CF6

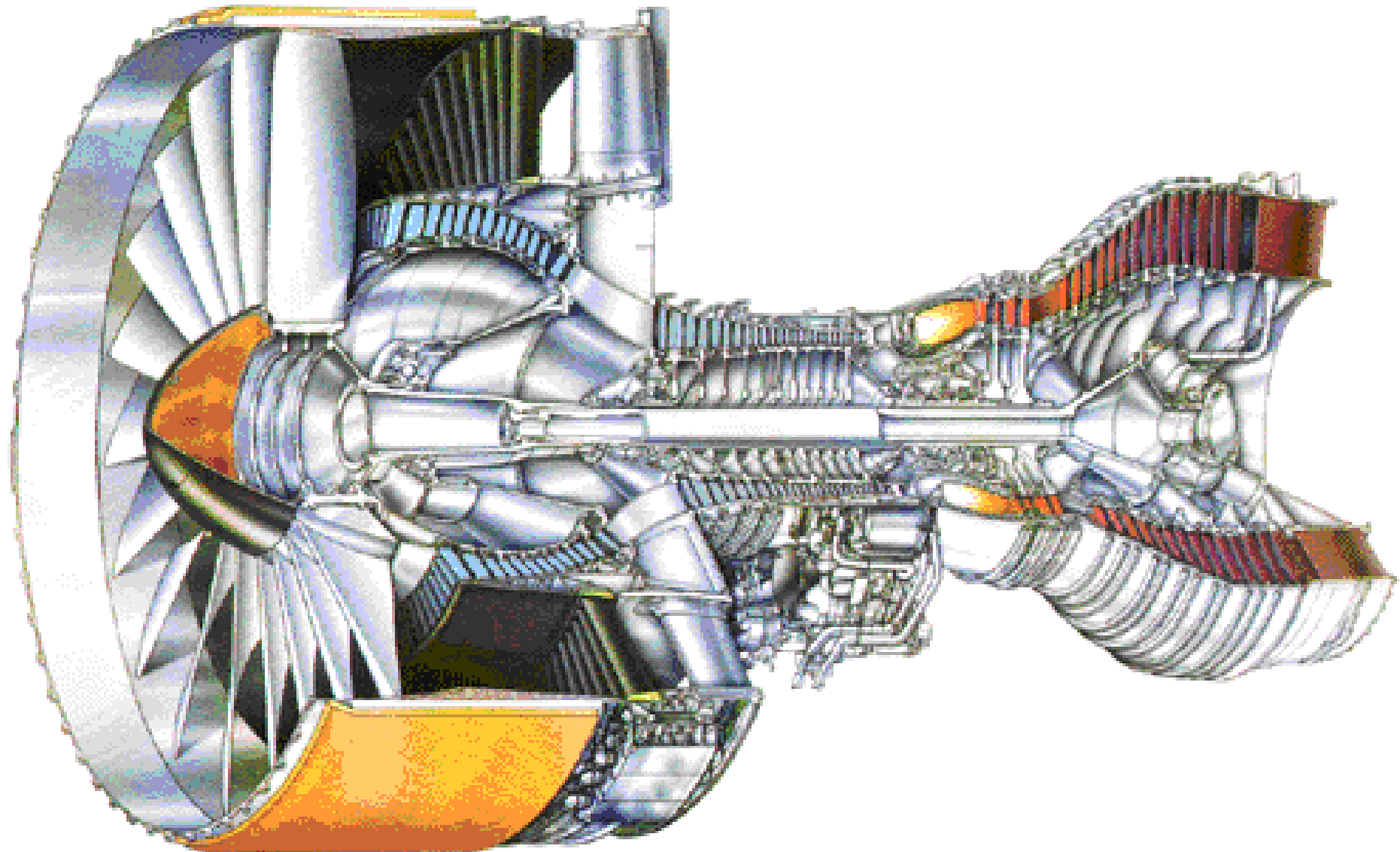


**GE High Bypass
Turbofan**



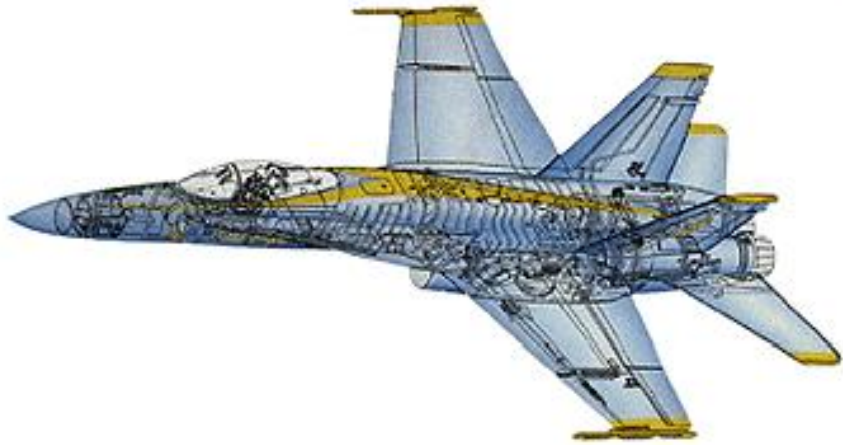
**Presidential
Boeing 747**

PW4000 112-INCH FAN ENGINE





**Boeing 777 With Pratt
and Whitney PW4000**



Jet Aircraft

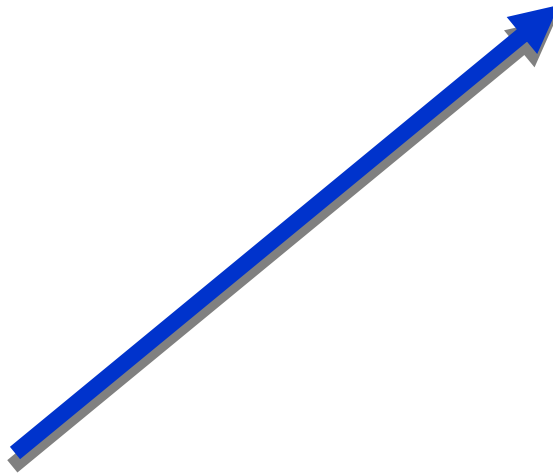


Stationary Sources



Marine Power

Gas Turbine Uses



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

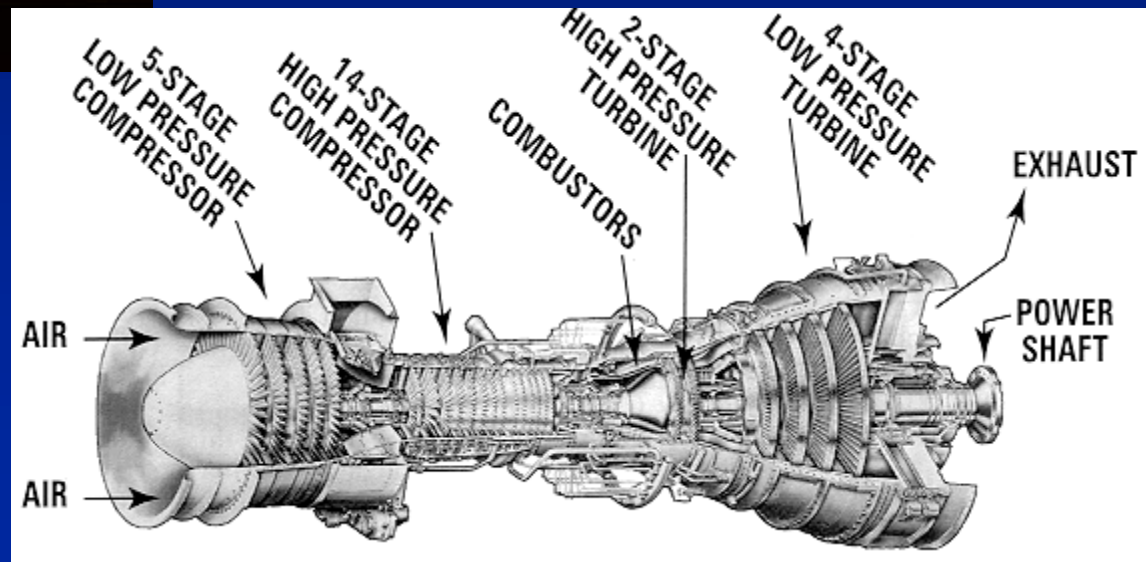




400MW (MEGAWATT) GAS TURBINE



Marine Engines

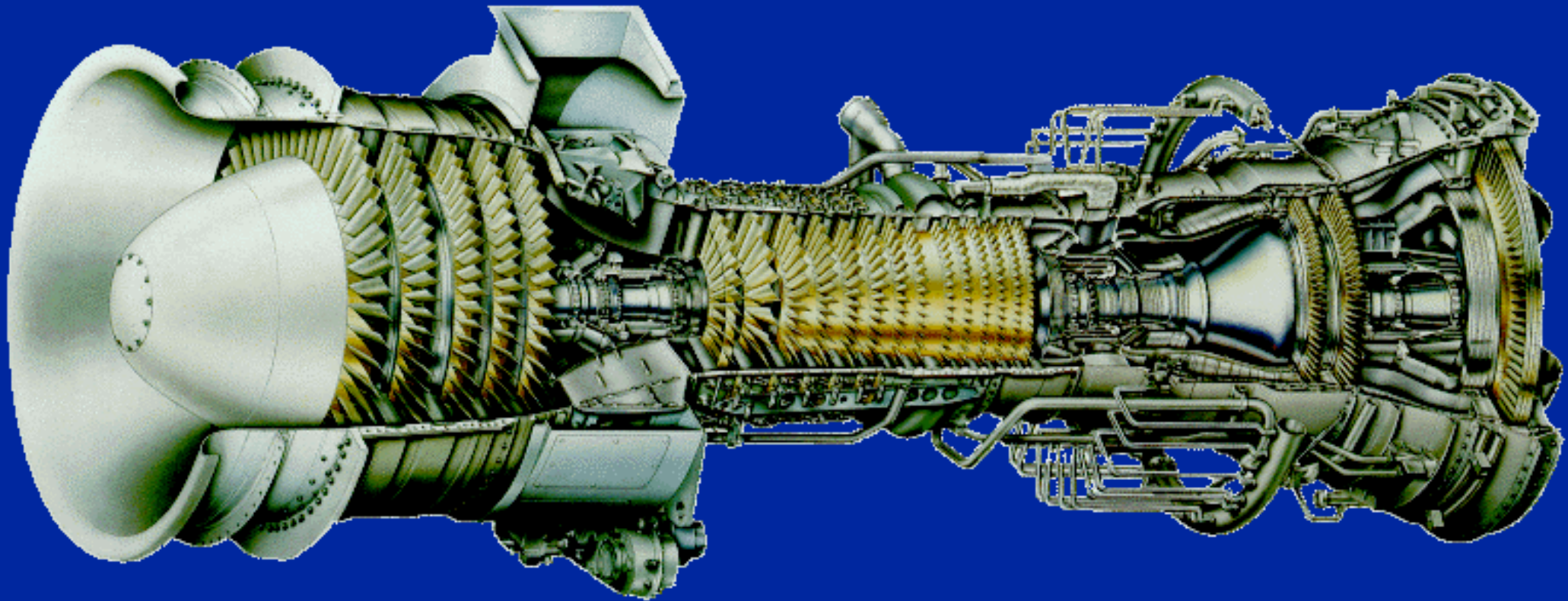




Aeroderivative Turbines

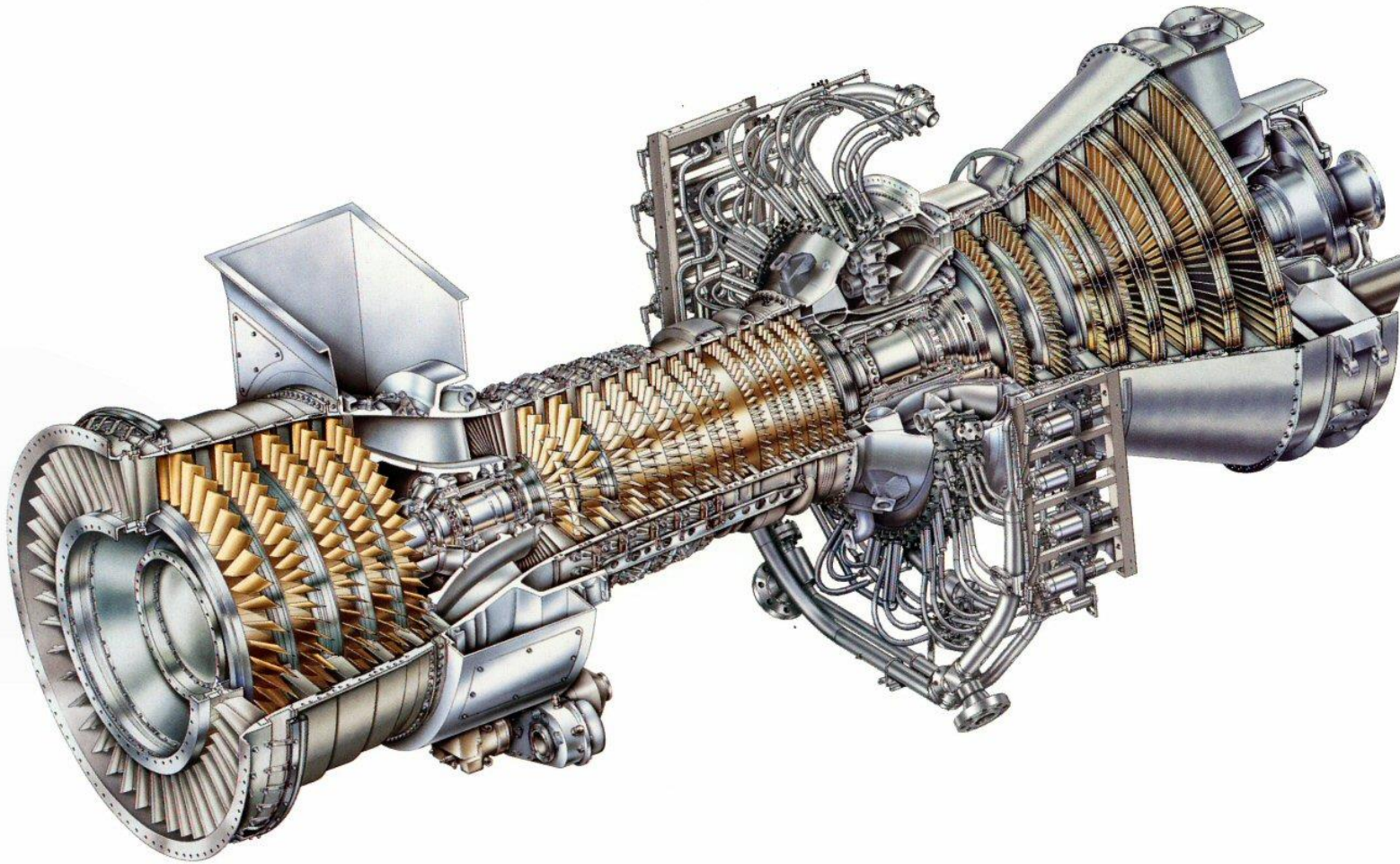
- ◆ **Based on established product**
- ◆ **High simple cycle efficiency**
- ◆ **High power to weight ratio**
- ◆ **Direct generator drive capability**
- ◆ **Ease and speed of maintenance**
- ◆ **Parts availability**

GE LM5000 Gas Turbine

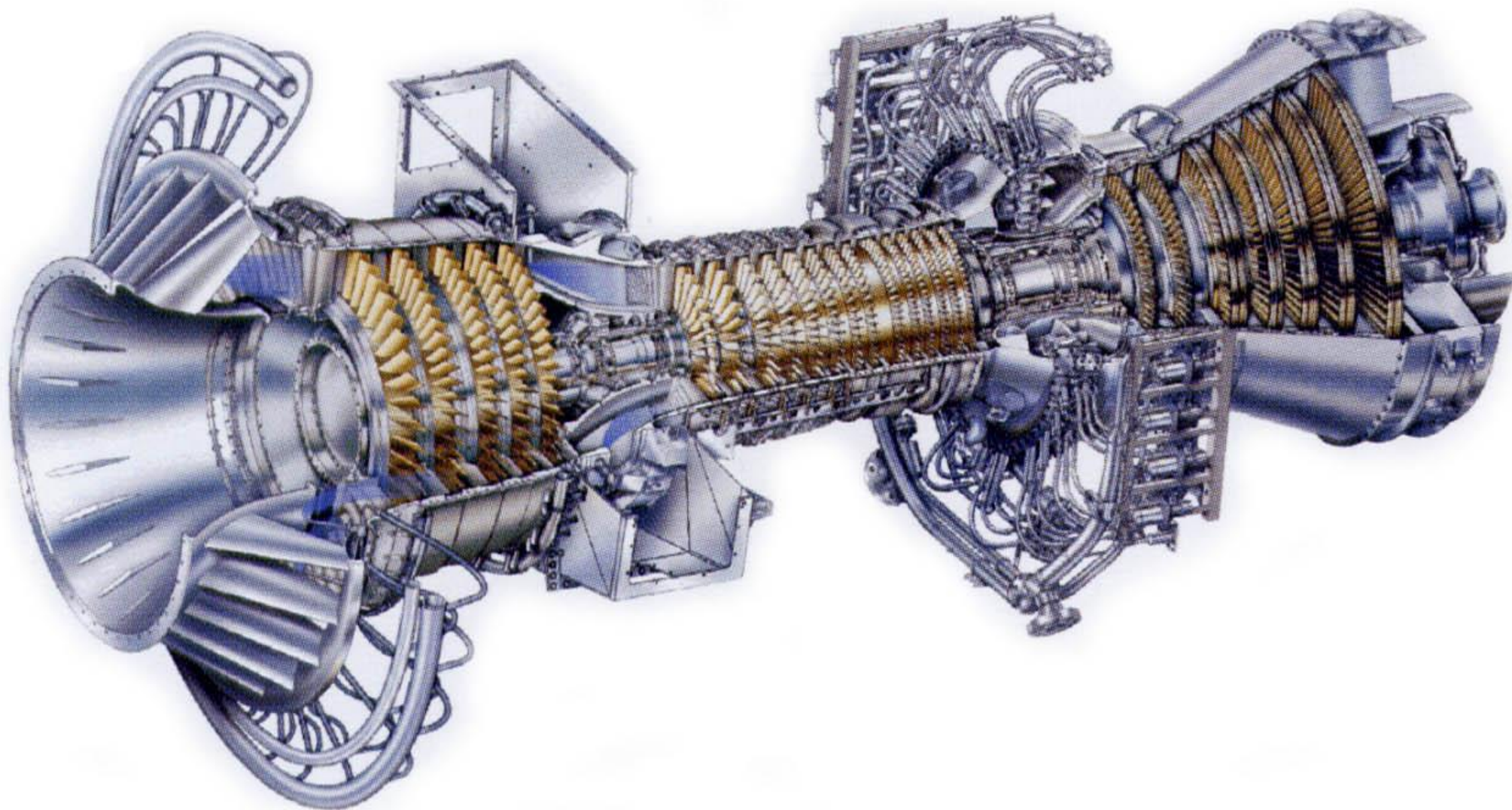


Graphic Courtesy of General Electric

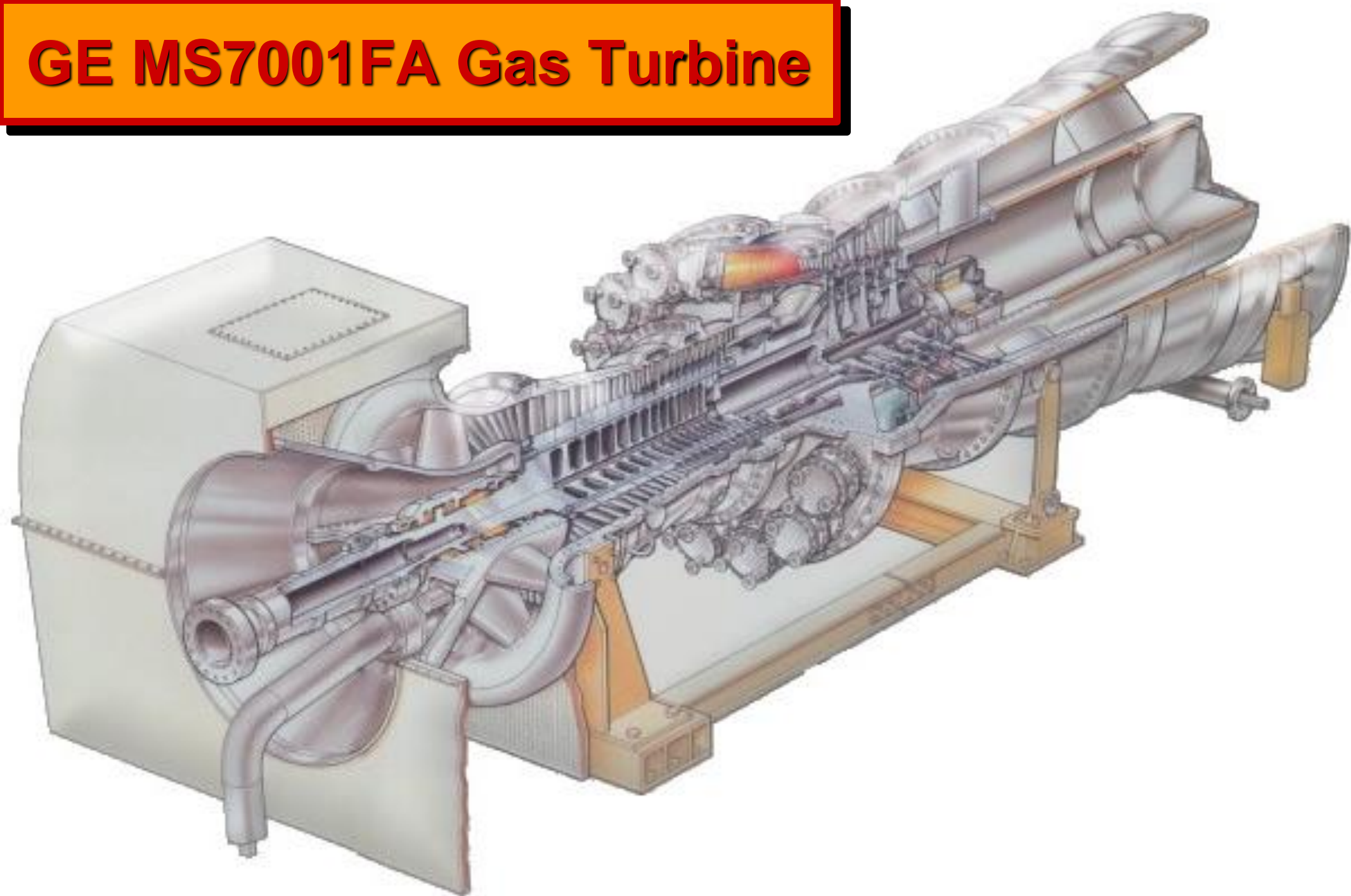
GE LM6000 Gas Turbine



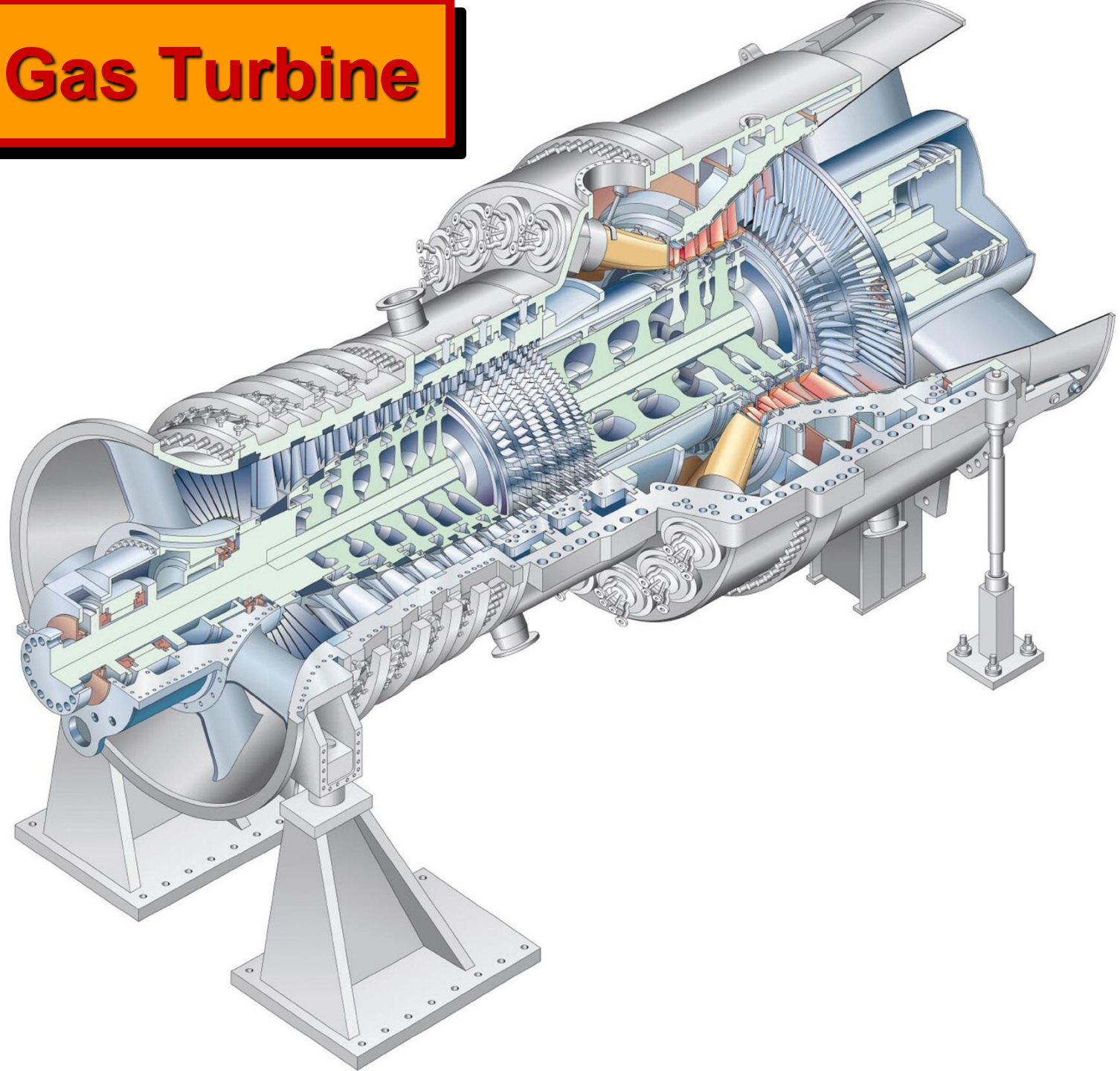
GE LM6000 with Sprint



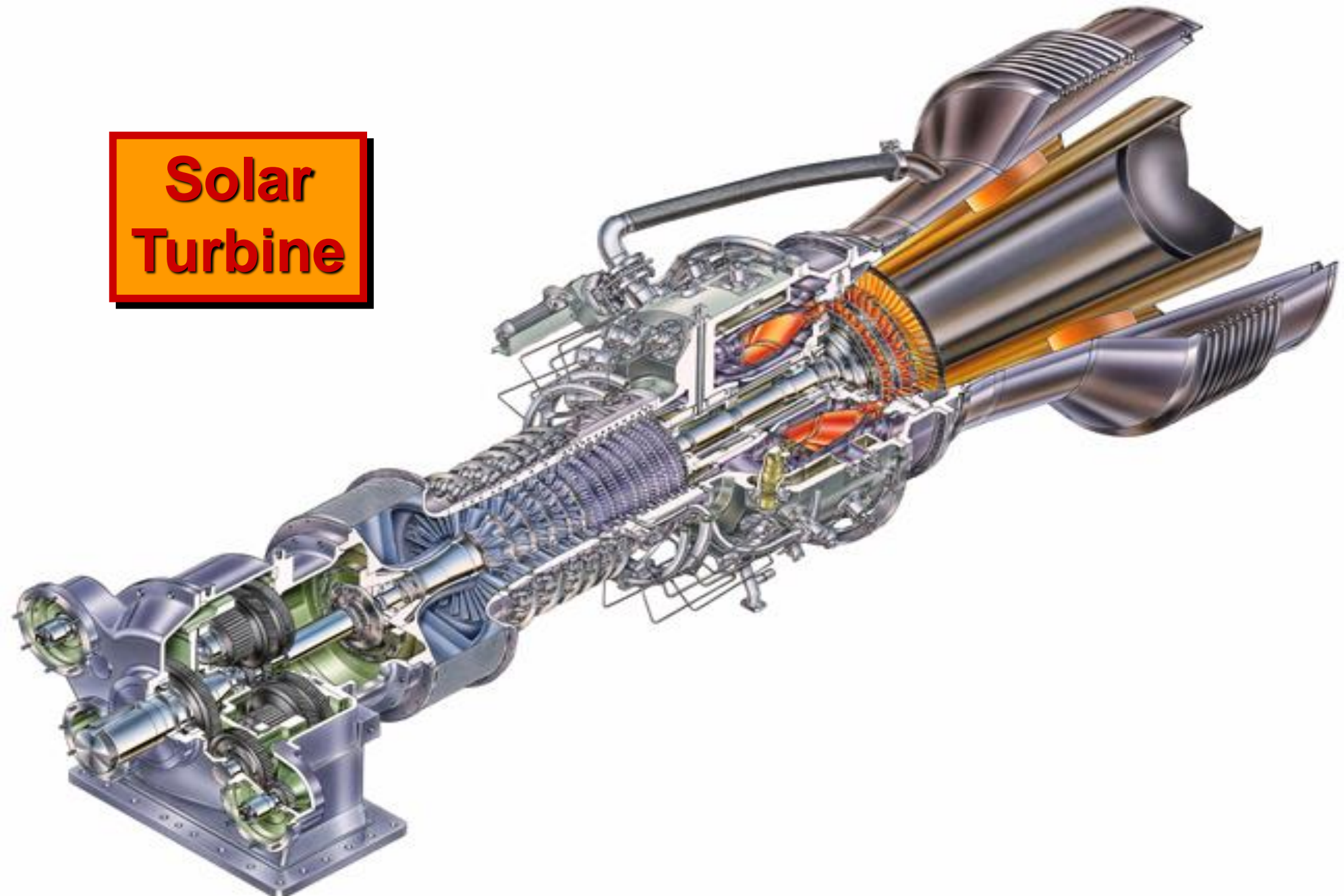
GE MS7001FA Gas Turbine



Siemens Gas Turbine



Solar Turbine

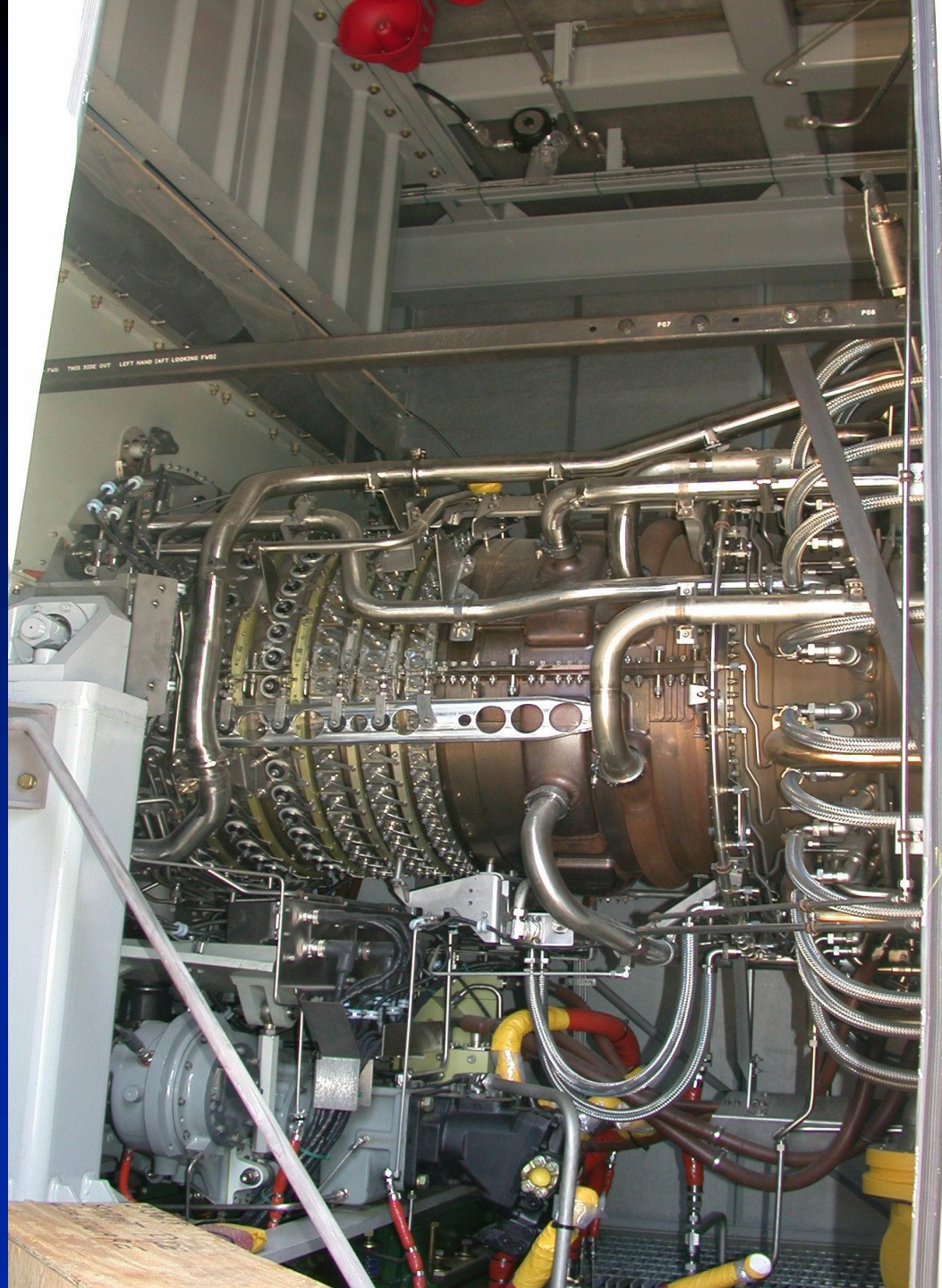


Aeroderivative Turbine



Aeroderivative Turbine

LM 6000 : 50 MW



Important Terms

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

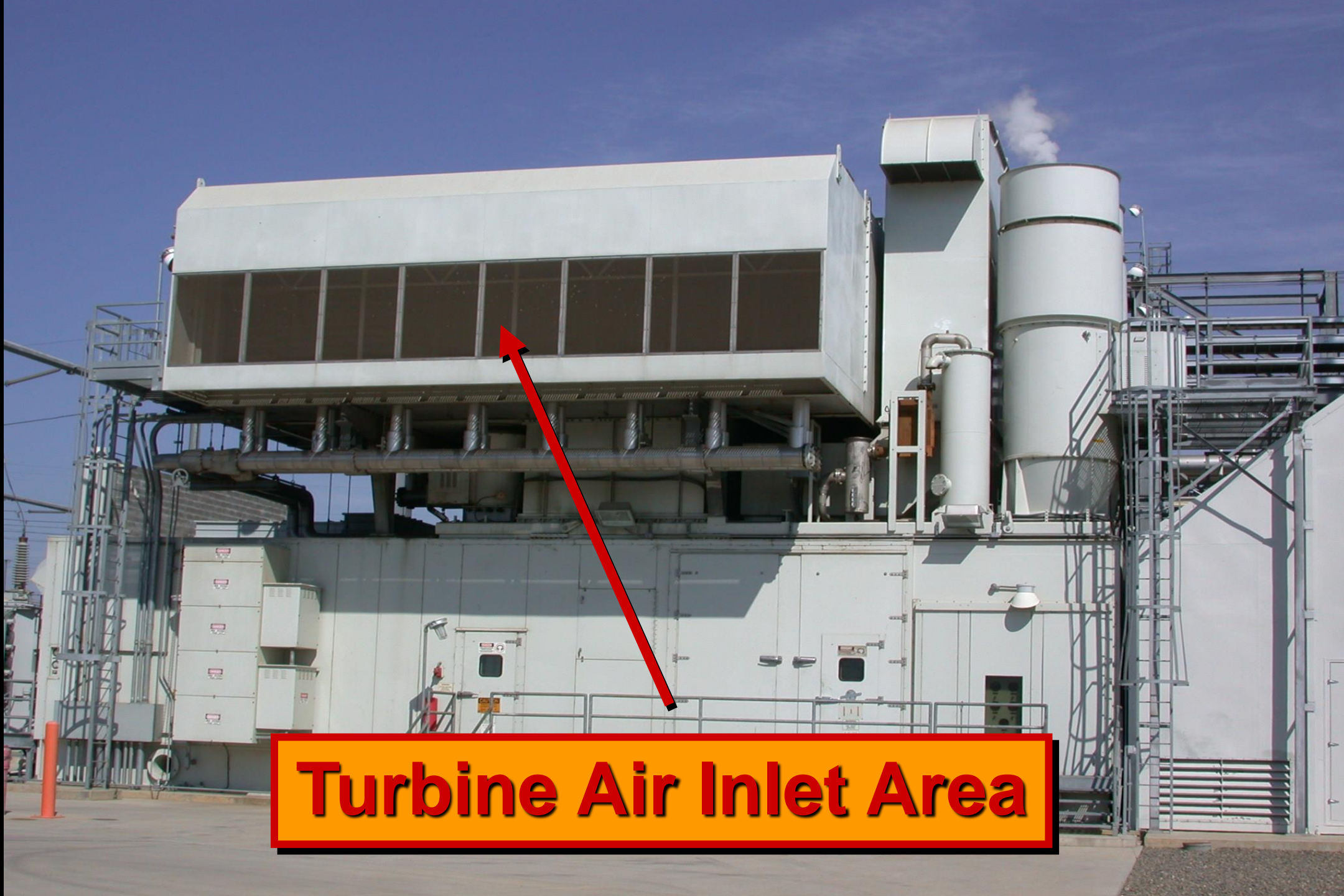


Gas Turbine Power Plant



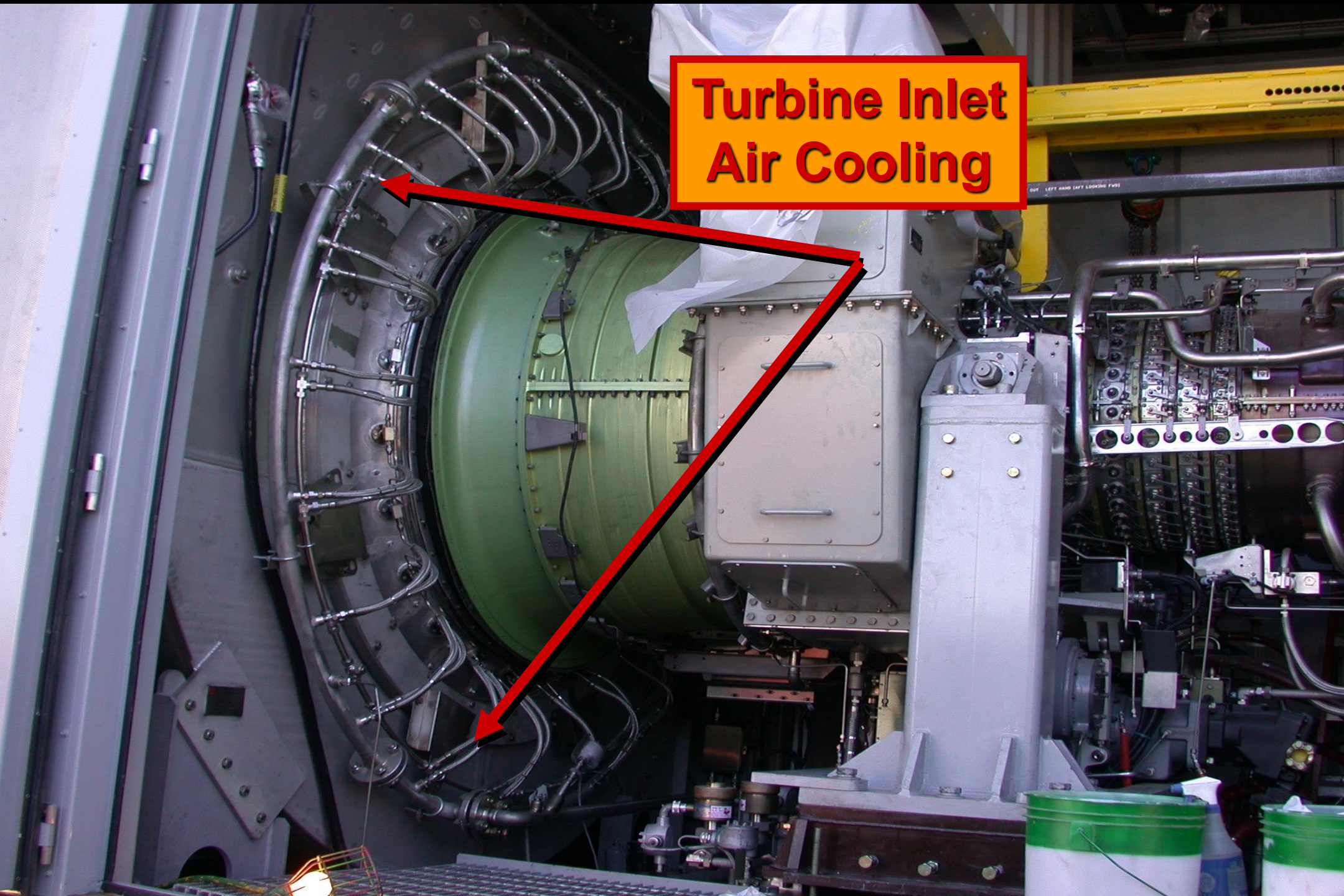
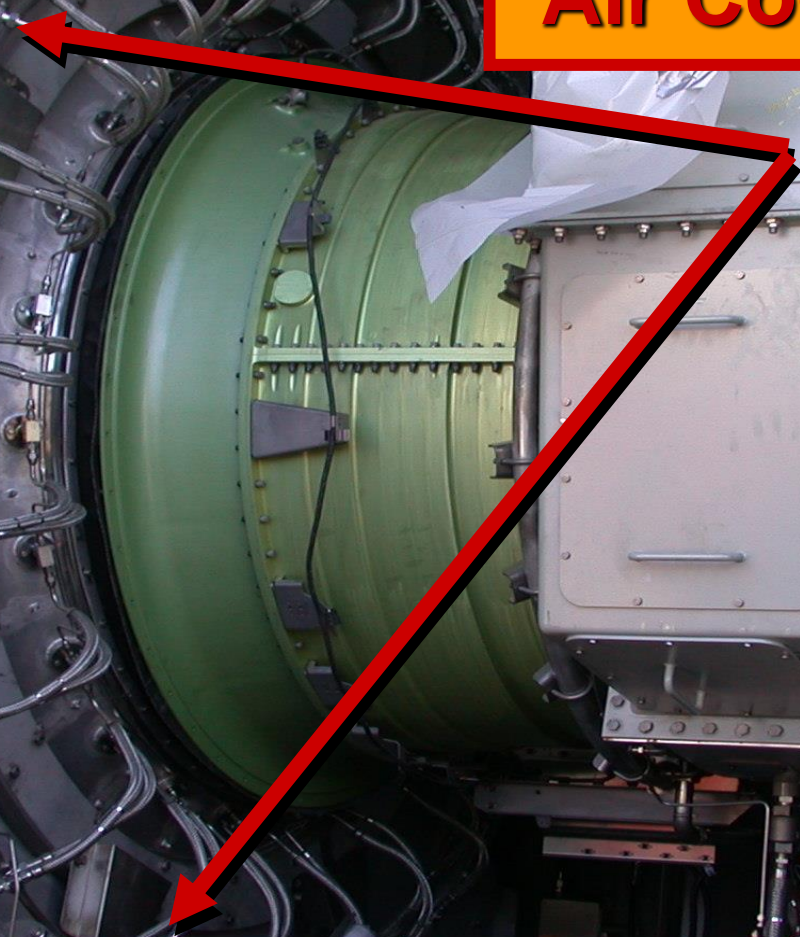


**Turbine
Inlet Air**



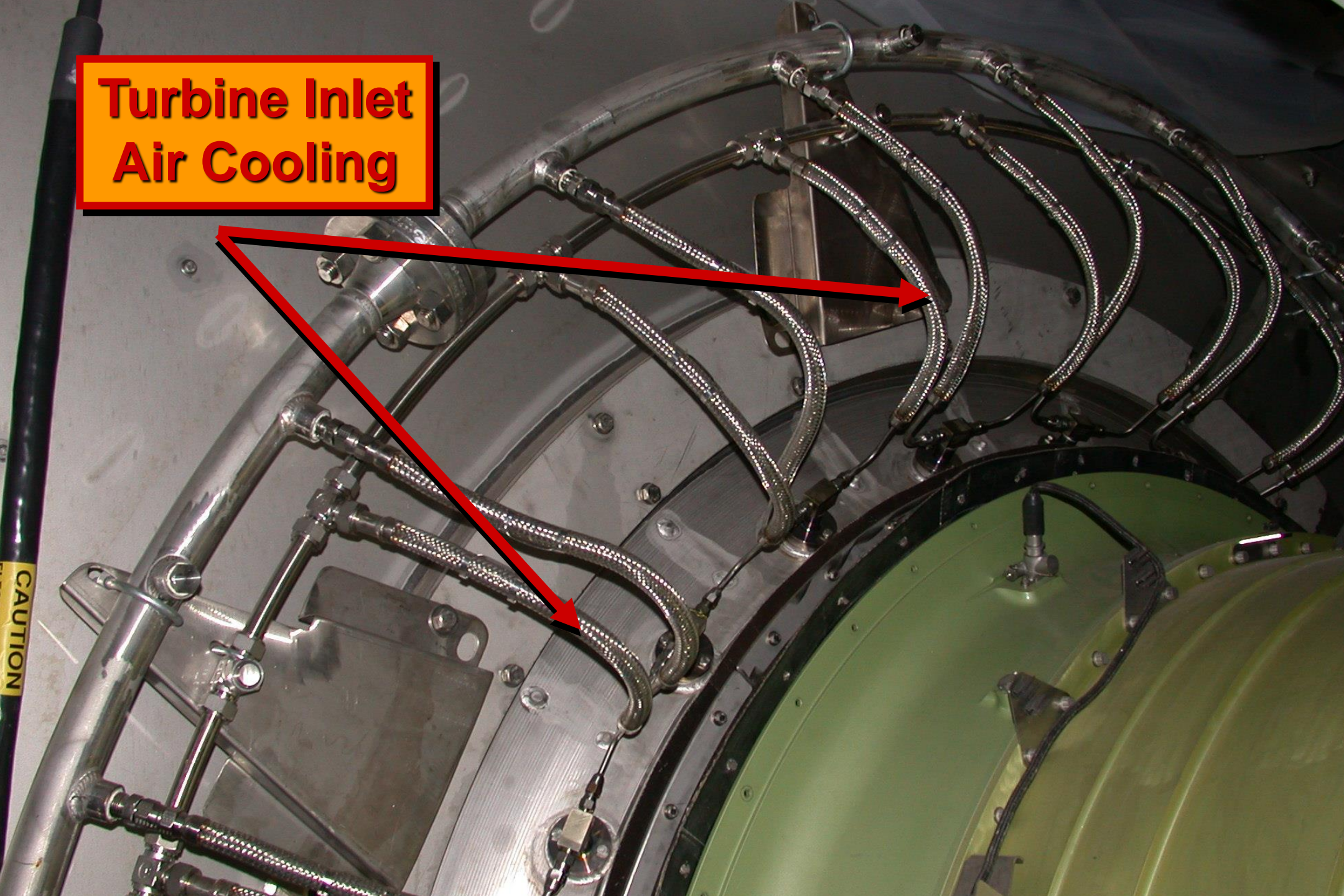
Turbine Air Inlet Area

**Turbine Inlet
Air Cooling**



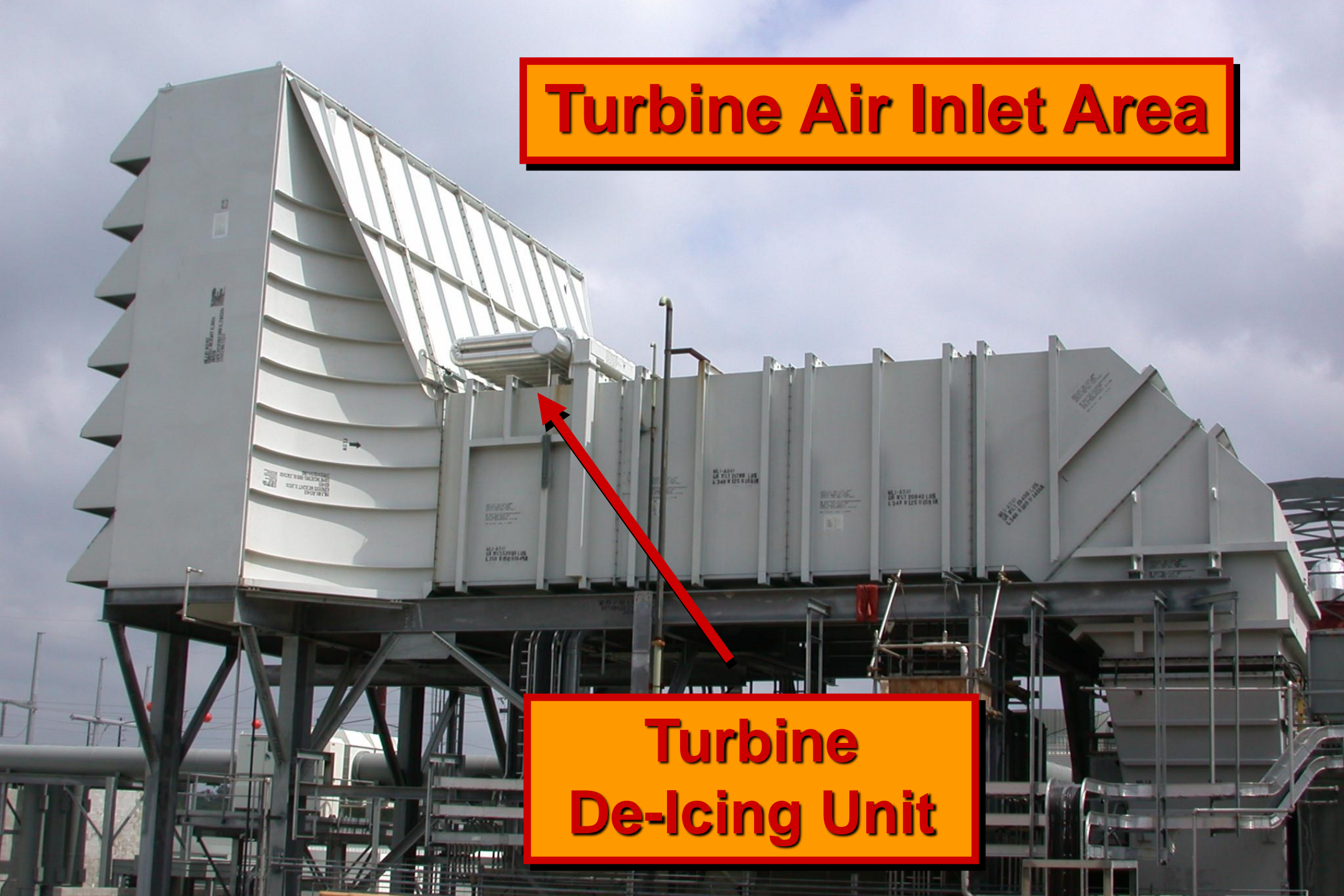
**Turbine Inlet
Air Cooling**

CAUTION



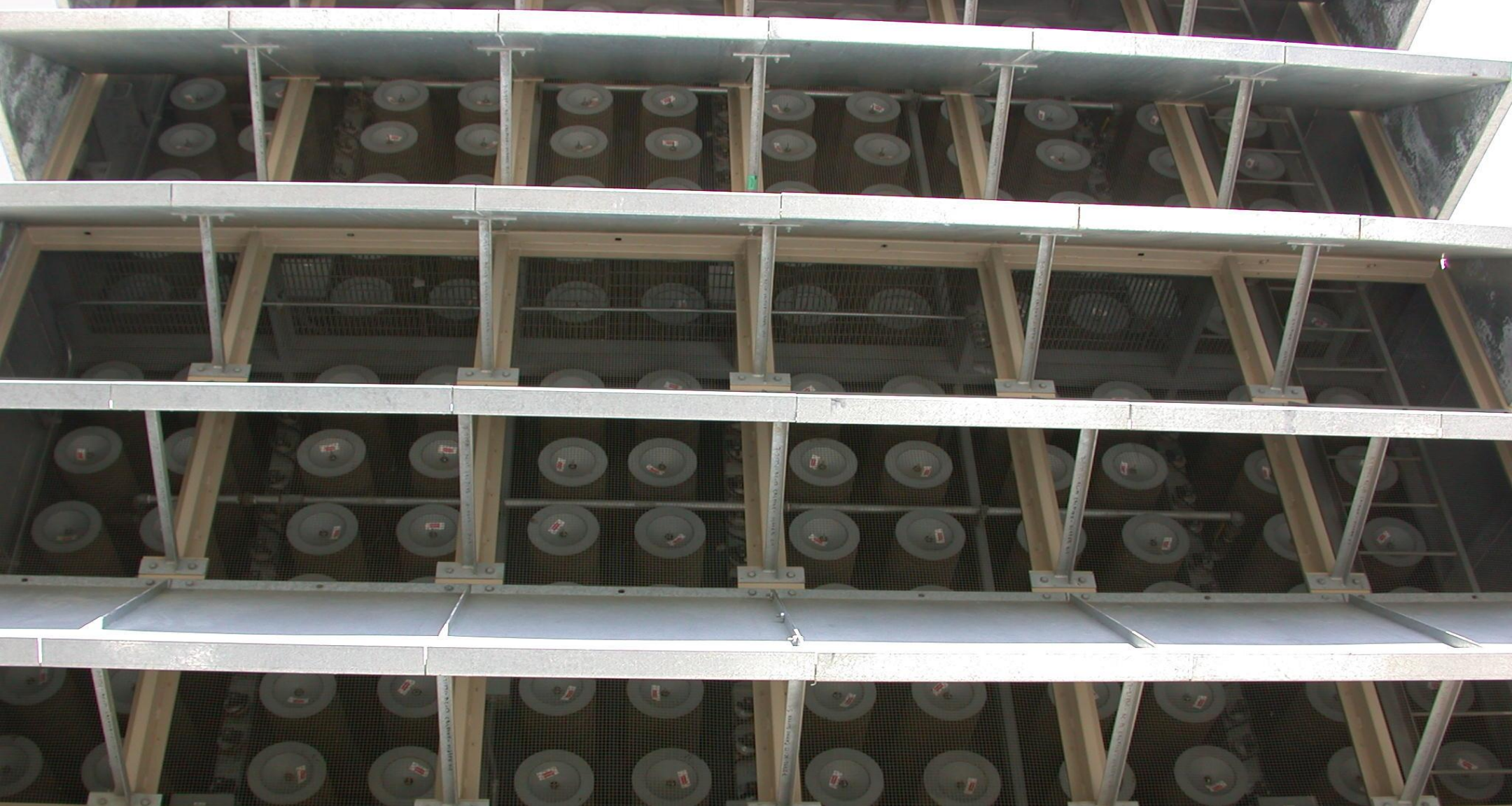
Turbine Air Inlet Area

**Turbine
De-Icing Unit**

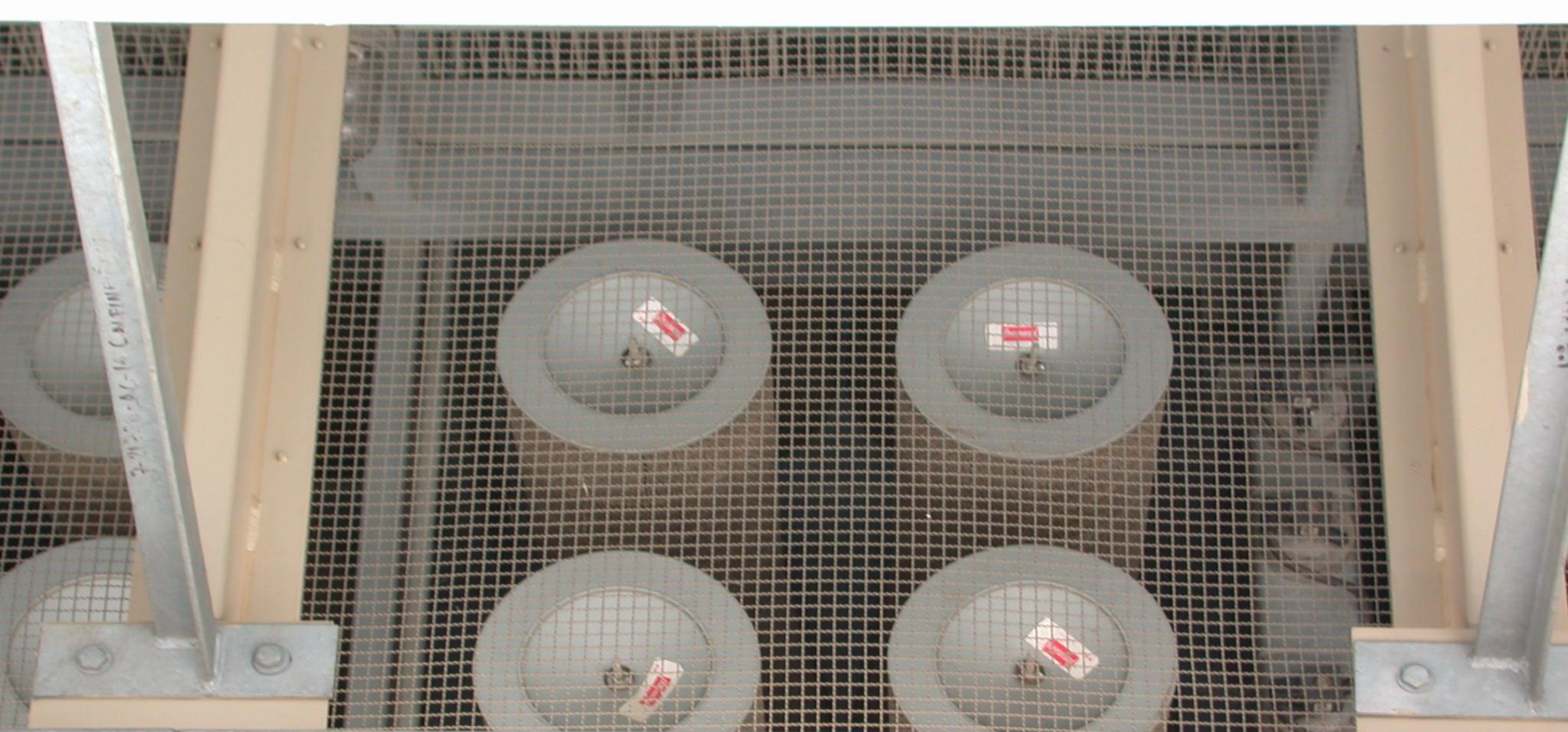




Turbine Air Inlet



Turbine Inlet Air Filters

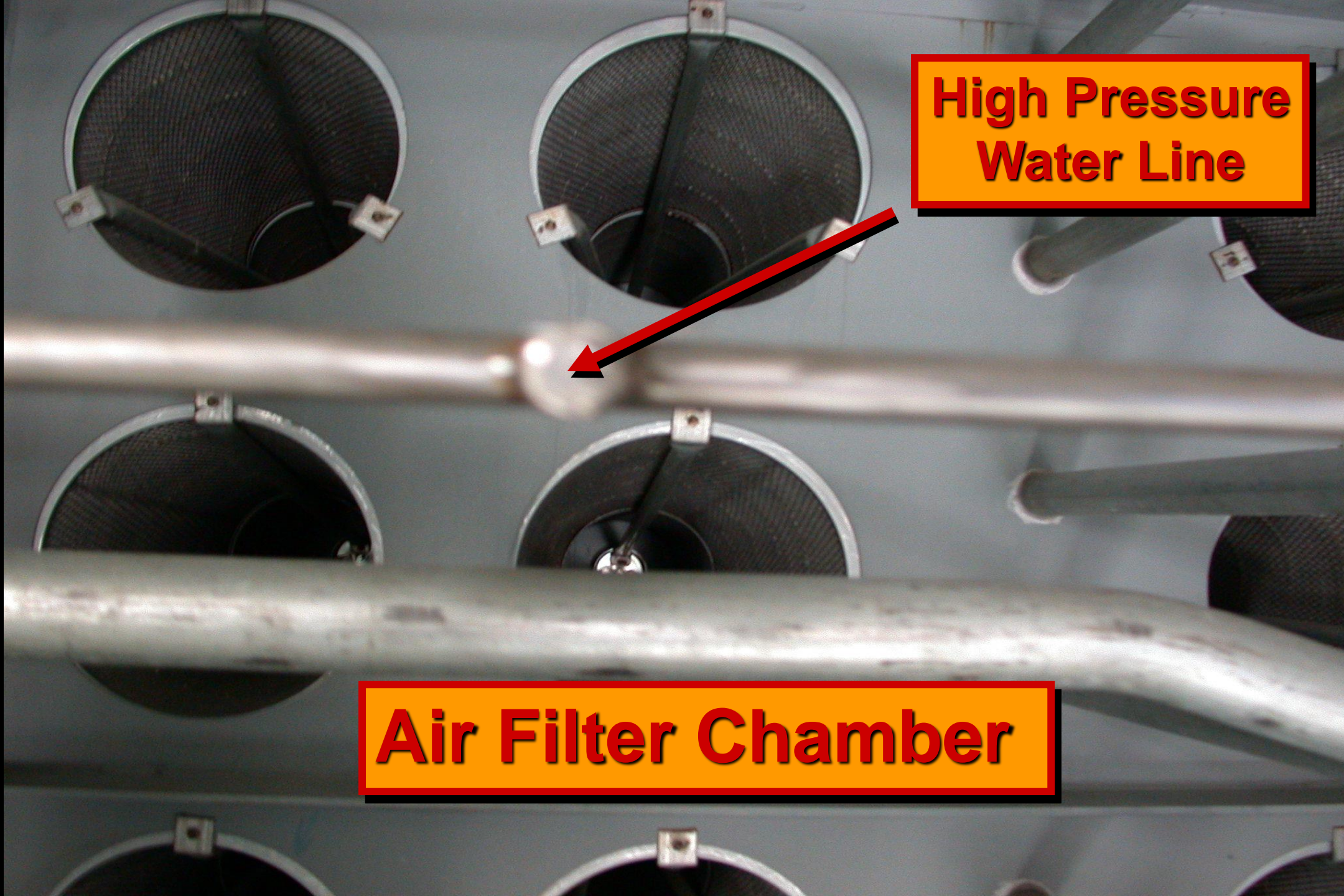


Turbine Inlet Air Filters

**High Pressure
Water Line**



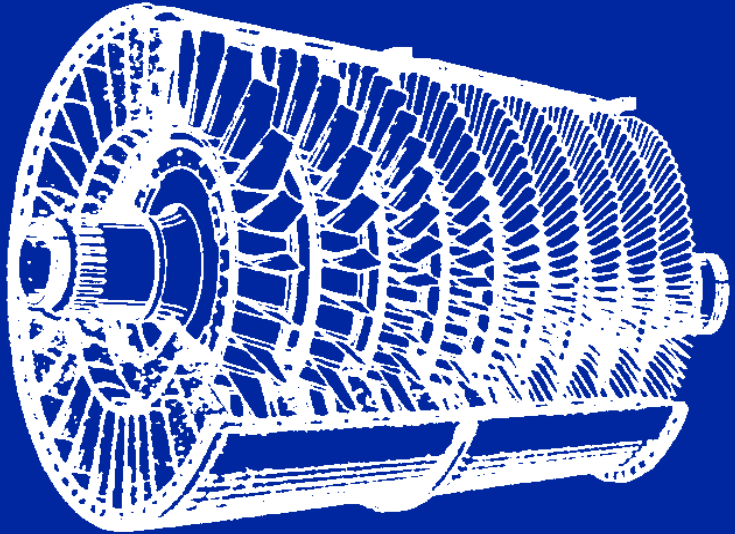
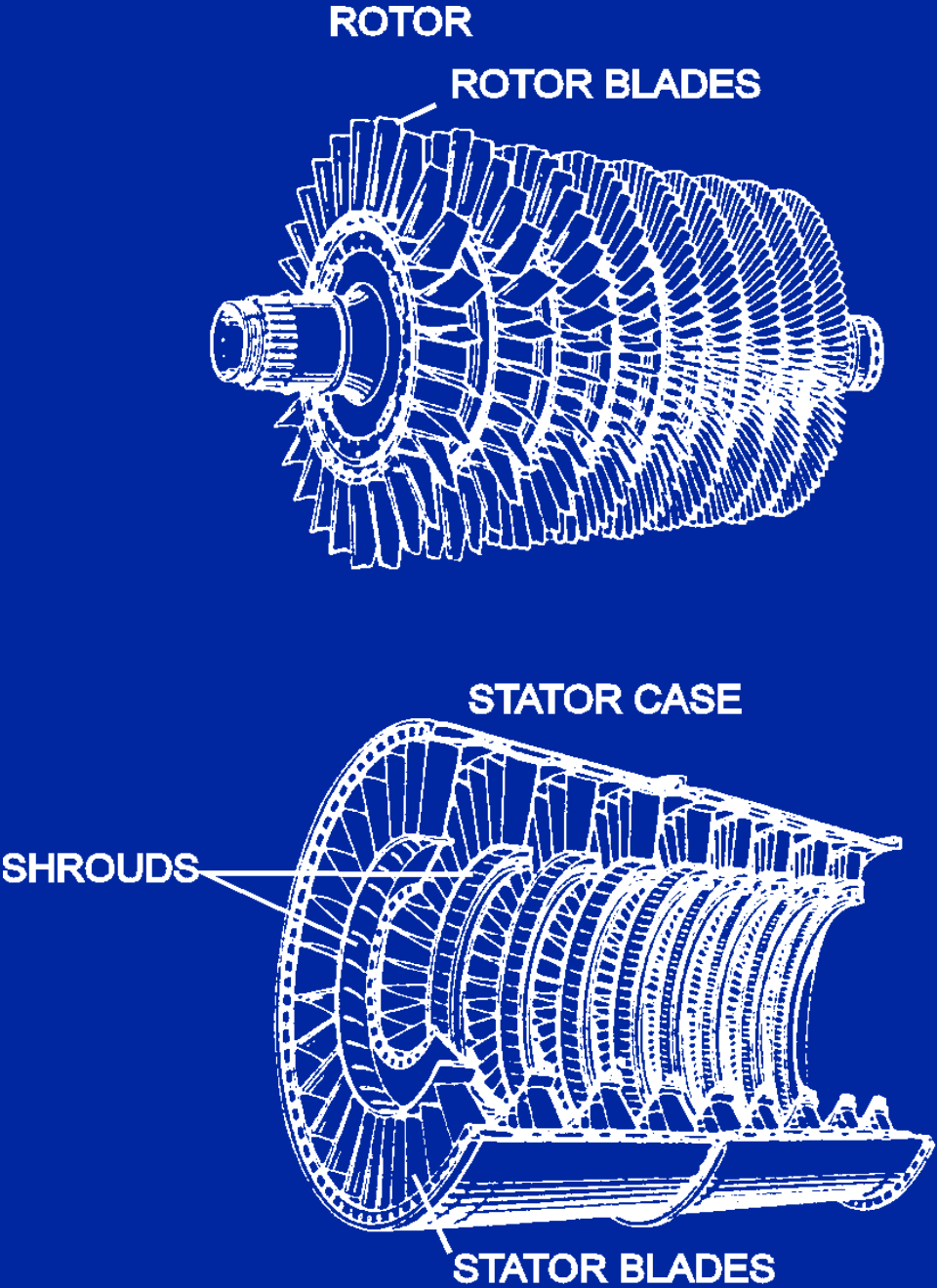
Air Filter Chamber





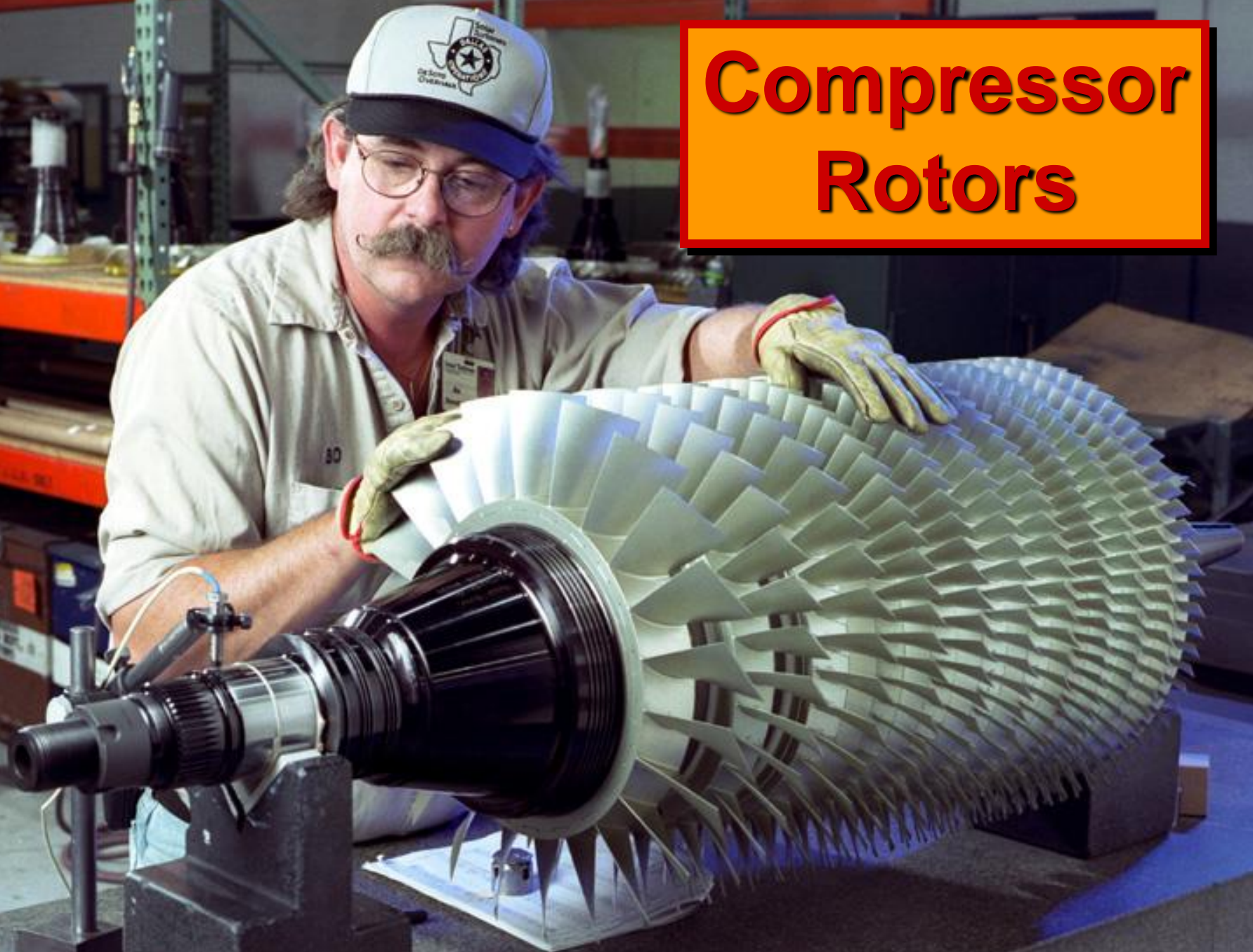
Compressor Section

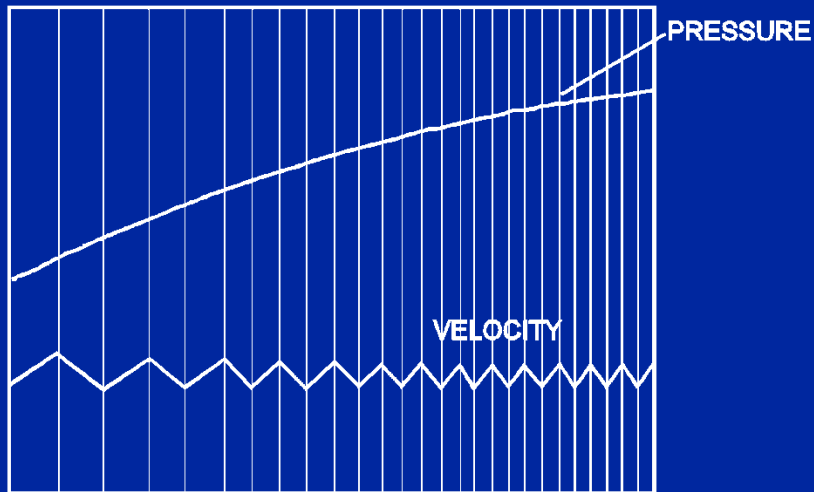
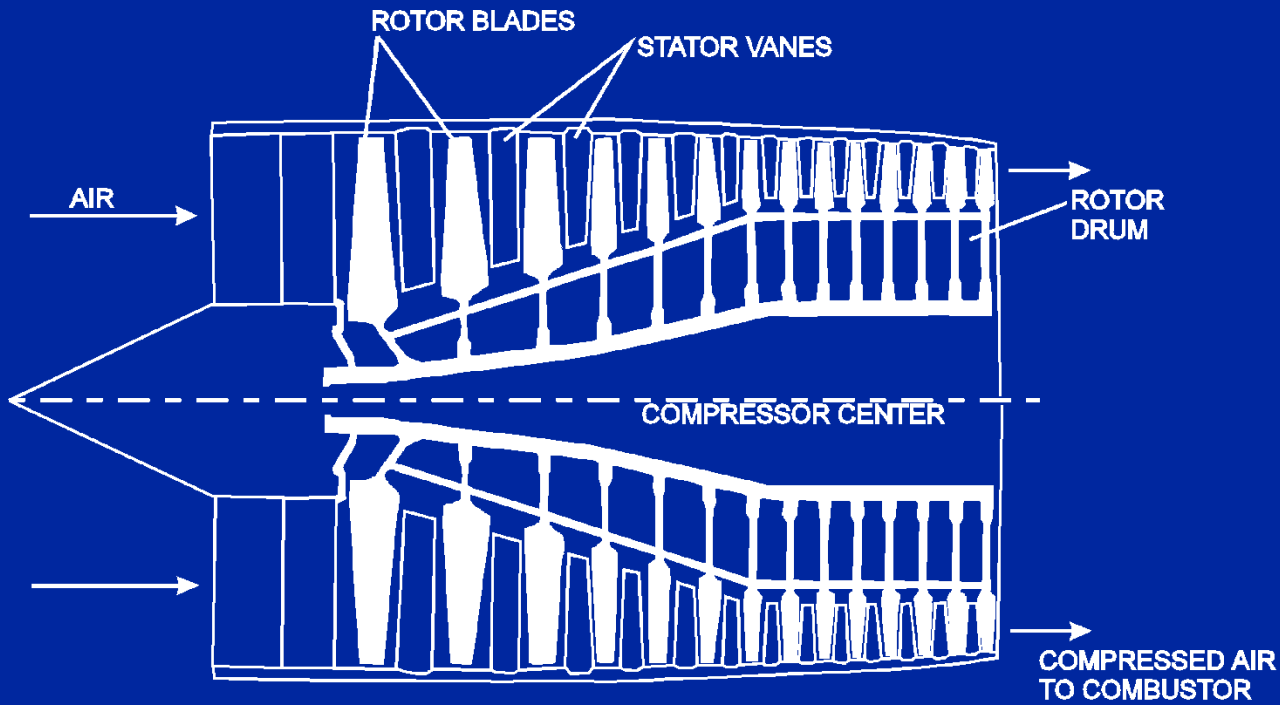
Axial Compressor



Graphic Courtesy of
General Electric

Compressor Rotors



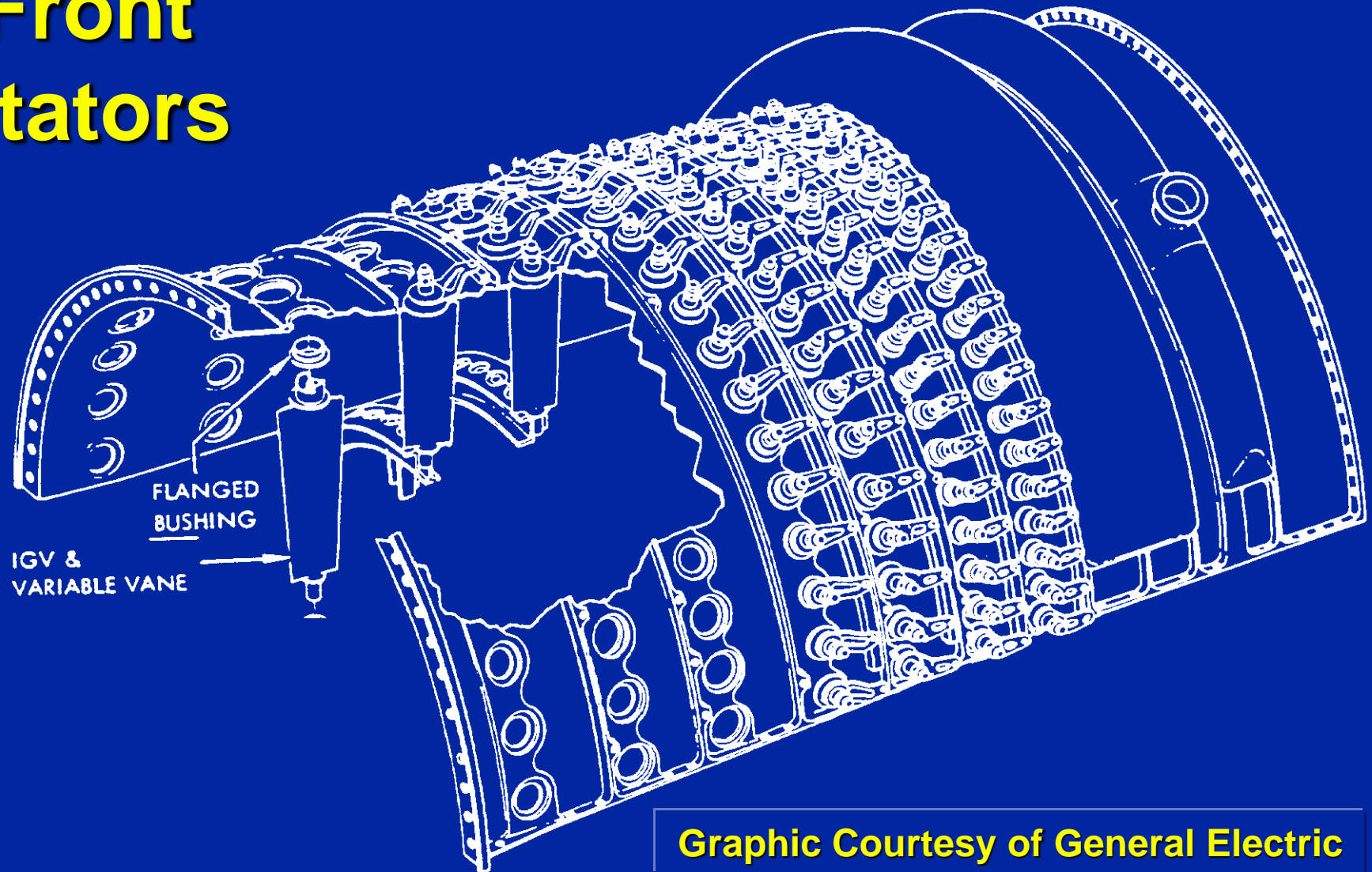


Velocity & Pressure in an Axial Compressor



General Electric 9HA
(397 MW – 532KHP)

Compressor Front Stators

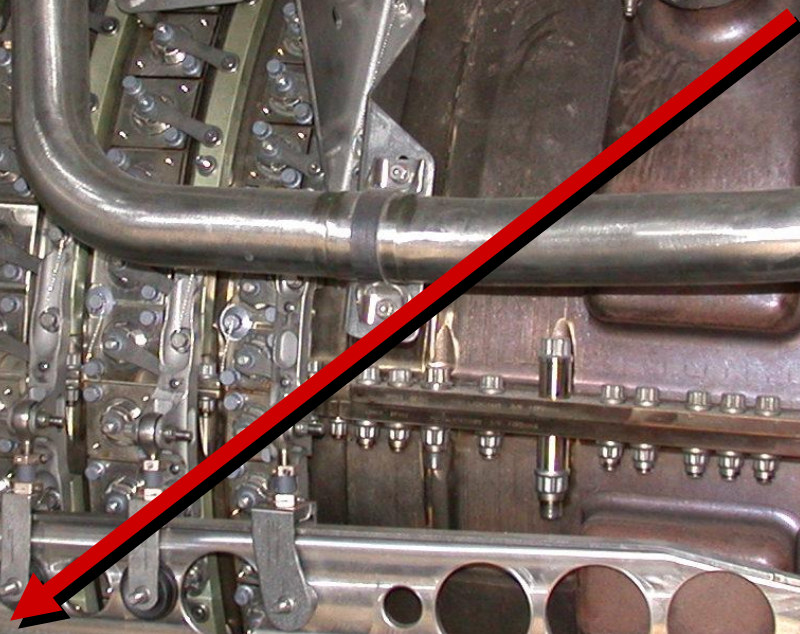


Graphic Courtesy of General Electric



**Front
Stators**

**VSV
System**



Combustor Section



Can Combustor

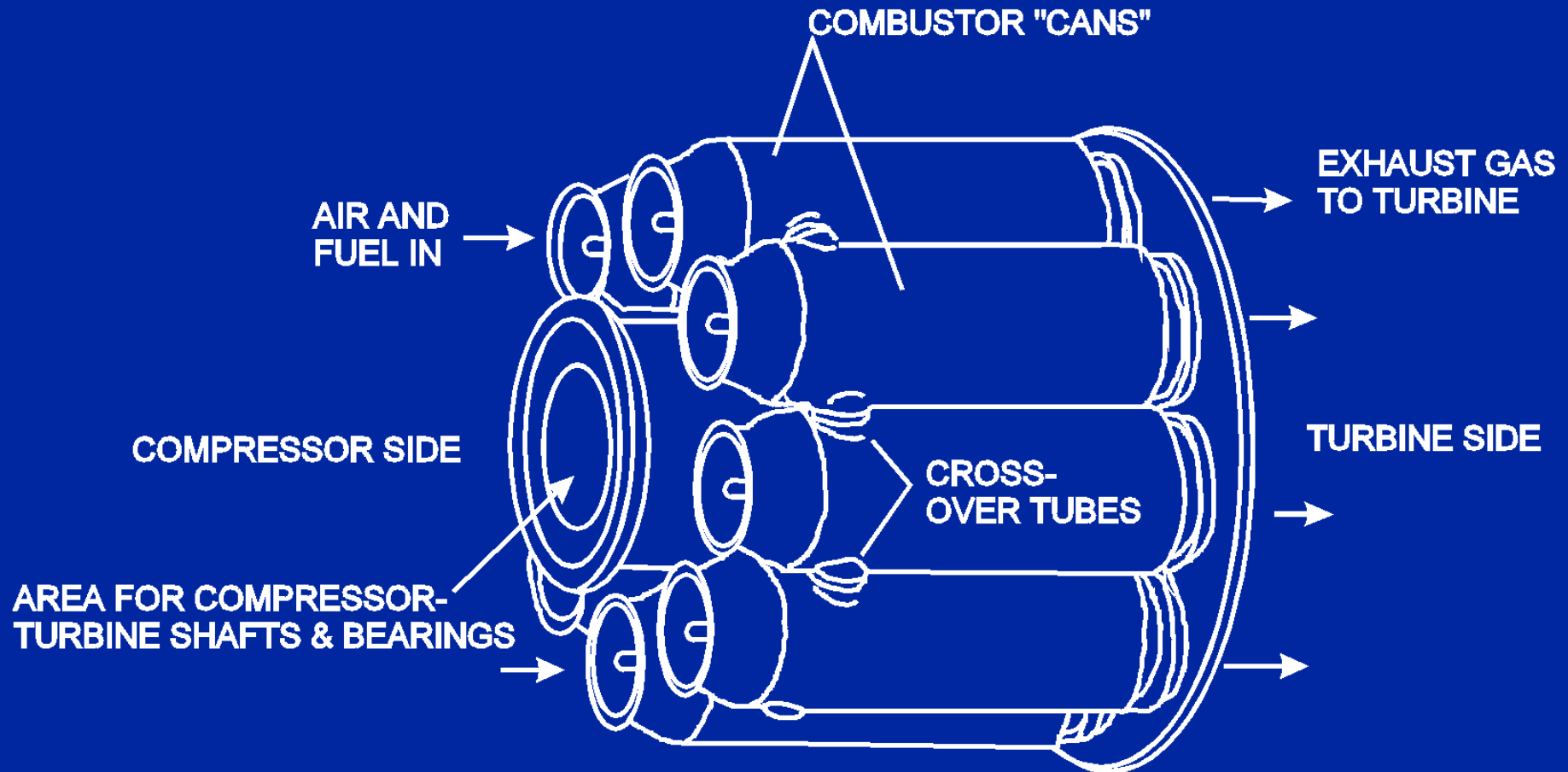



Figure 206.9

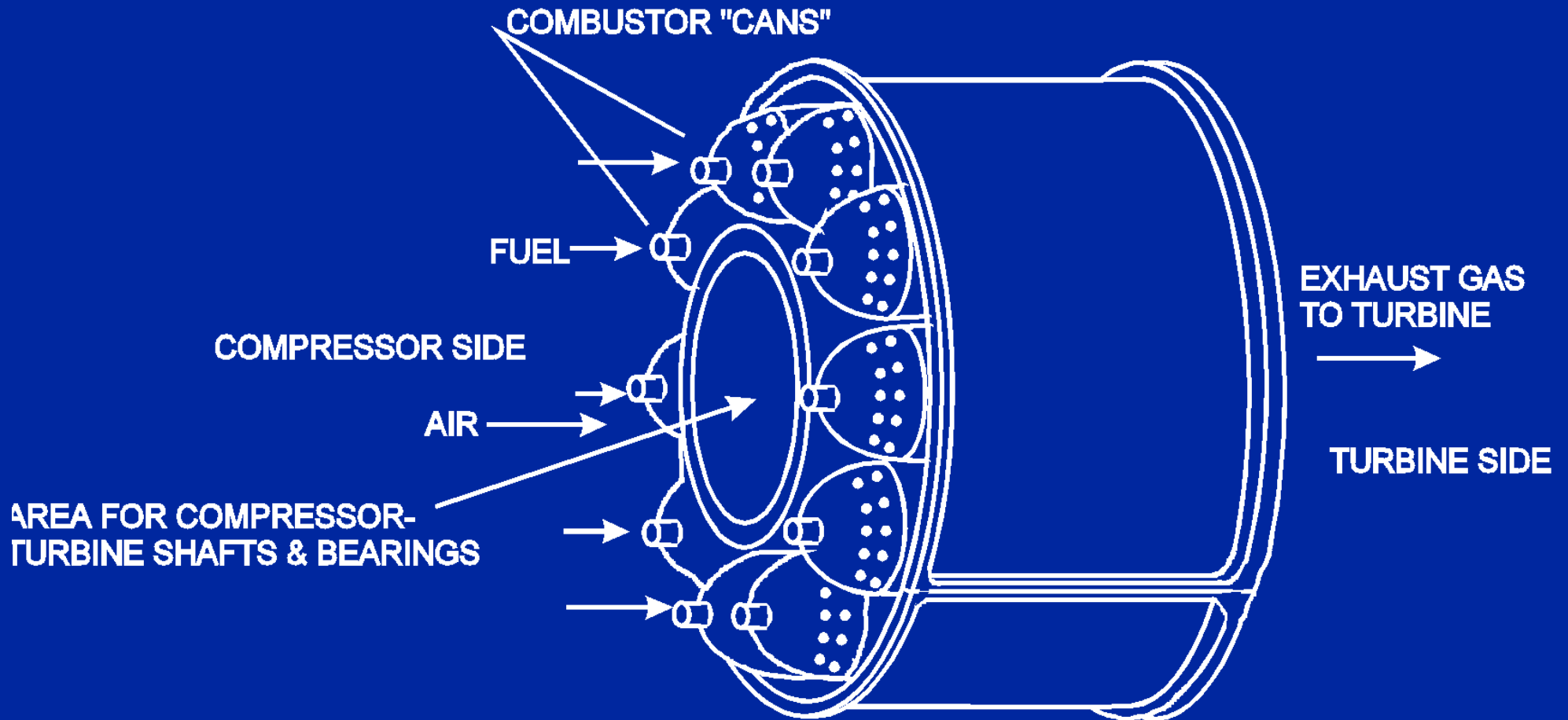
A close-up photograph of a gas turbine engine's external can combustors and crossover tubes. The image shows two cylindrical combustor cans connected by a central crossover tube. The assembly is mounted on a dark, metallic engine casing. The combustor cans are secured with multiple bolts. Below the combustors, a series of crossover tubes are visible, each secured with a bolt. The overall appearance is industrial and metallic.

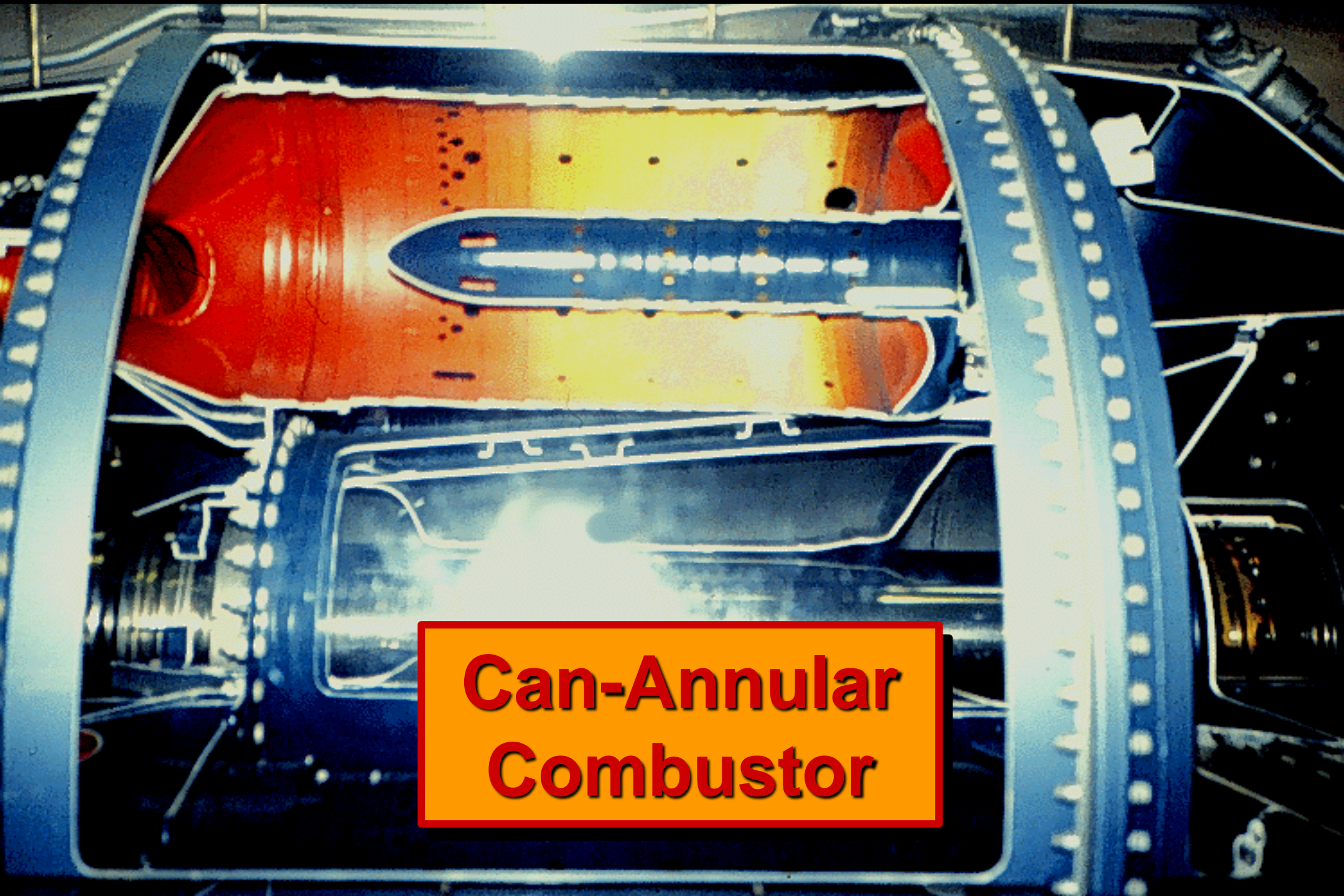
**External
Can
Combustors
& Cross-
Over Tubes**

Can Combustors & Thermocouple



Can-Annular Combustor





**Can-Annular
Combustor**

**Can-Annular Lean
Premix Burner**

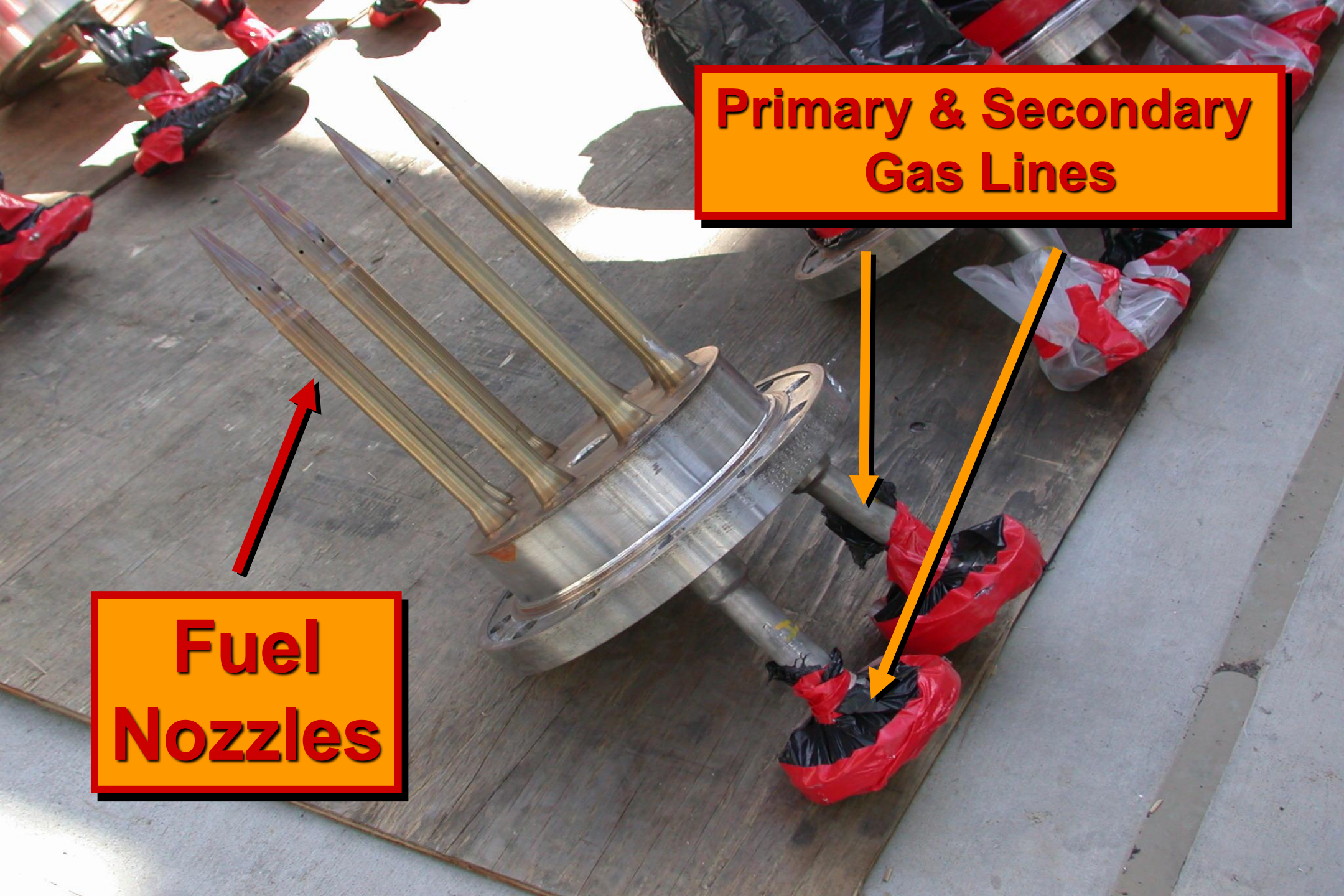


Fuel Nozzles

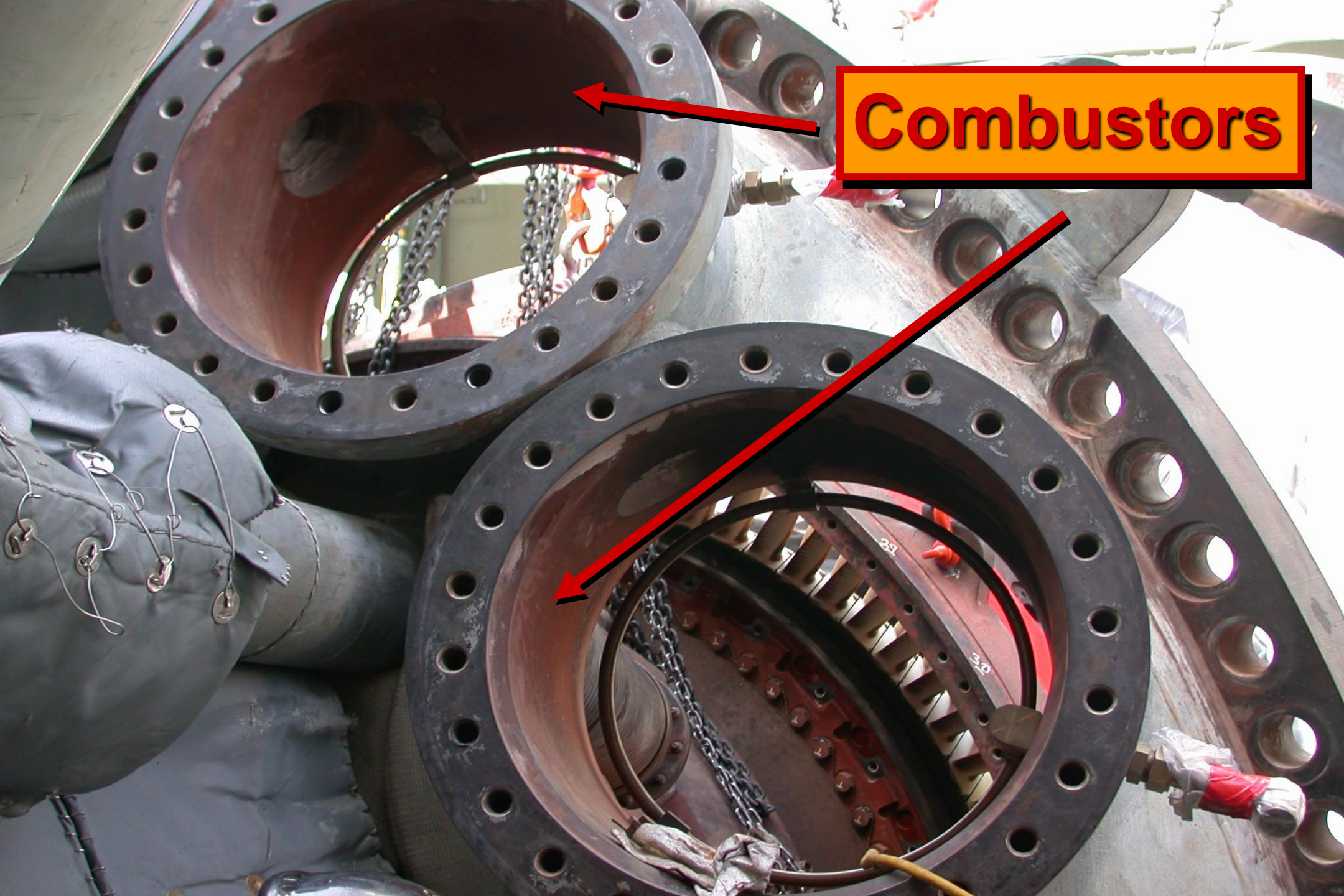


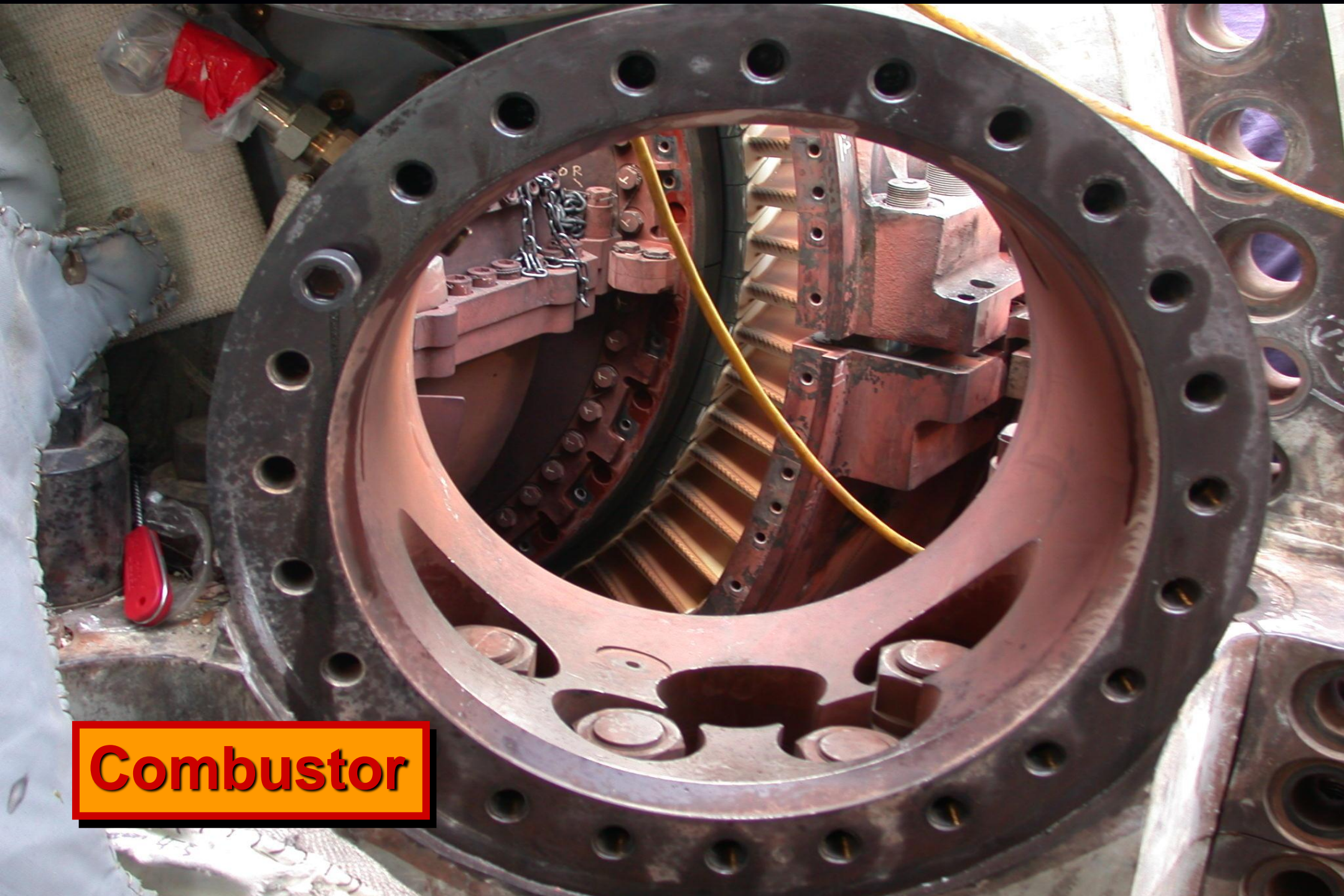
**Primary & Secondary
Gas Lines**

**Fuel
Nozzles**



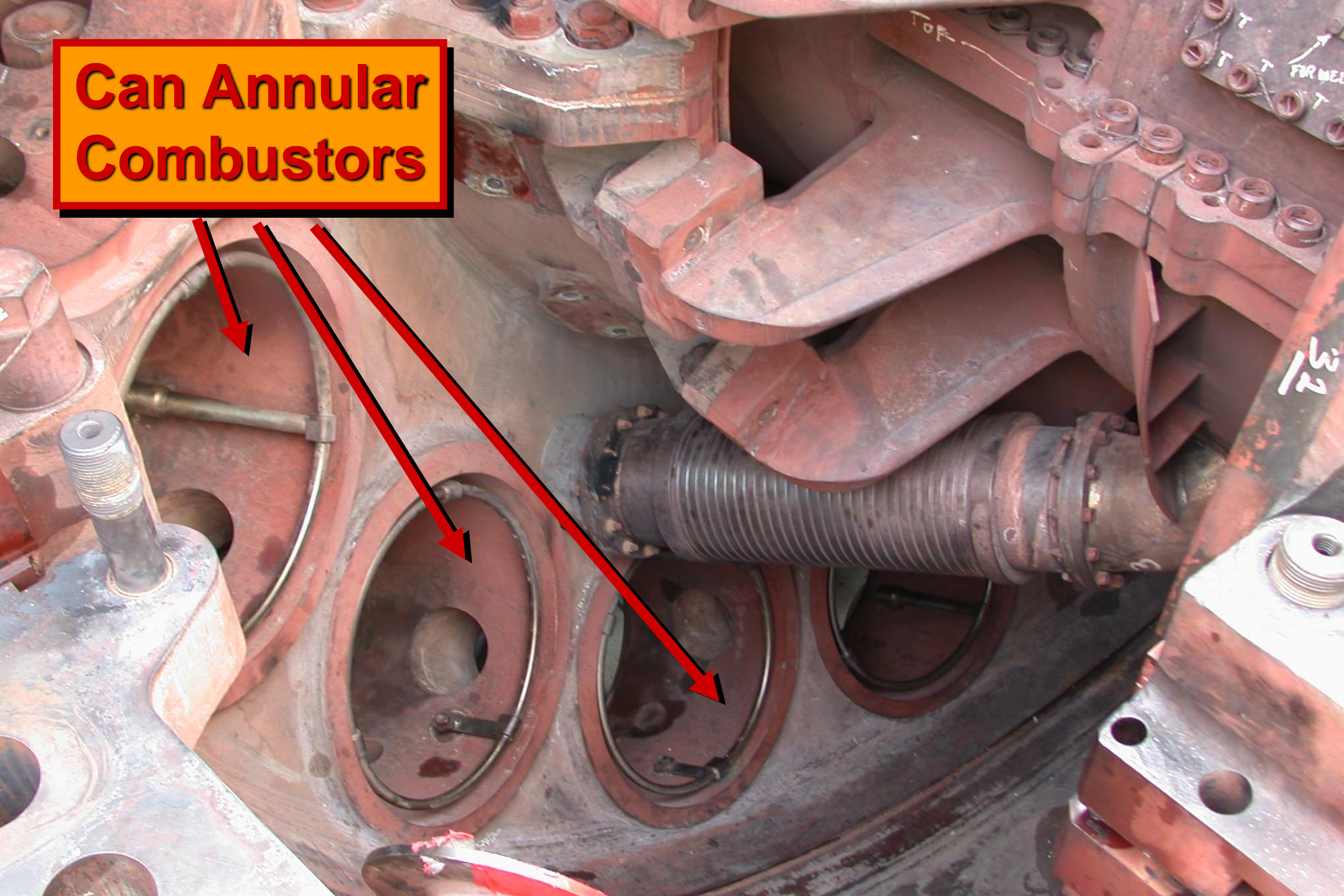
Combustors





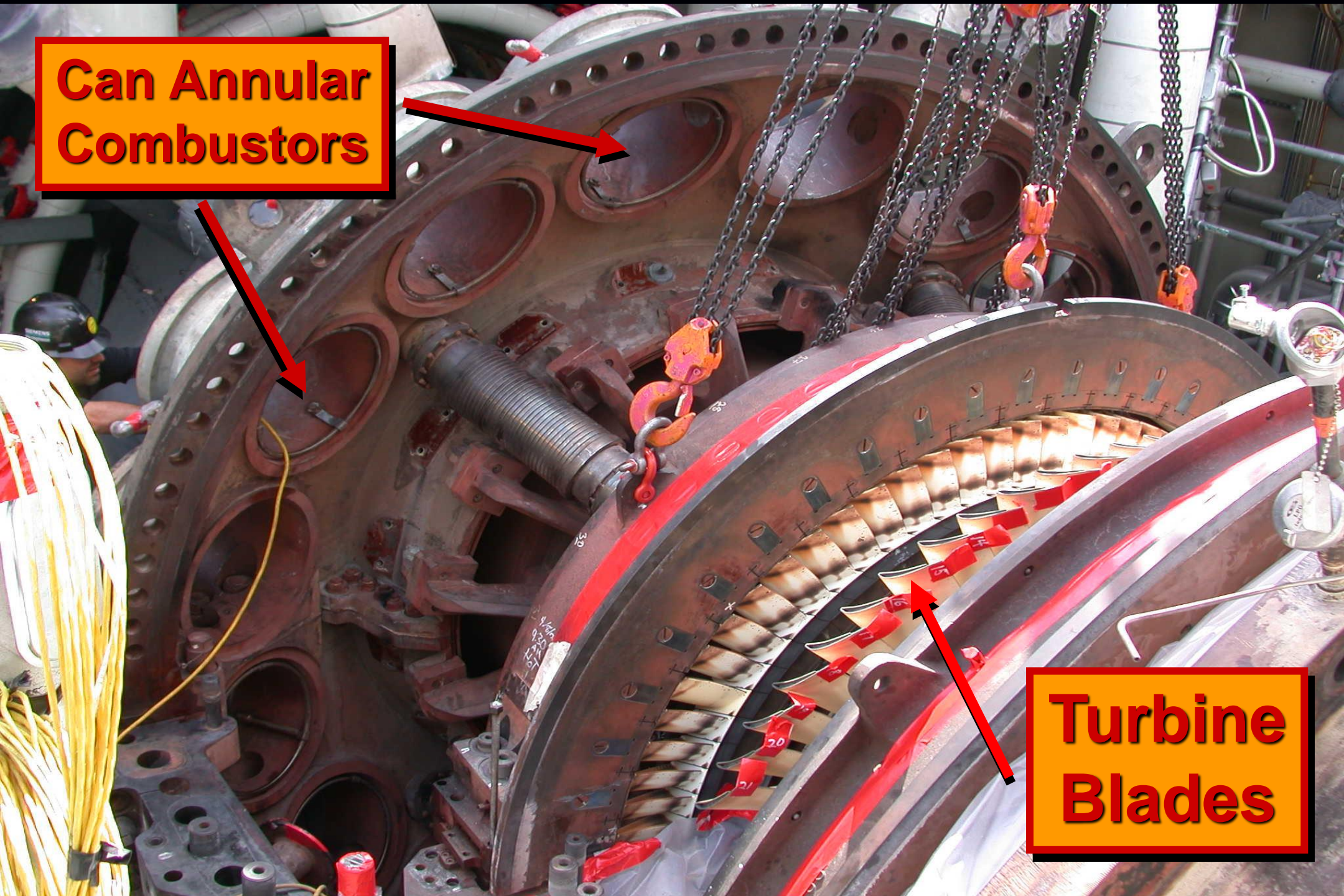
Combustor

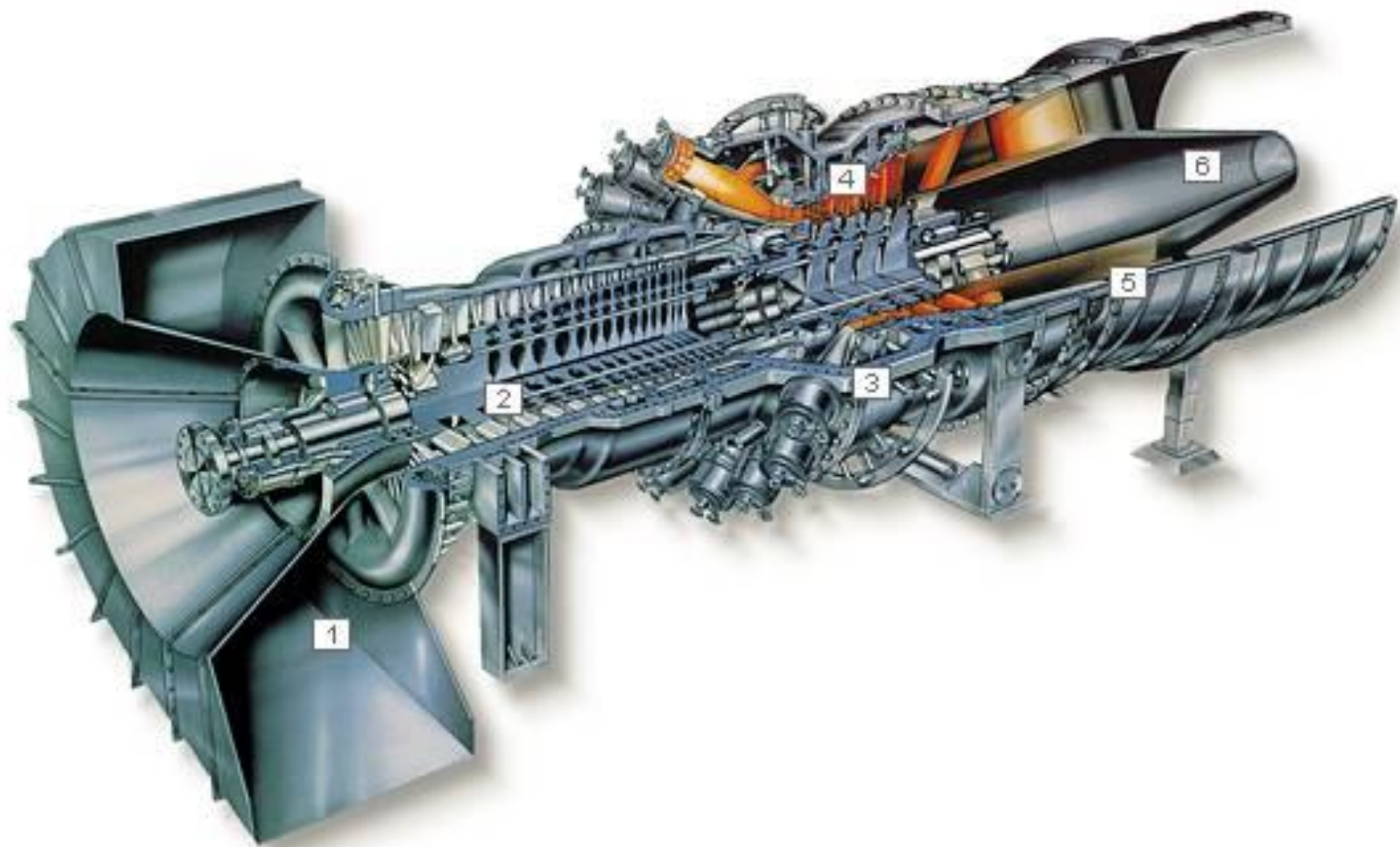
Can Annular Combustors

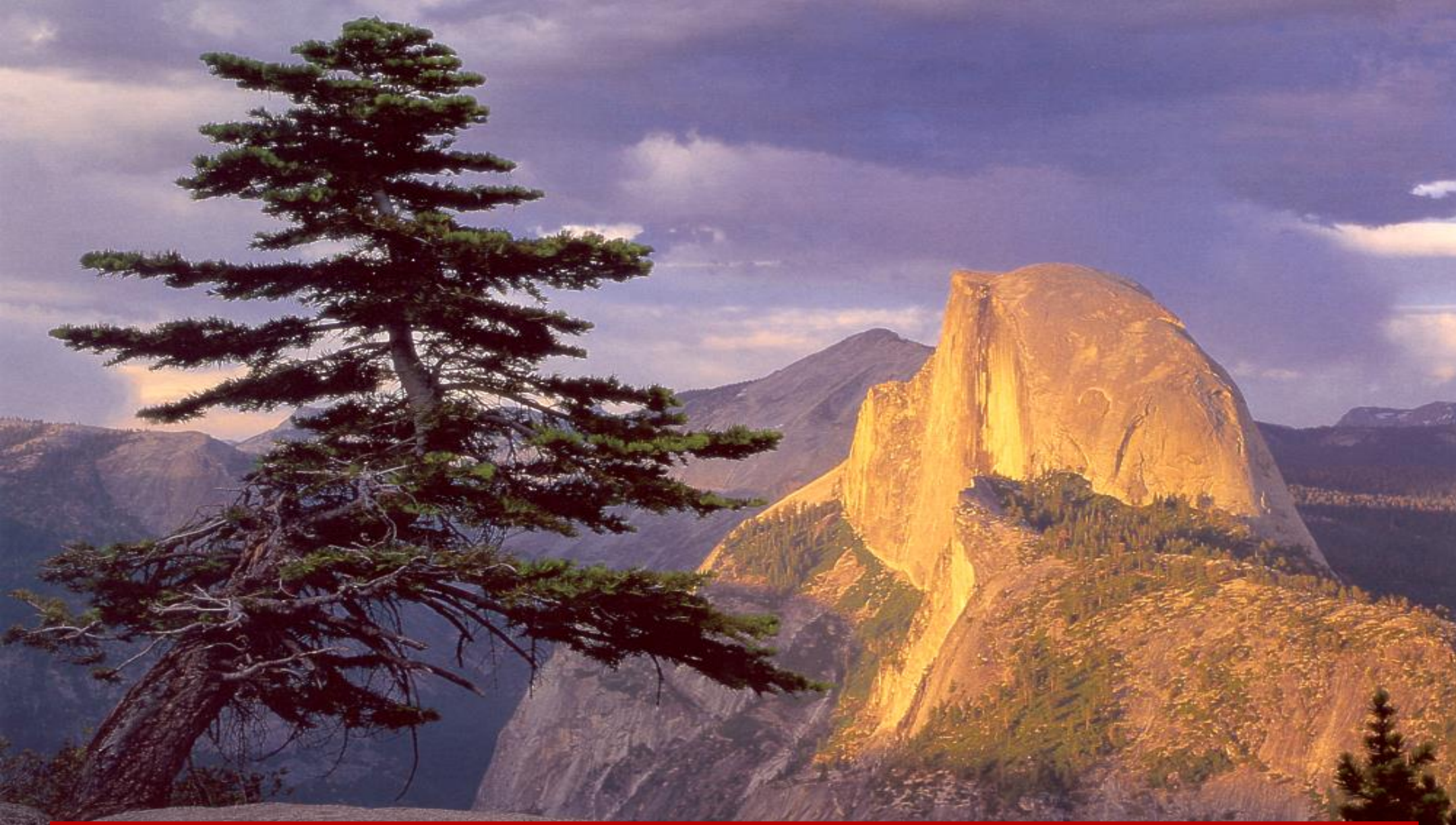


**Can Annular
Combustors**

**Turbine
Blades**

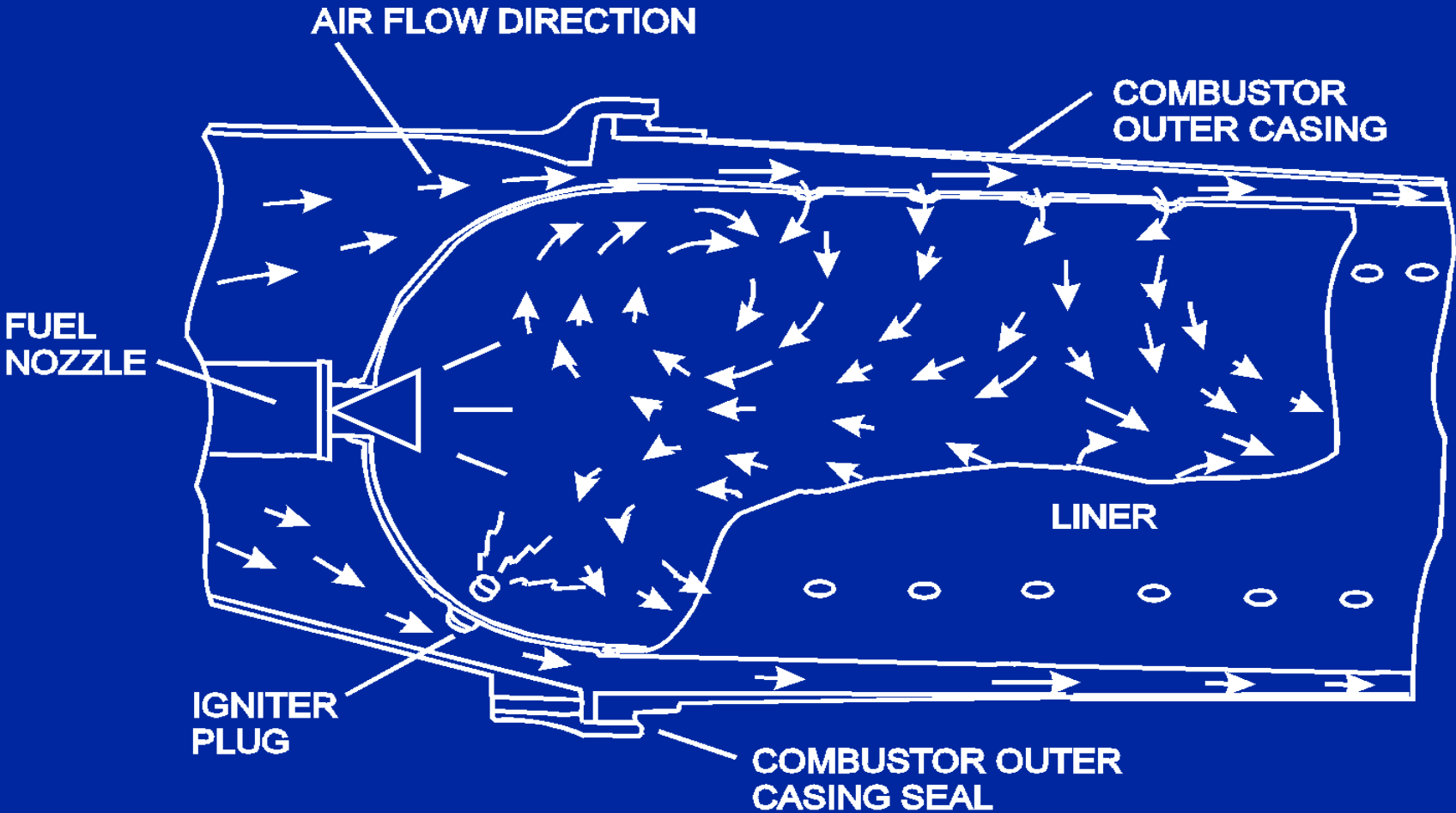






Let's Discuss Gas Turbine Air & Gas Flows

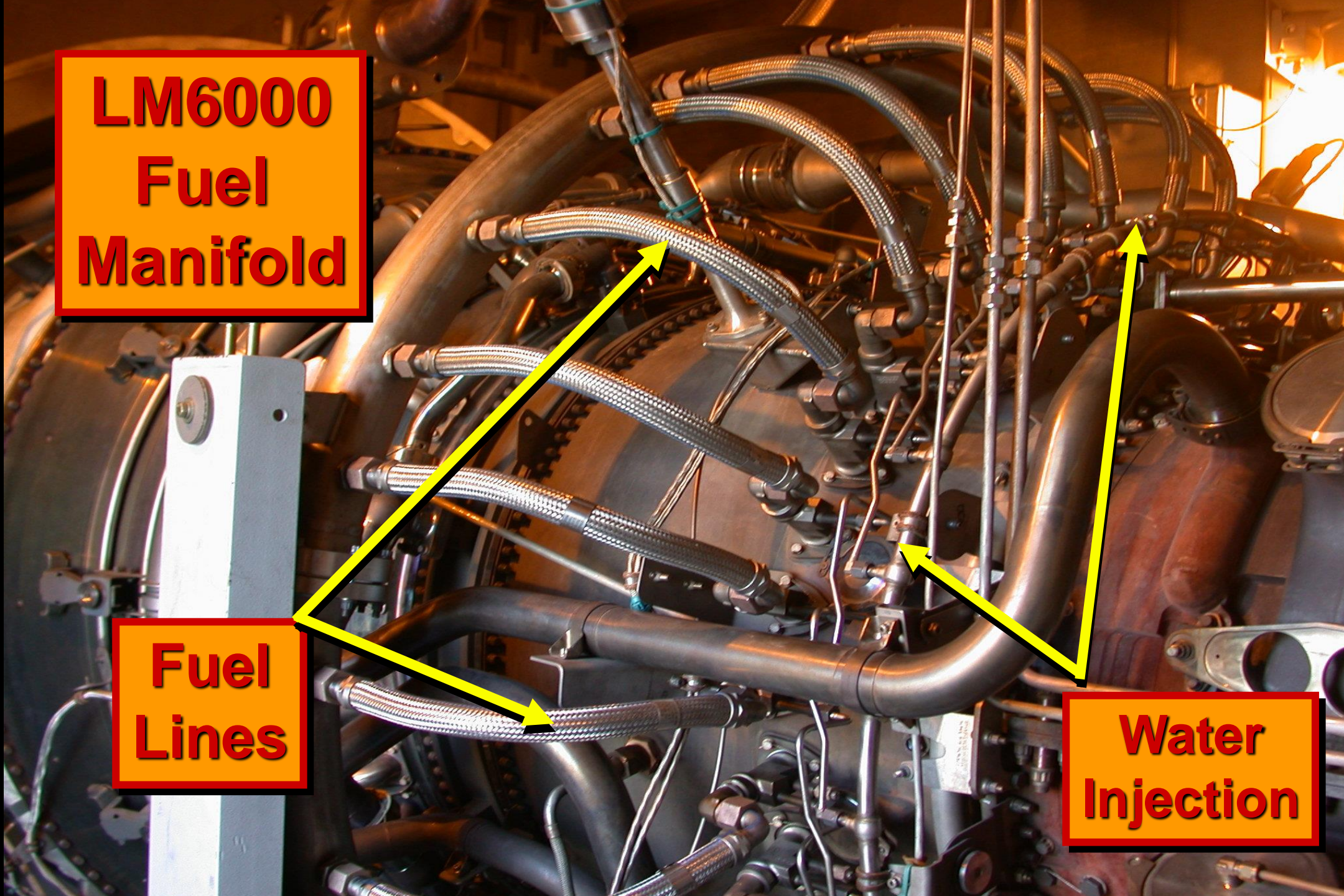
Combustor Liner and Air Flow



**LM6000
Fuel
Manifold**

**Fuel
Lines**

**Water
Injection**





**Fuel
Manifold**

C

A

B

C

P

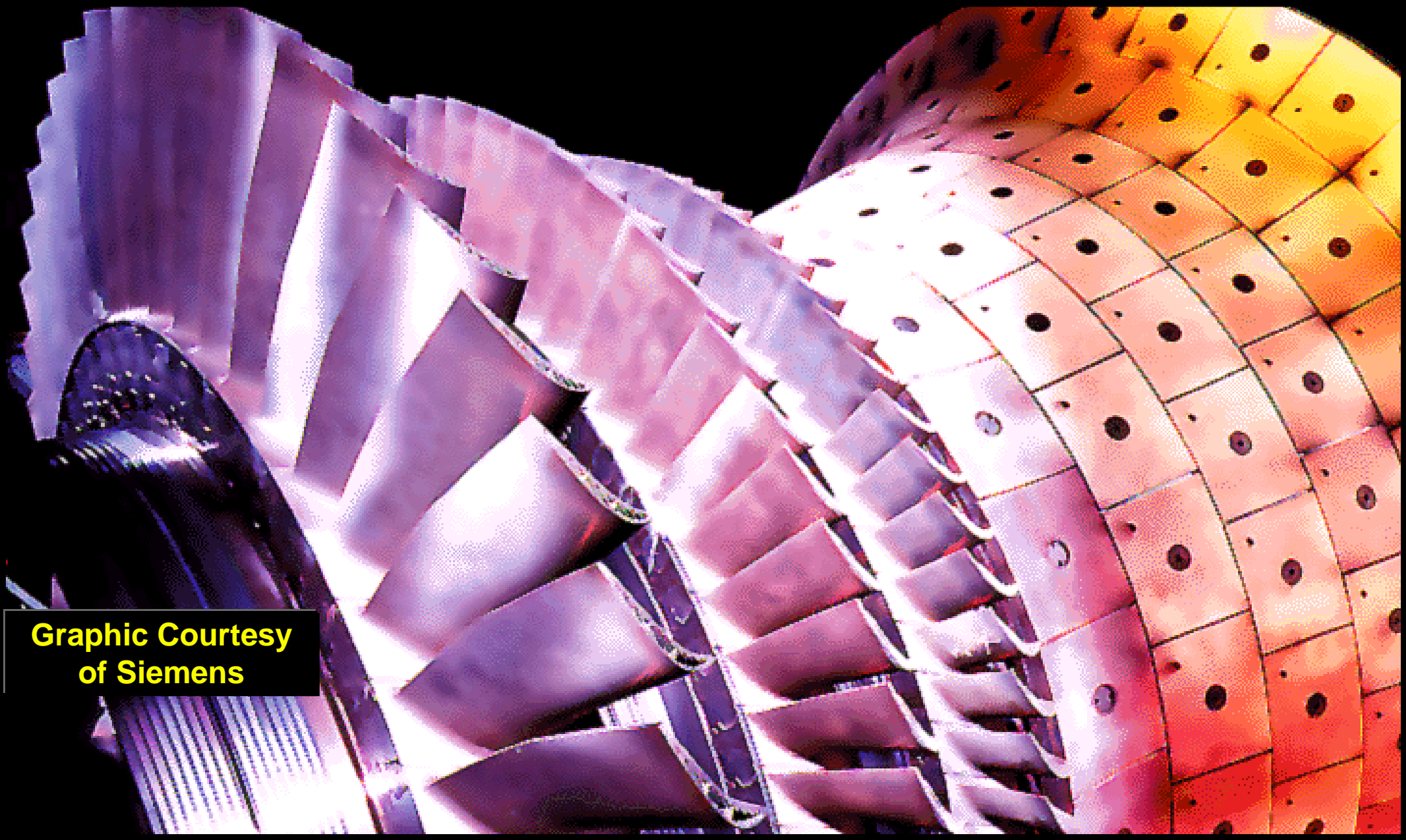
A

10
B



Let's Discuss Turbine Sections

Siemens Hybrid Combustor & Turbine Blades



Graphic Courtesy
of Siemens

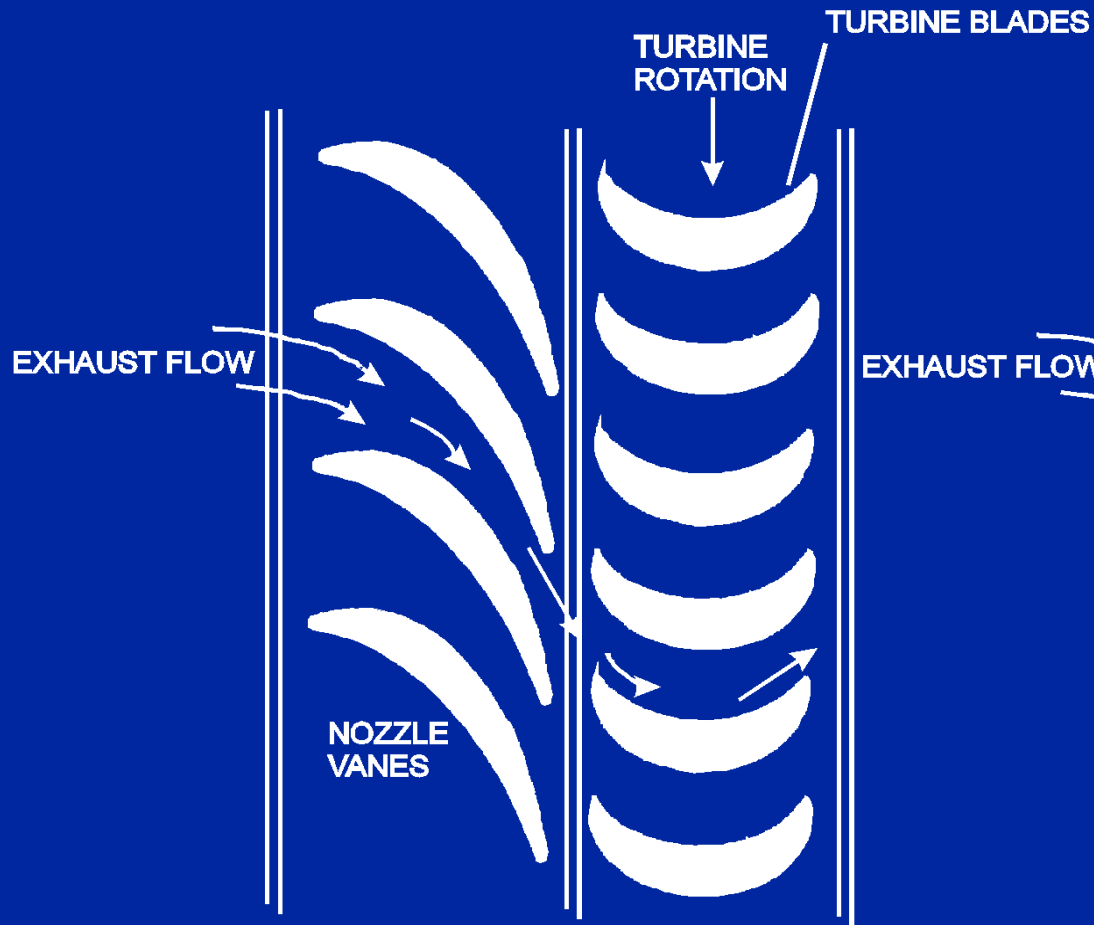


**LP Turbine
Section**

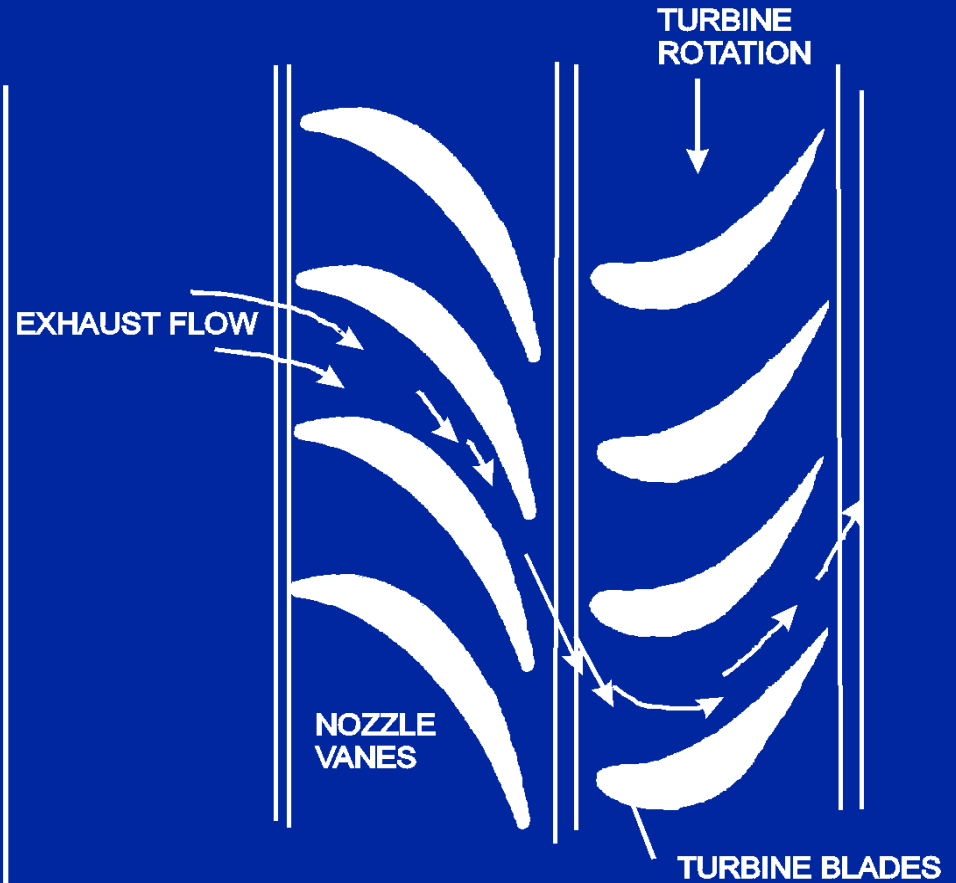
**HP Turbine
Section**

Turbine Blades

IMPULSE TURBINE



REACTION TURBINE



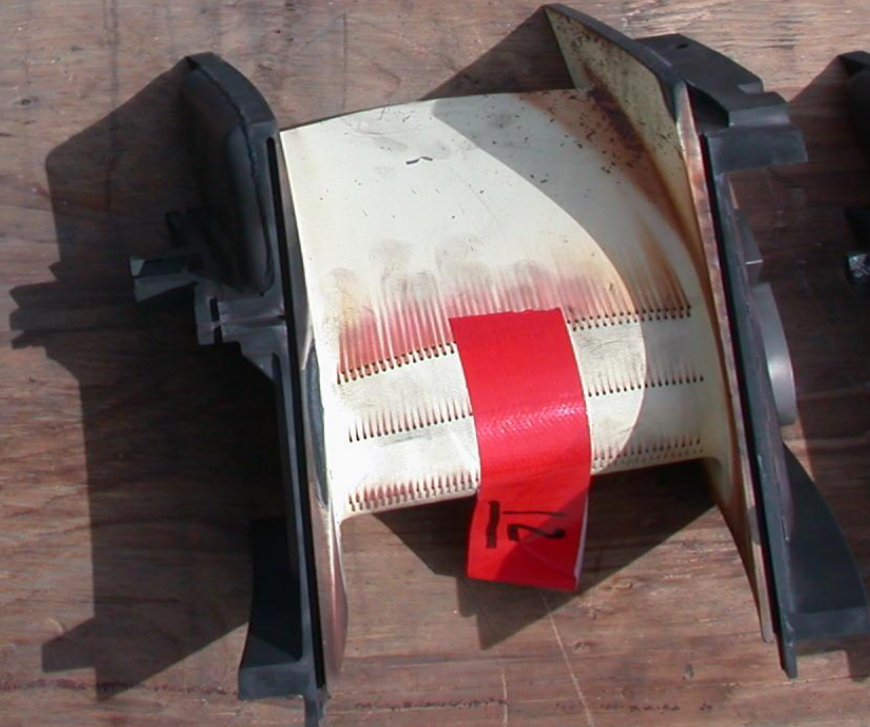
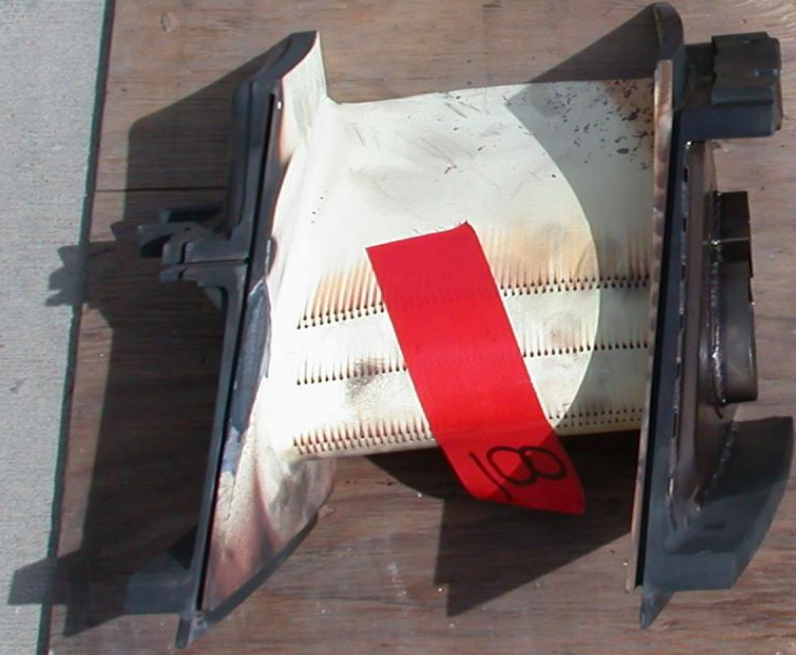
Turbine Blades





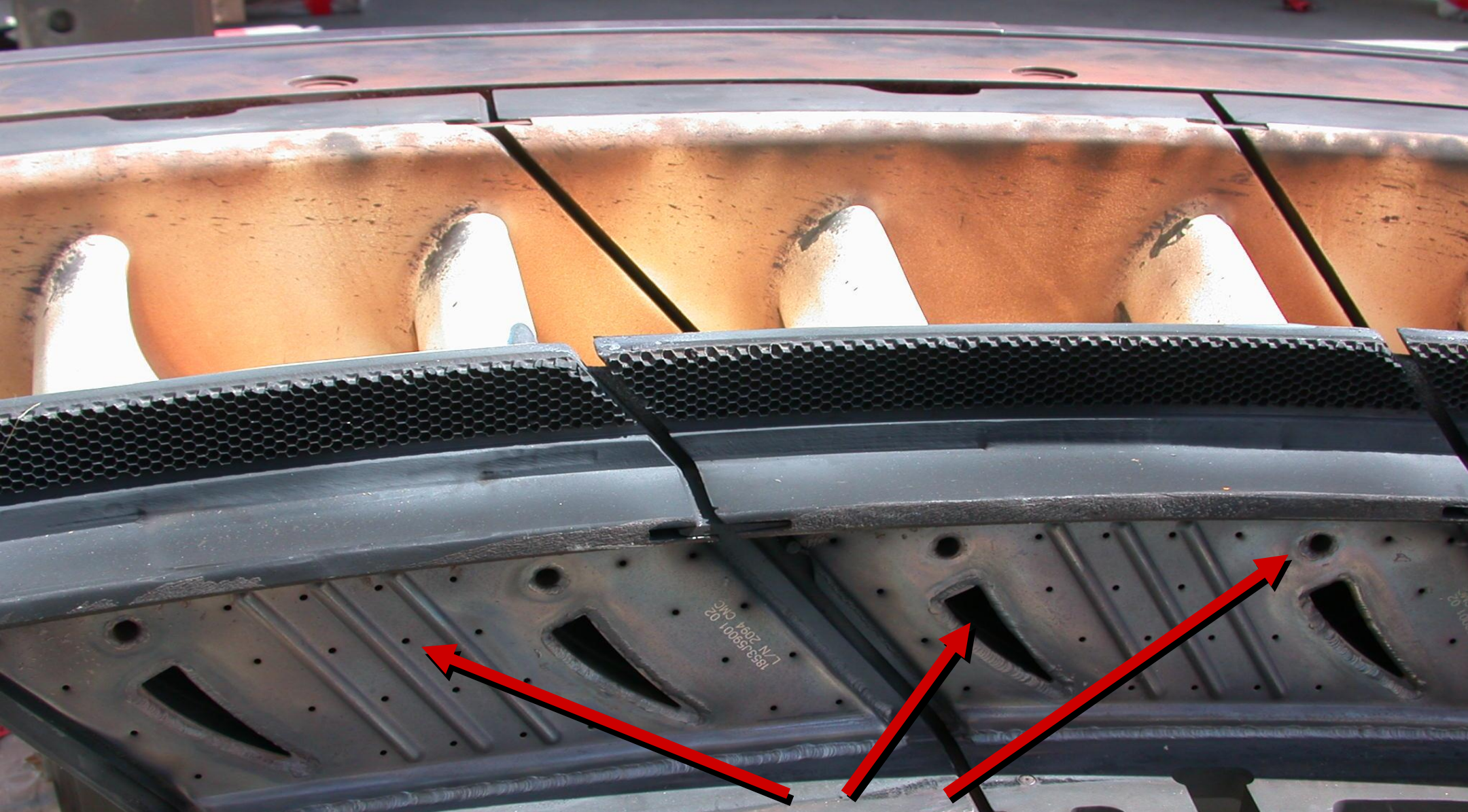
**Turbine
Discs**

Turbine Blades



Turbine Disc





Let's Discuss Turbine Air Cooling



HQ11169

9984J83 603 01



Inlet Air Cooling

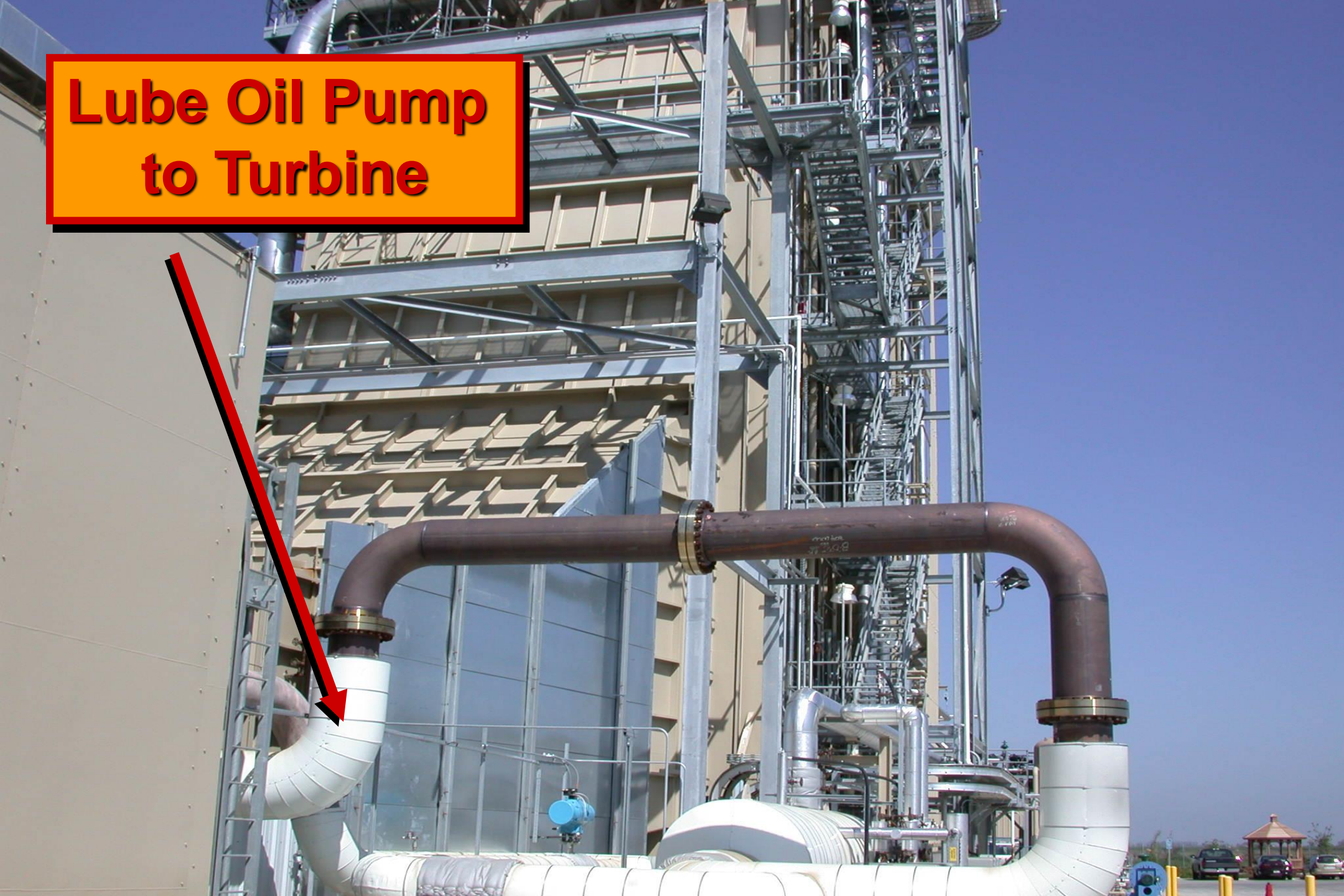
Turbine Lube Oil System





Lube Oil Pump

**Lube Oil Pump
to Turbine**



A photograph showing a large industrial air conditioning unit. The unit consists of multiple rows of horizontal coils supported by a metal frame. A red and yellow text box is overlaid on the bottom center of the image. The background shows an industrial setting with pipes and structural elements.

Lube Oil Air Cooling



**Air-Oil
Separator
Exhaust**

Compressor
Front Frame

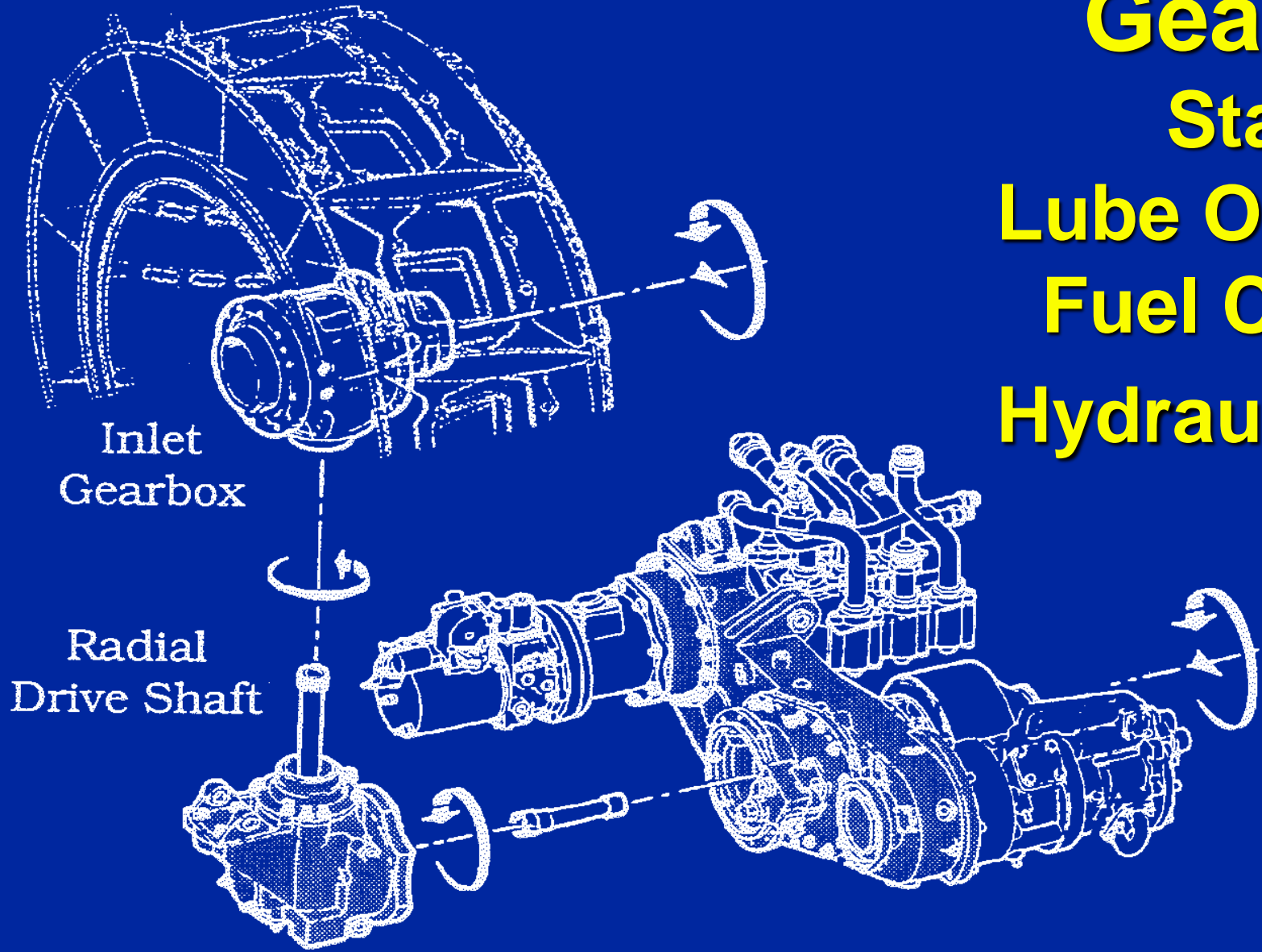
Accessory Gearbox:

Starter

Lube Oil Pumps

Fuel Controls

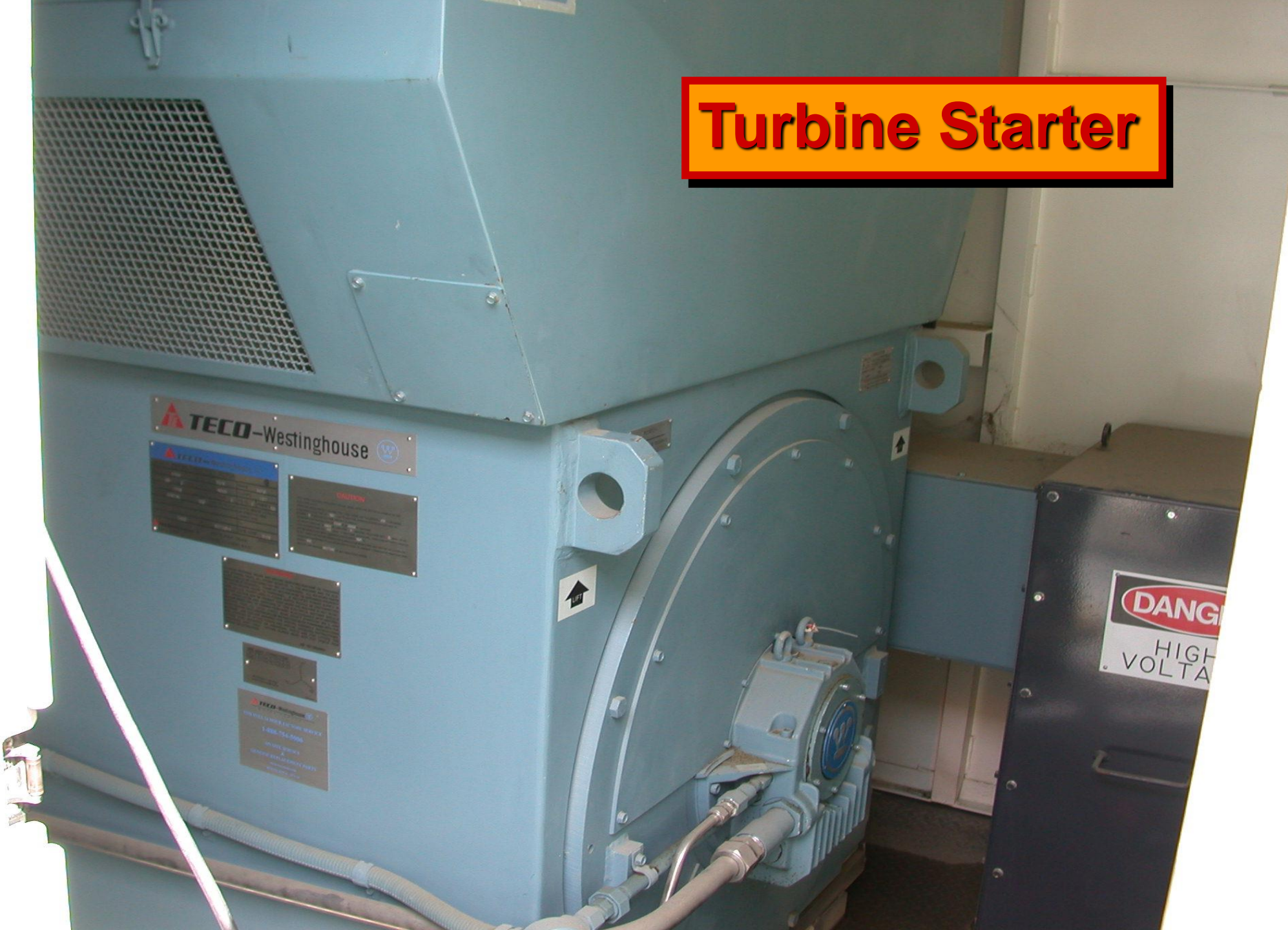
Hydraulic Pump





Gear Box

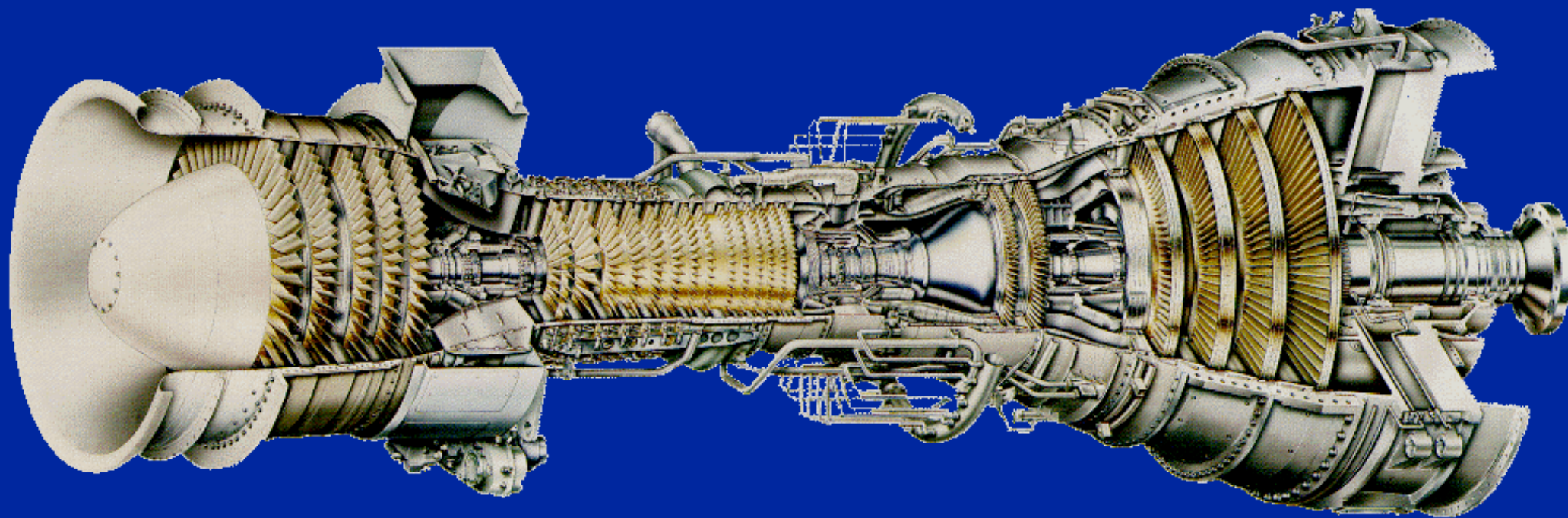
Turbine Starter





Let's have some fun!!

GE LM6000 Gas Turbine



Exercise

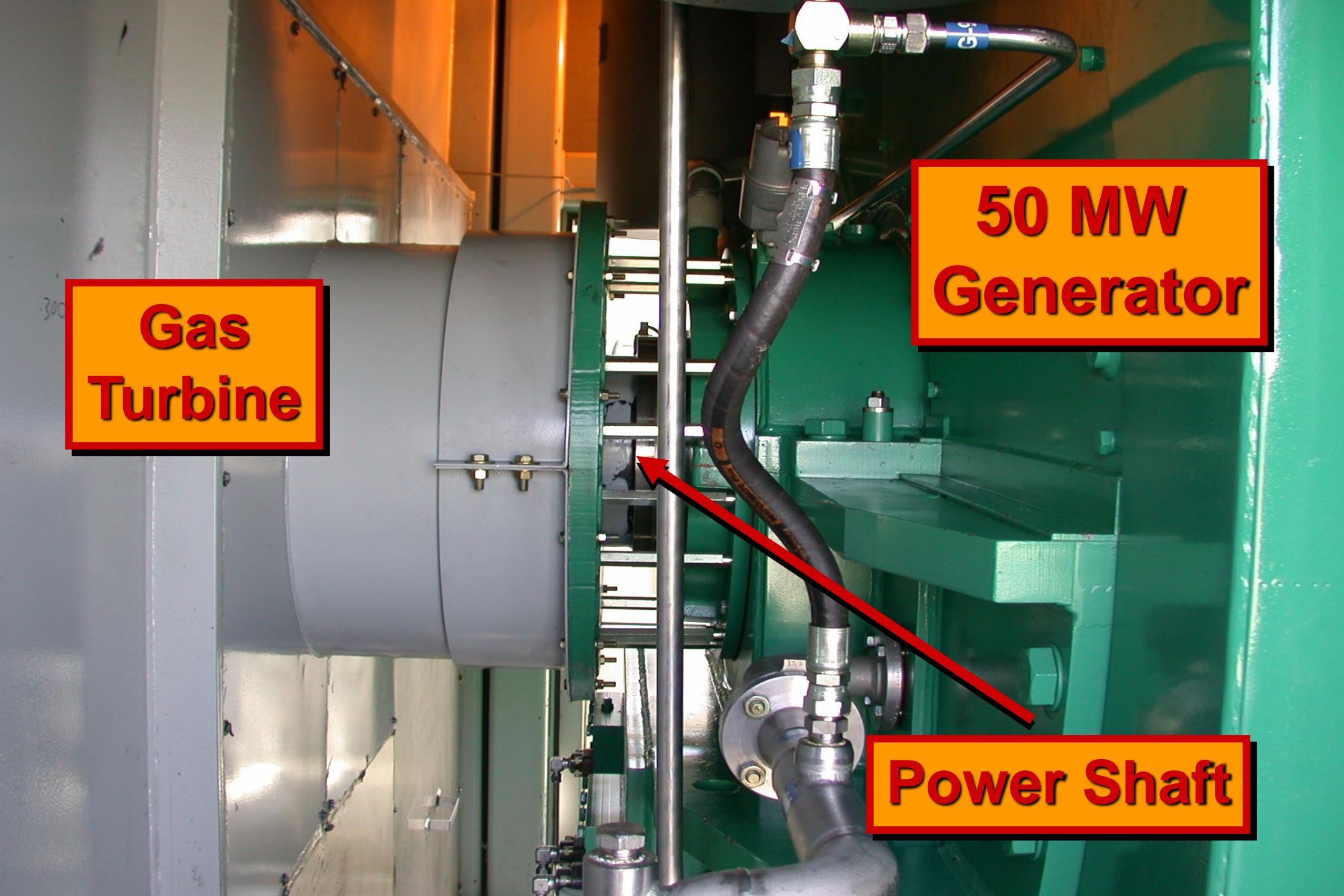


**Power
Generation**

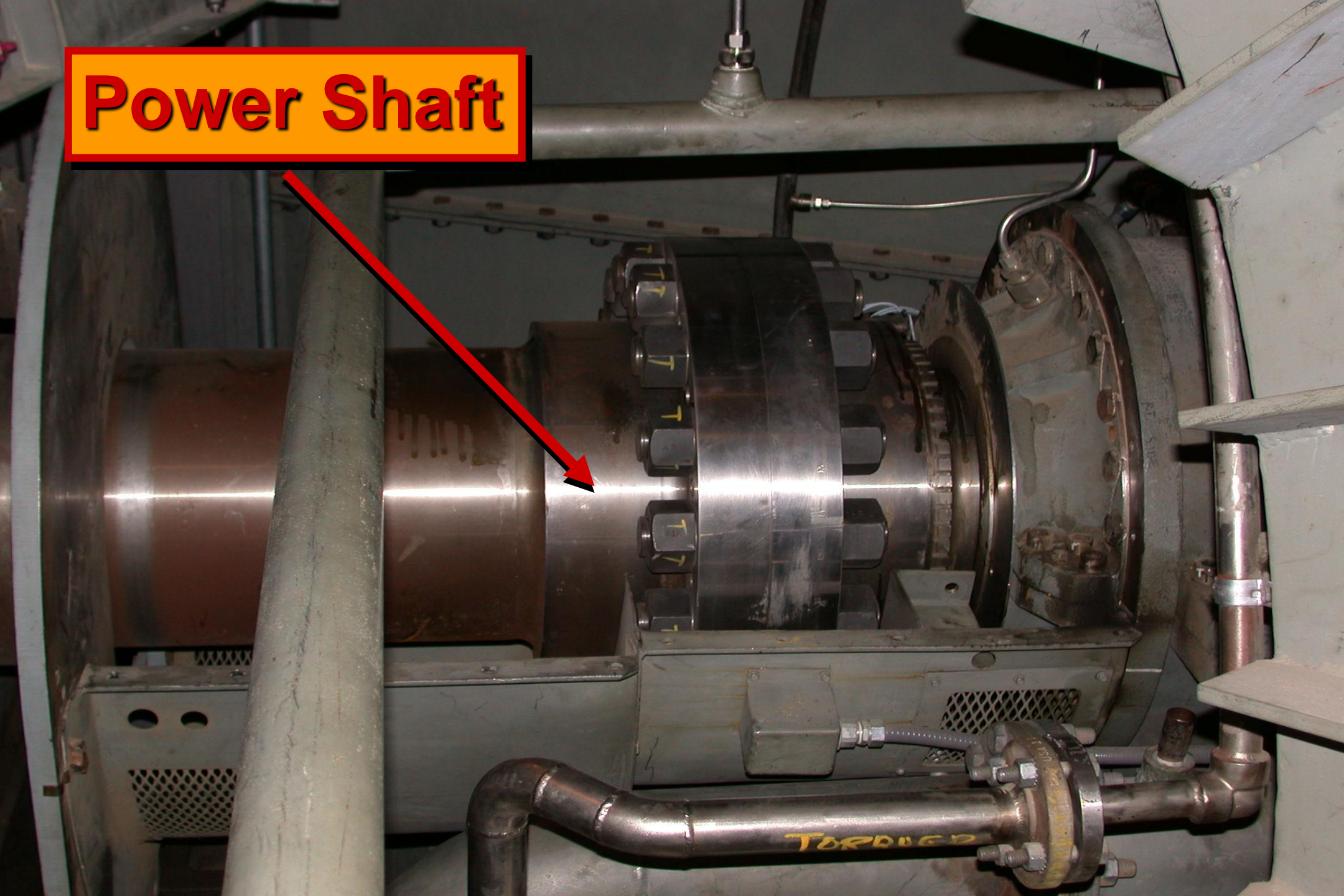
**Gas
Turbine**

**50 MW
Generator**

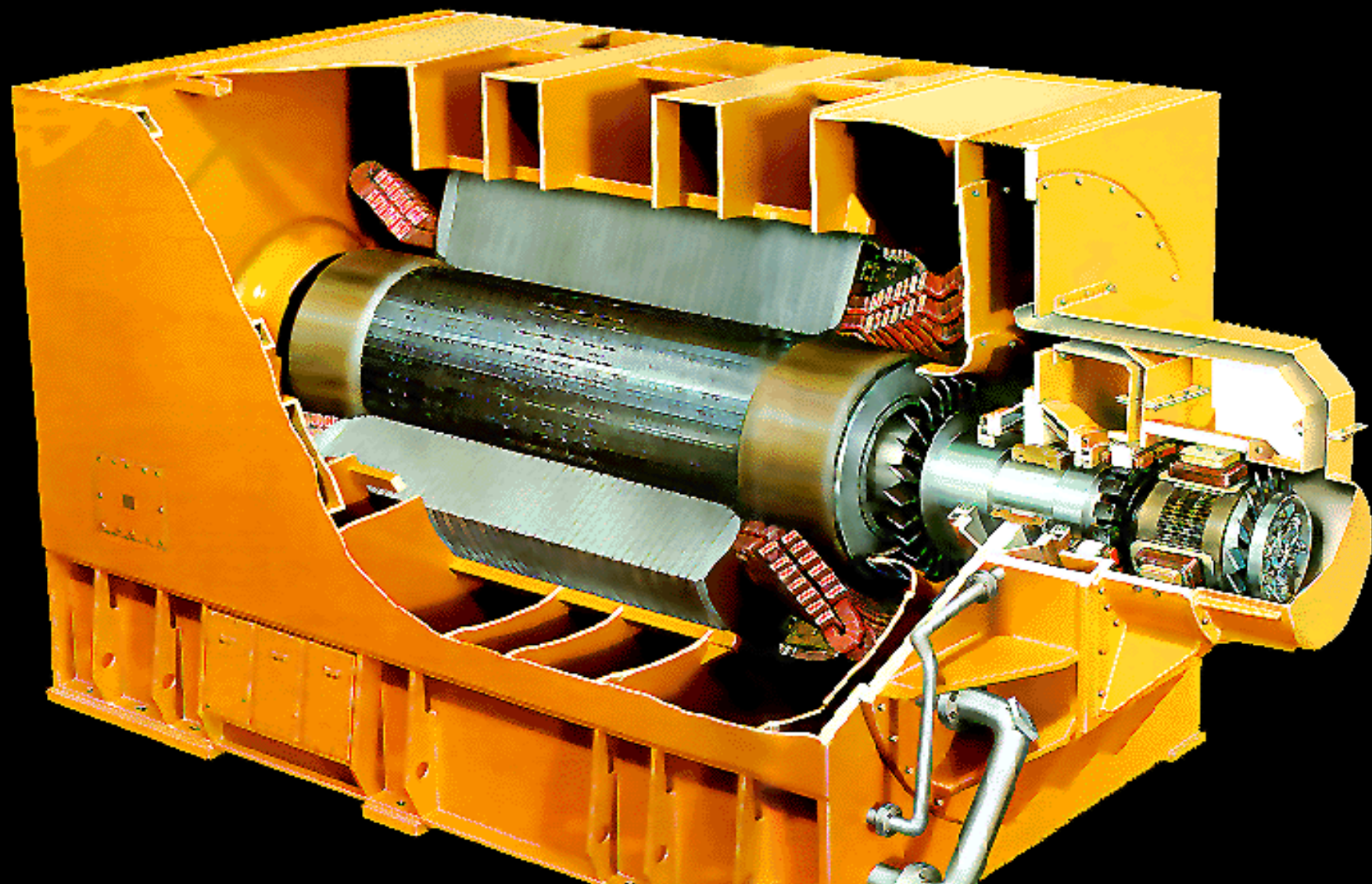
Power Shaft

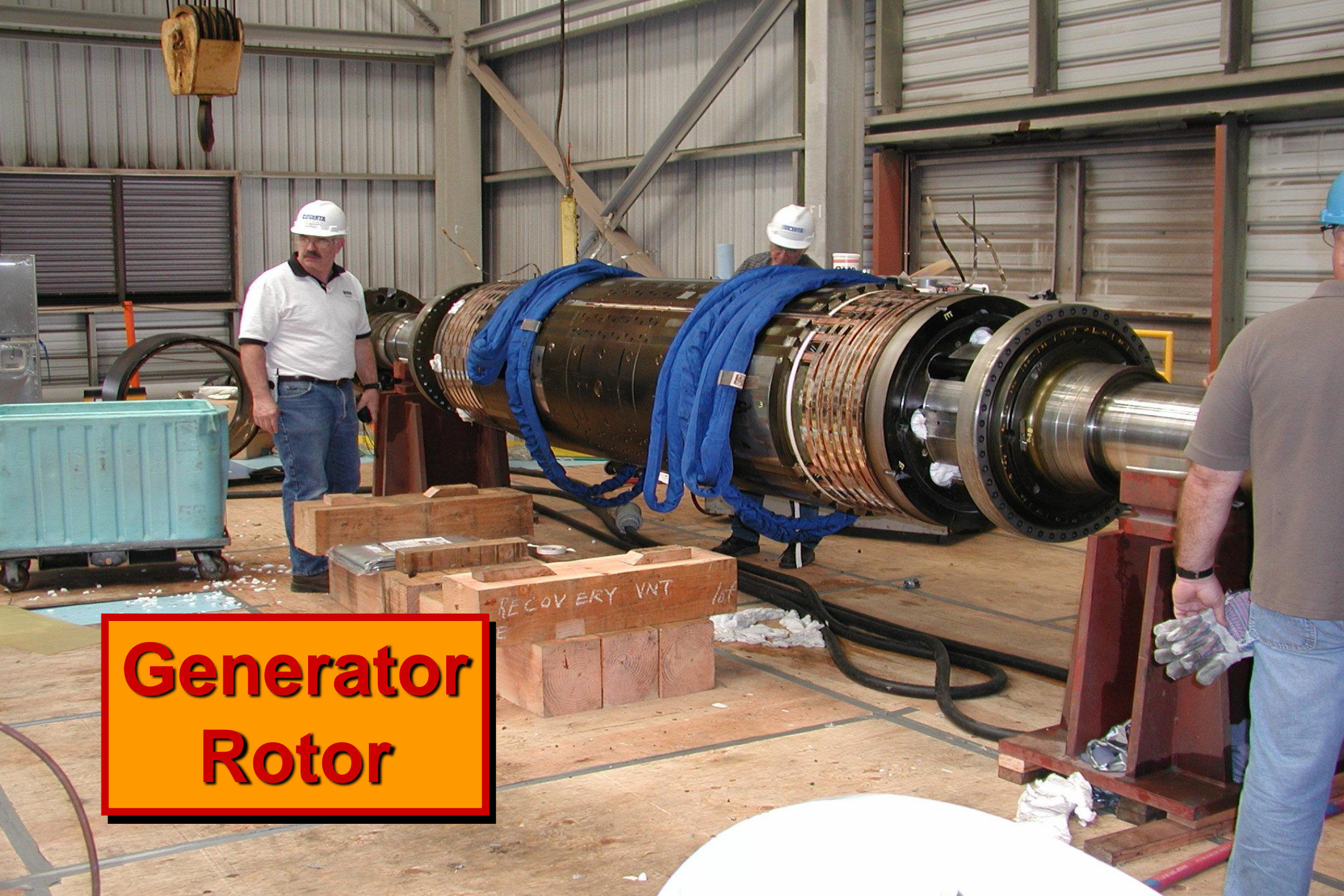


Power Shaft



Brush DAX Turbogenerator





**Generator
Rotor**

A close-up photograph of a generator stator winding. The image shows a dense array of copper windings, which are coated with a bright red insulating varnish. The windings are arranged in a circular pattern, with each coil overlapping the next. The lighting is dramatic, highlighting the glossy texture of the red insulation. In the lower-left corner, there is a yellow rectangular label with a red border containing the text "Generator Stator".

**Generator
Stator**



Step-up Transformers



**Let's Discuss
Steam Generation**

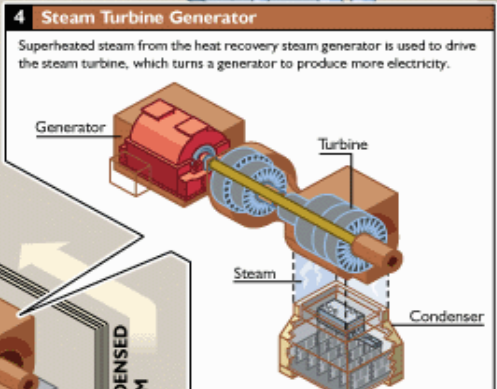
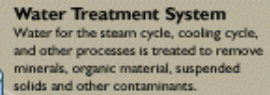
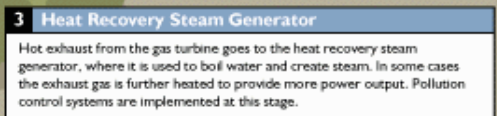
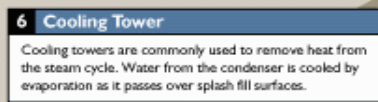
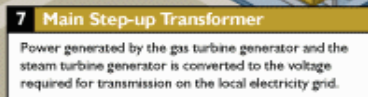
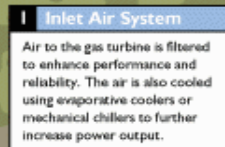
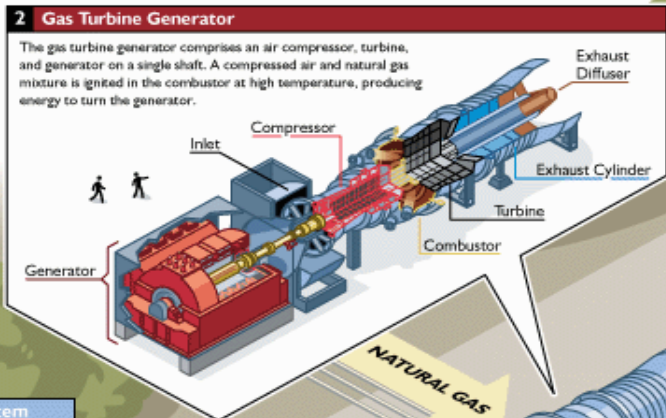
Combined Cycle Power Plants

XPLANATIONS™ by XPLANE

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.

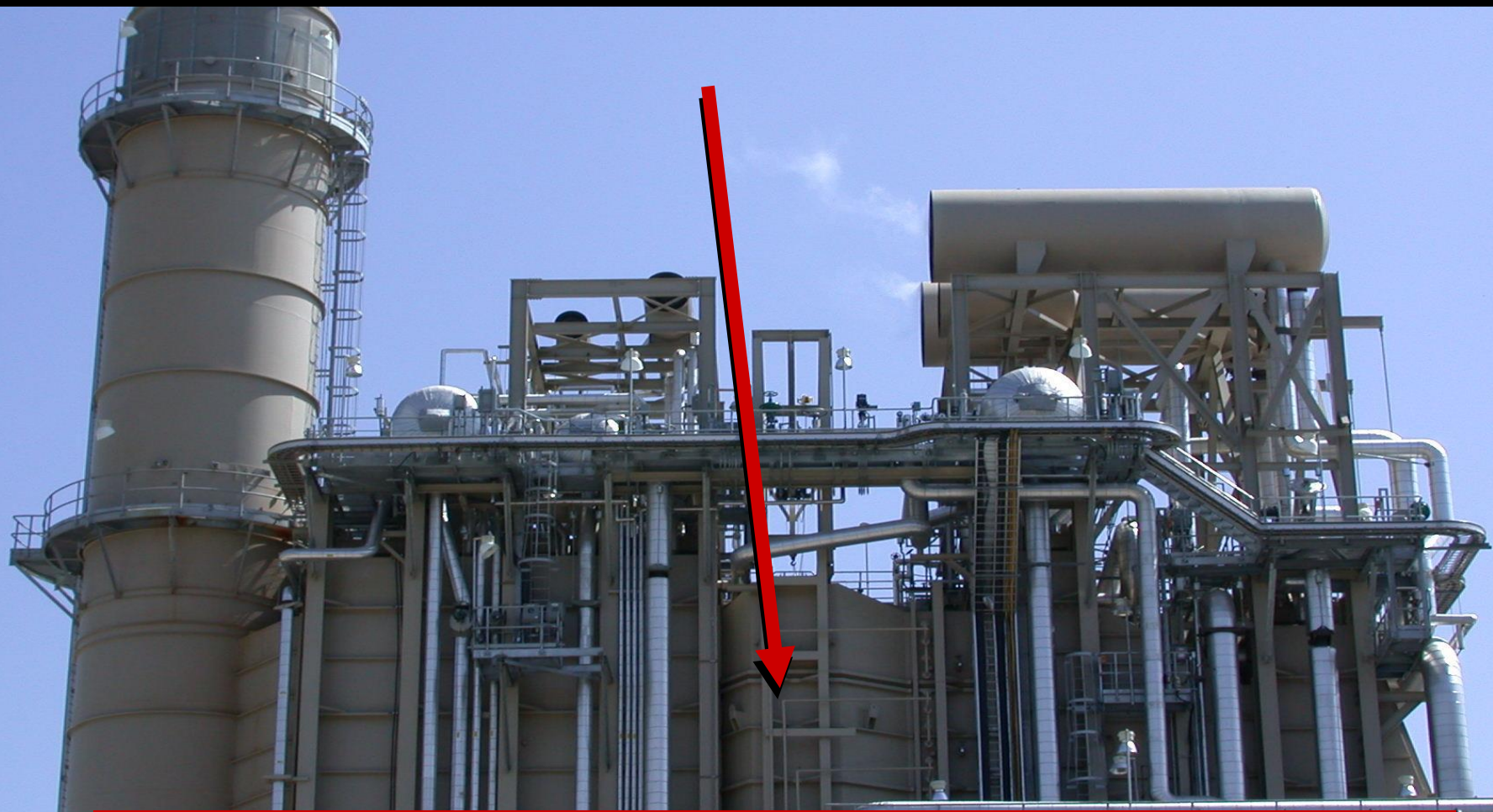


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Combined Cycle Power Plant

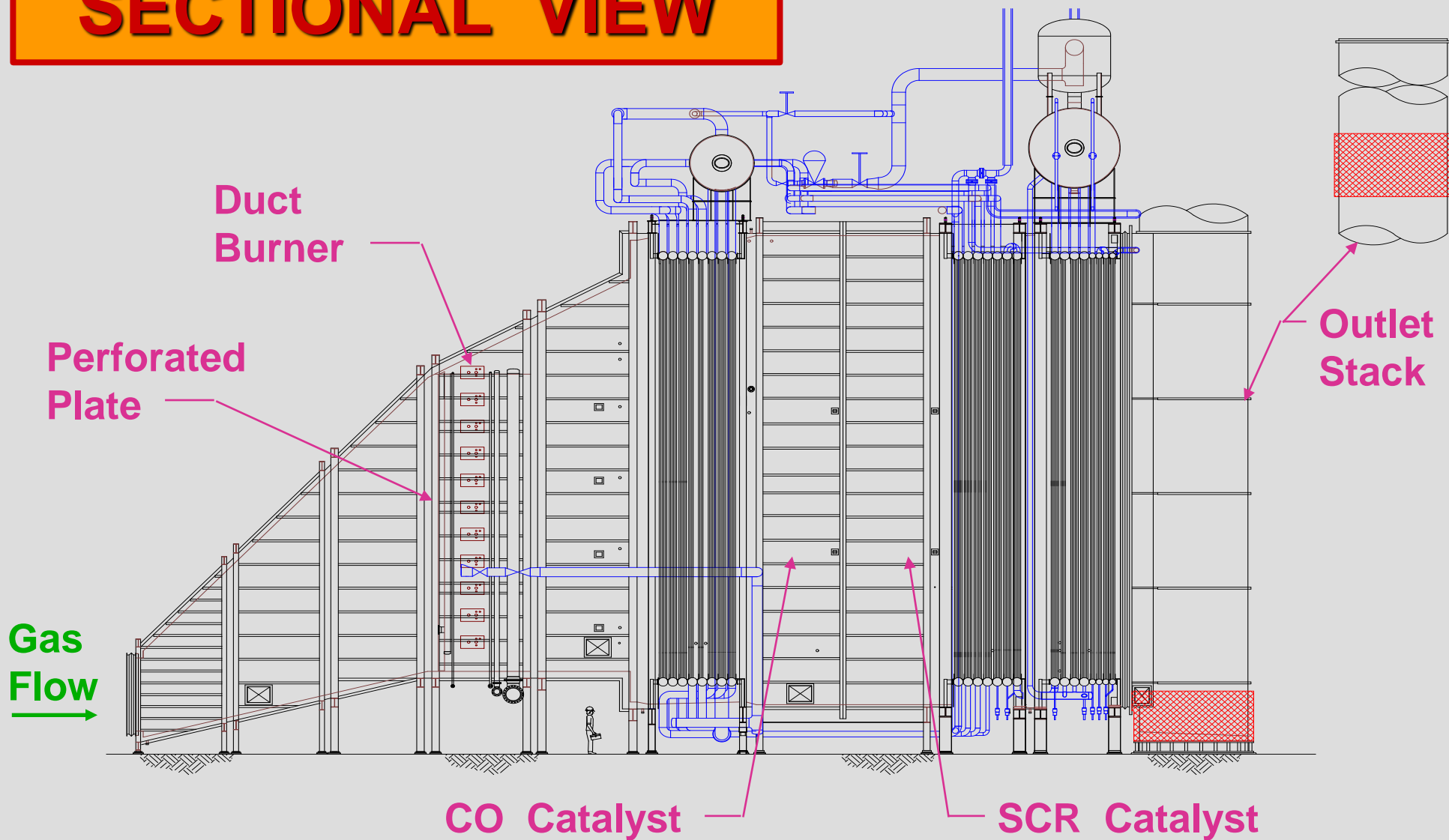


Heat Recovery Steam Generator Unit



Combined Cycle with HRSG

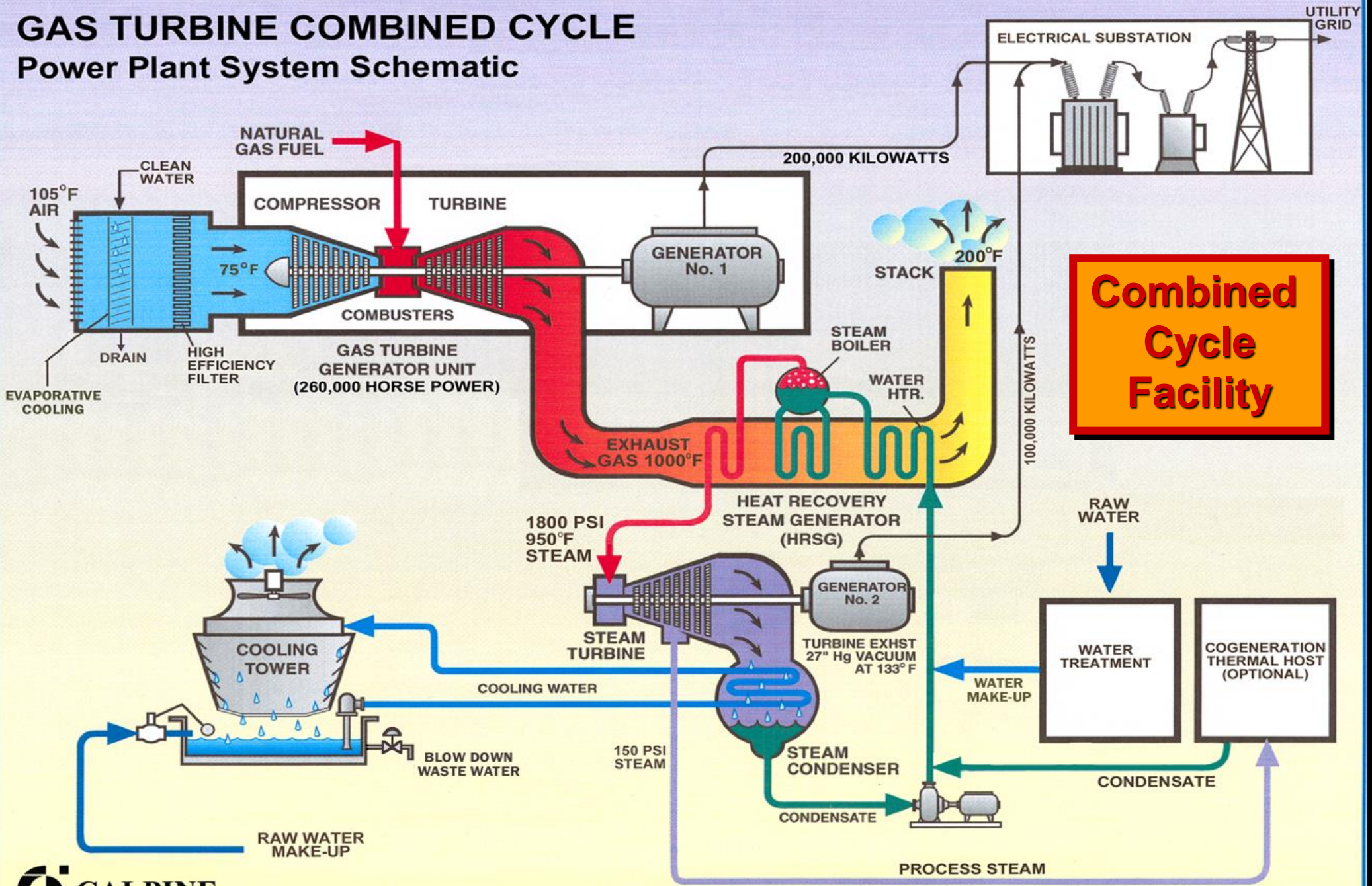
SECTIONAL VIEW



LM6000 Peaking Plant

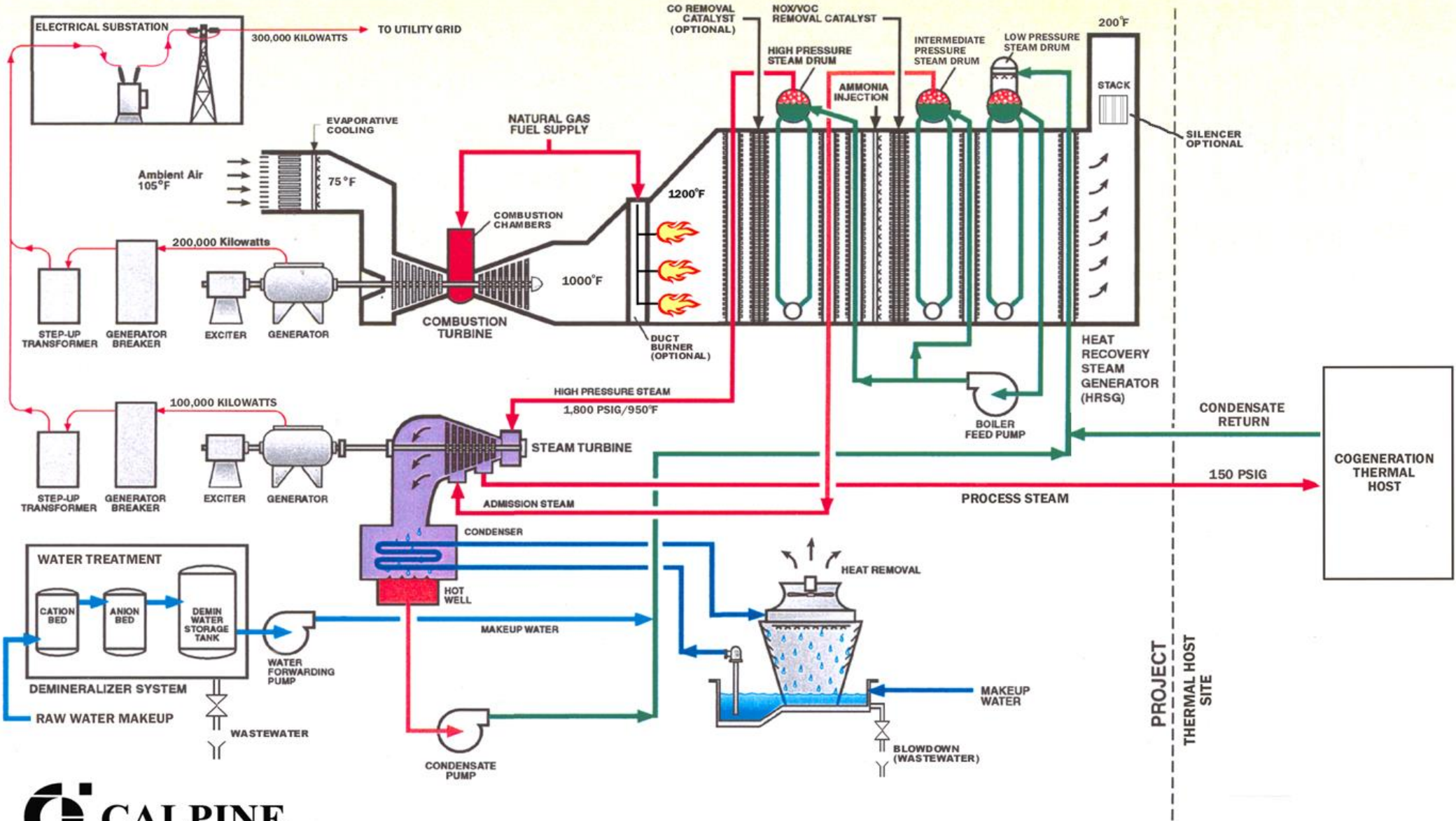


GAS TURBINE COMBINED CYCLE Power Plant System Schematic



GAS TURBINE COMBINED CYCLE COGENERATION PROJECT

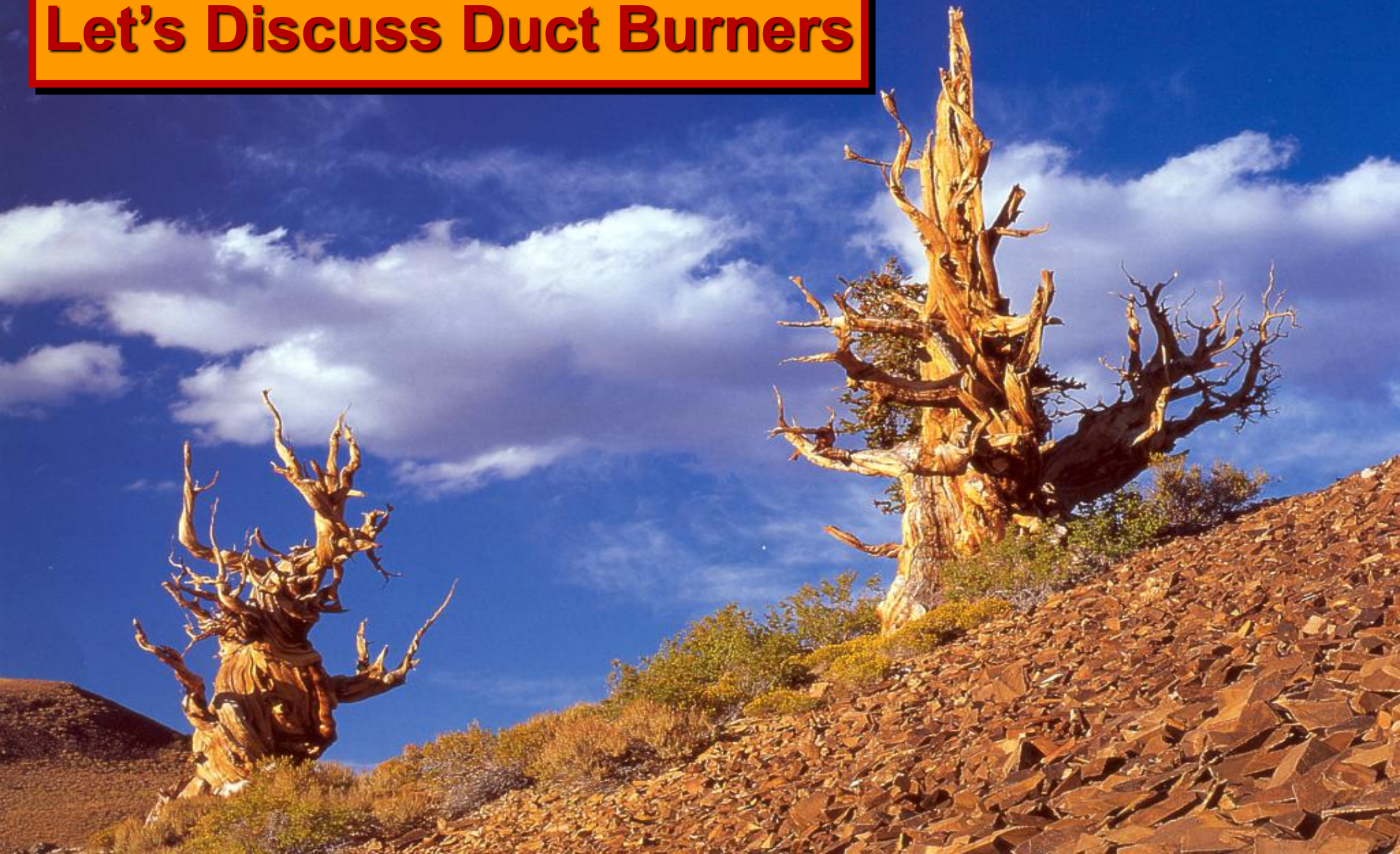
Cogeneration System Schematic



Combined Cycle w/By-pass



Let's Discuss Duct Burners



**Duct
Burners**



**Boiler
Installation**





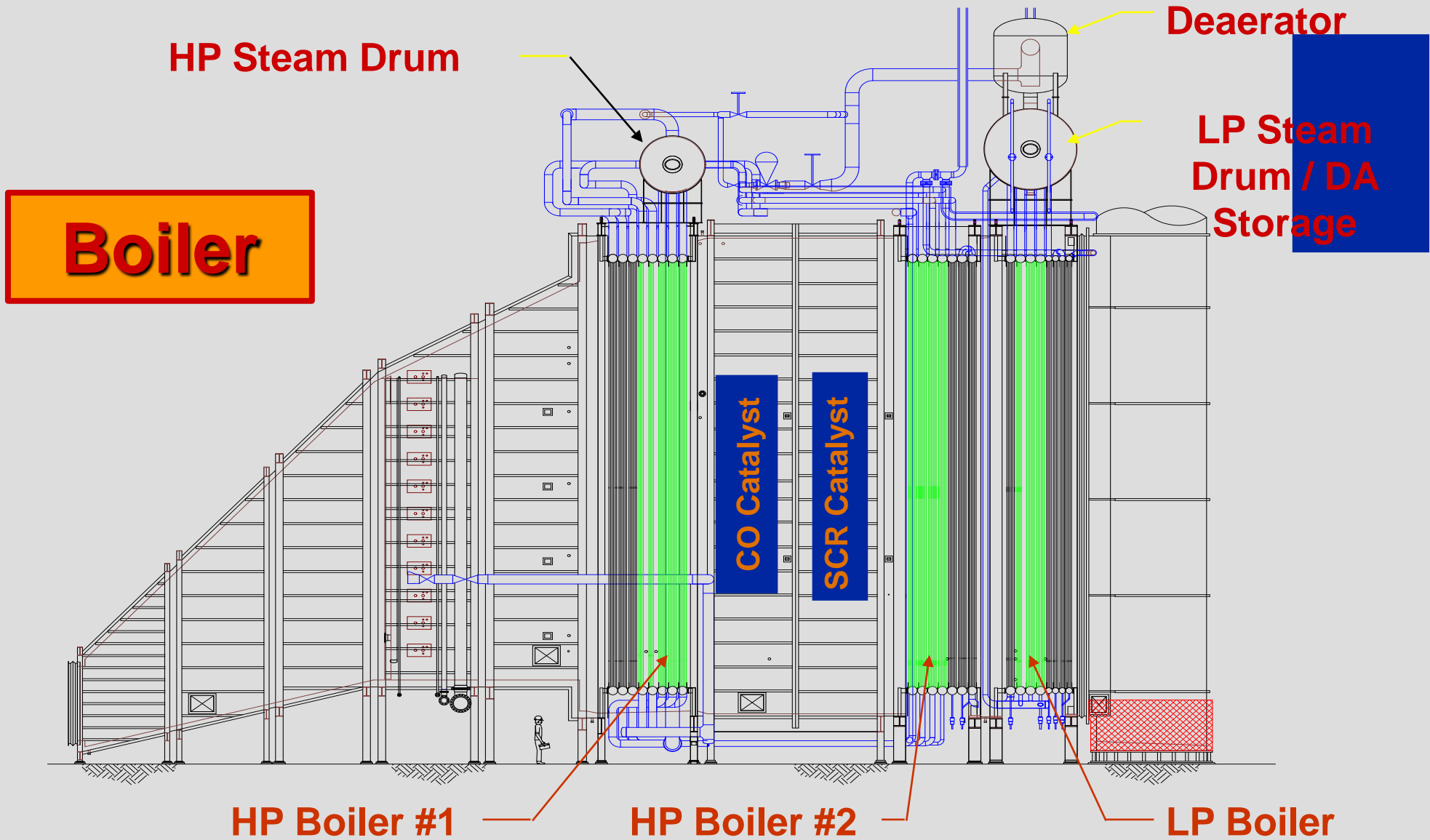
HRSG Overview

◆ Superheater

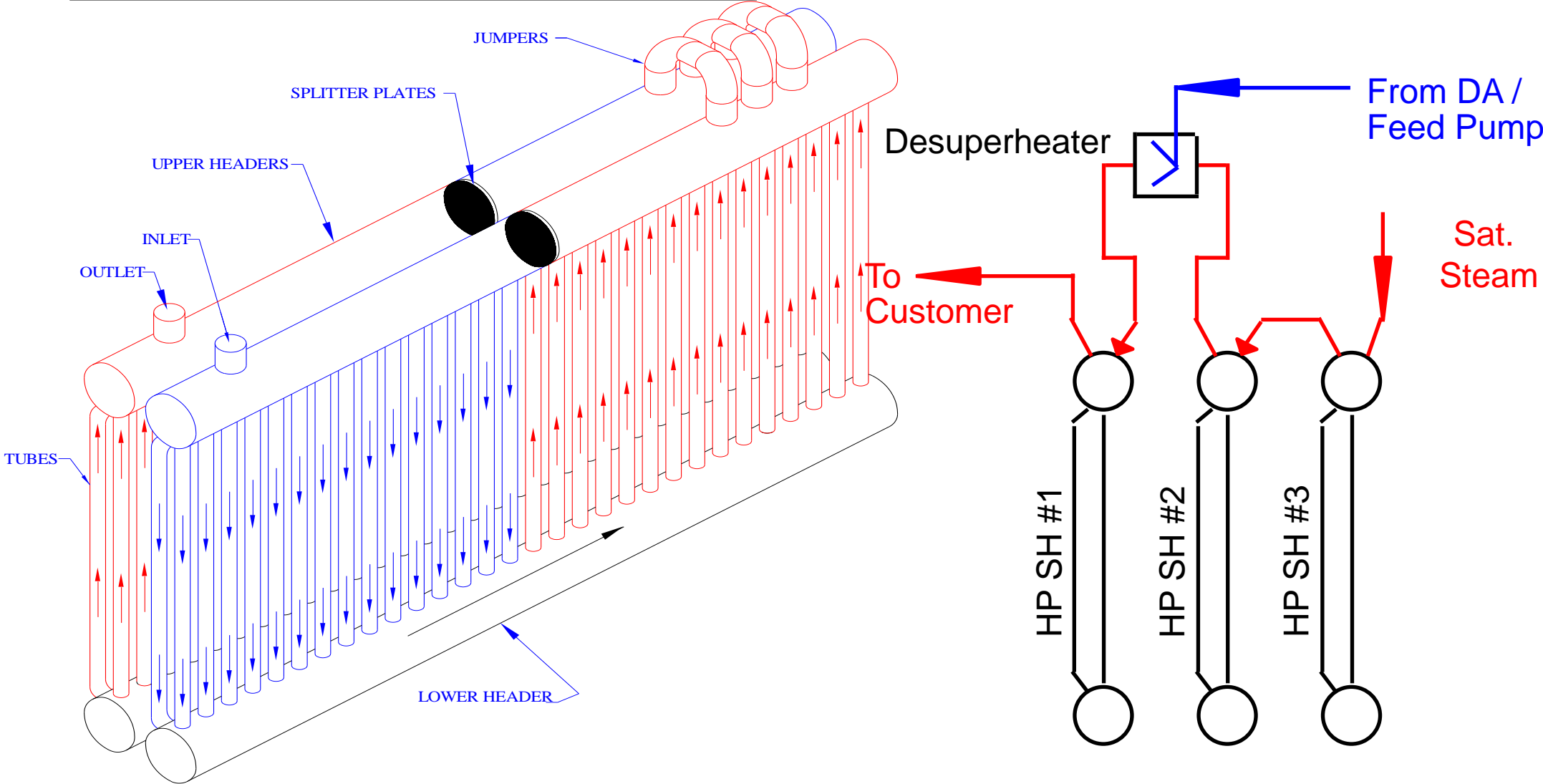
- take saturated steam from the drum and increase the temperature of the steam

◆ Evaporator

◆ Economizer



TYPICAL STEAM FLOW





Steam Lines to Steam Turbine



Steam Turbine

LP Steam Turbine



The image shows a large, complex industrial rotor assembly, likely for a gas turbine engine. It features multiple rows of blades. The blades are arranged in a curved, cylindrical pattern. The first row of blades is highlighted with a red and yellow box. The blades are dark in color, possibly black or dark grey, and have a curved, aerodynamic shape. The rotor is supported by a metal frame. The background is a light blue color, possibly a tarp or a wall. The text "Row 1 LP Blades" is written in red on a yellow background in the top right corner. The text "10 Stage IP Rotor Blades" is written in red on a yellow background in the bottom center.

**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

The image shows a large industrial facility, likely a power plant, featuring several tall, segmented cooling towers. The towers are constructed from light-colored, cylindrical sections and are supported by a complex network of metal scaffolding and pipes. The background consists of a large, tan-colored building with a corrugated metal facade. The sky is clear and bright. In the foreground, there are more pipes and structural elements, including a horizontal pipe running across the bottom of the frame. A red-bordered box with a yellow background is overlaid in the lower-left corner, containing the text "Steam Turbine to 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



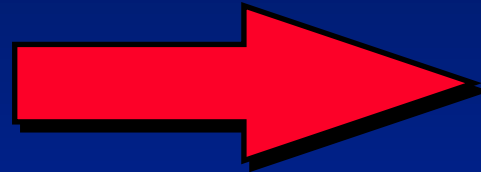
Prometheus Tree – 4,844 years old





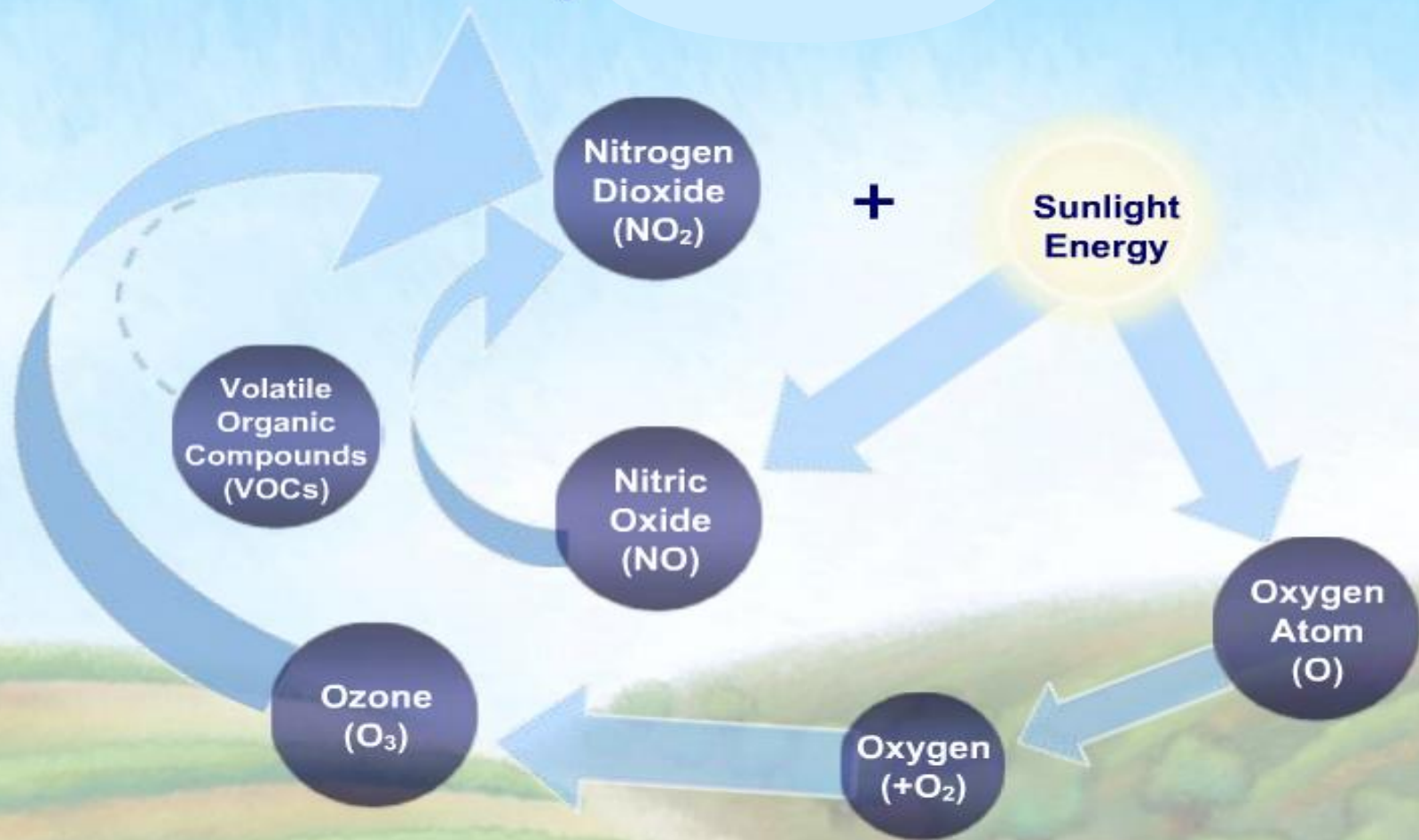
Emissions From Gas Turbines

Fuel
+
Air
(N₂, O₂)



- ◆ H₂O
- ◆ CO₂
- ◆ CO
- ◆ VOC
- ◆ NO_x
- ◆ SO_x
- ◆ PM

Ozone Photochemistry



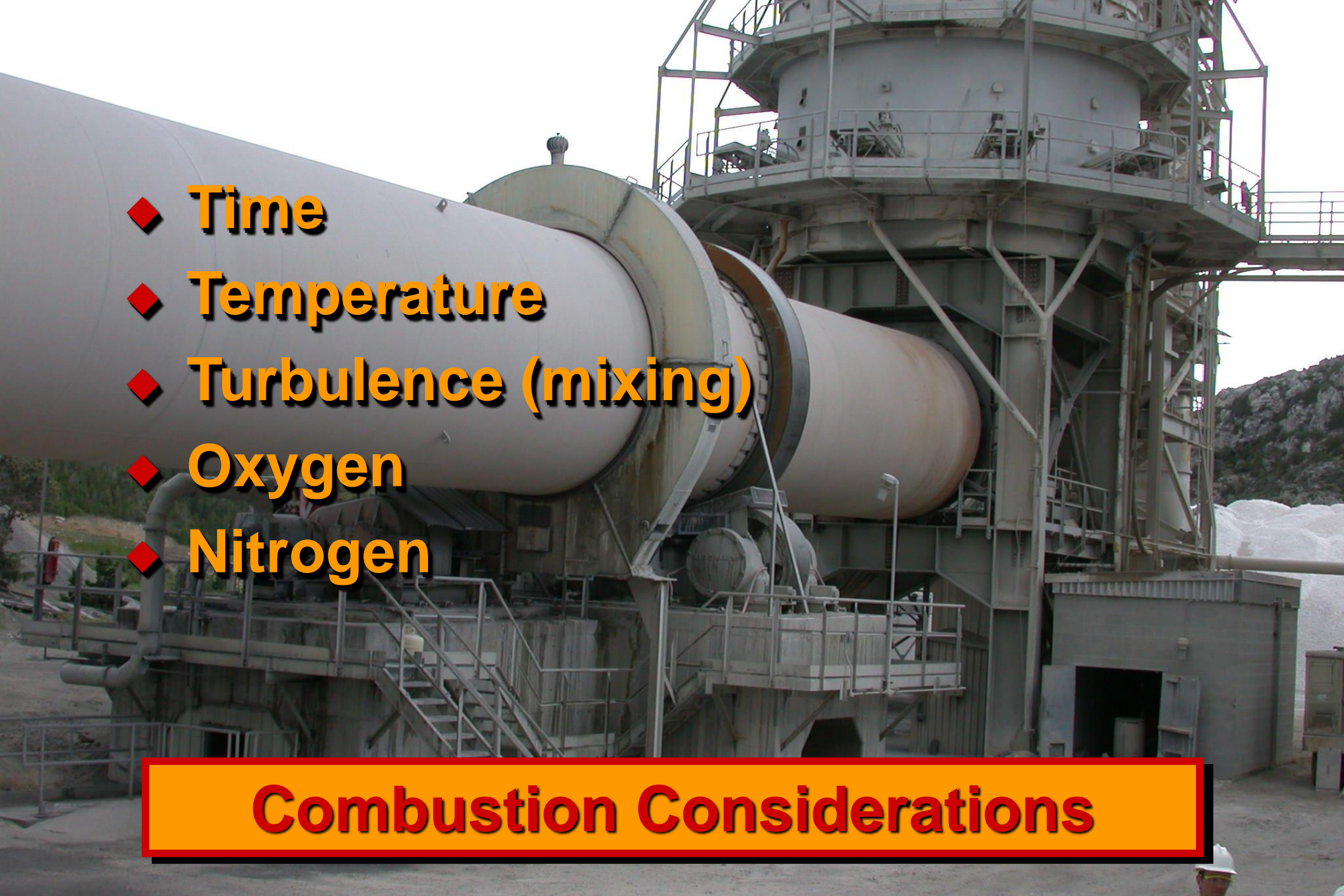
A wide-angle photograph of a mountain range. The central focus is a large, rugged mountain peak with a snow-dusted summit and steep, rocky slopes. The foreground and middle ground are filled with dense evergreen forests, their branches heavily laden with snow. The sky is a clear, deep blue. The overall scene is serene and majestic.

Let's Discuss Emissions Controls

Emissions Control Methods

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



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

Combustion Considerations

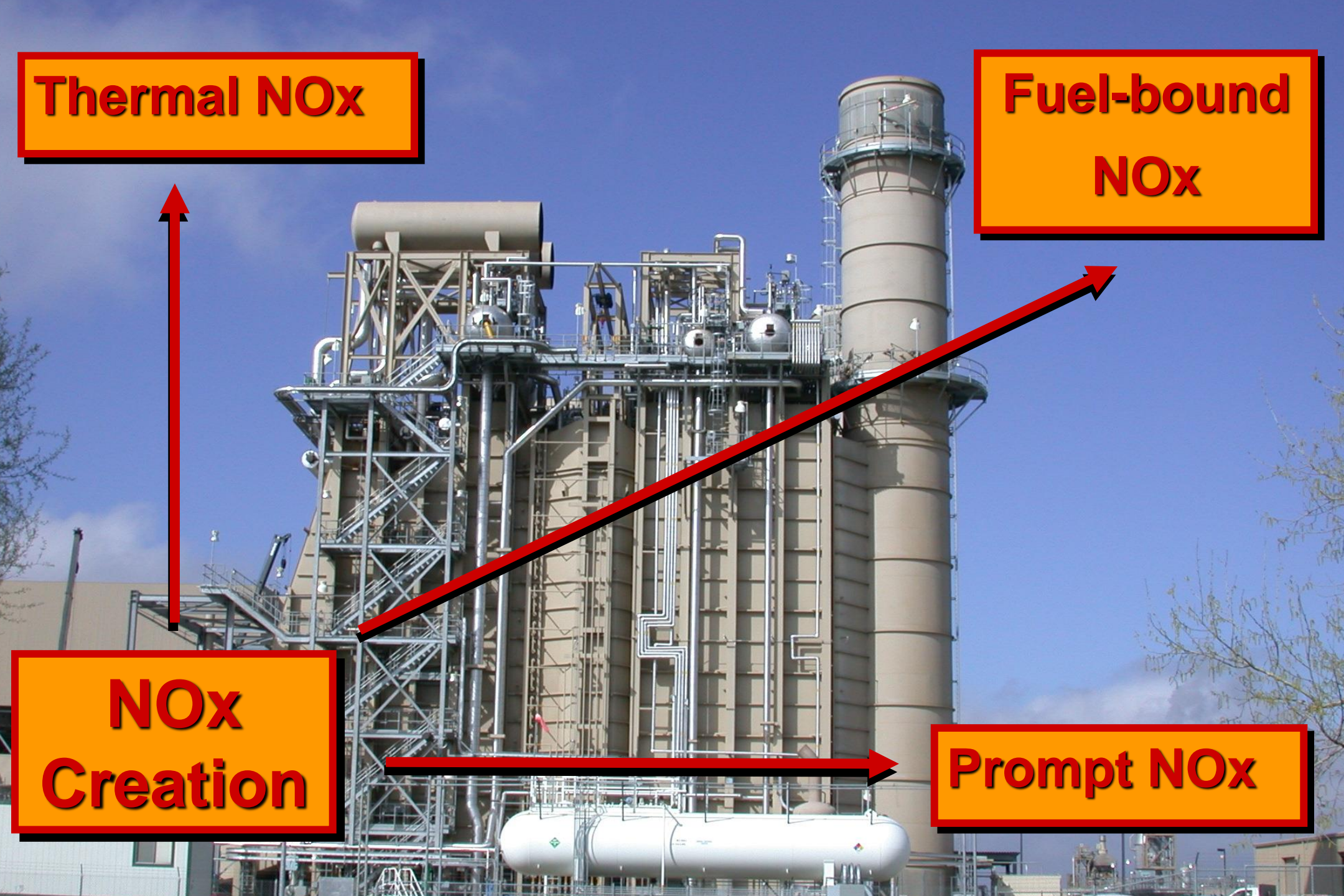
Thermal NOx

**Fuel-bound
NOx**

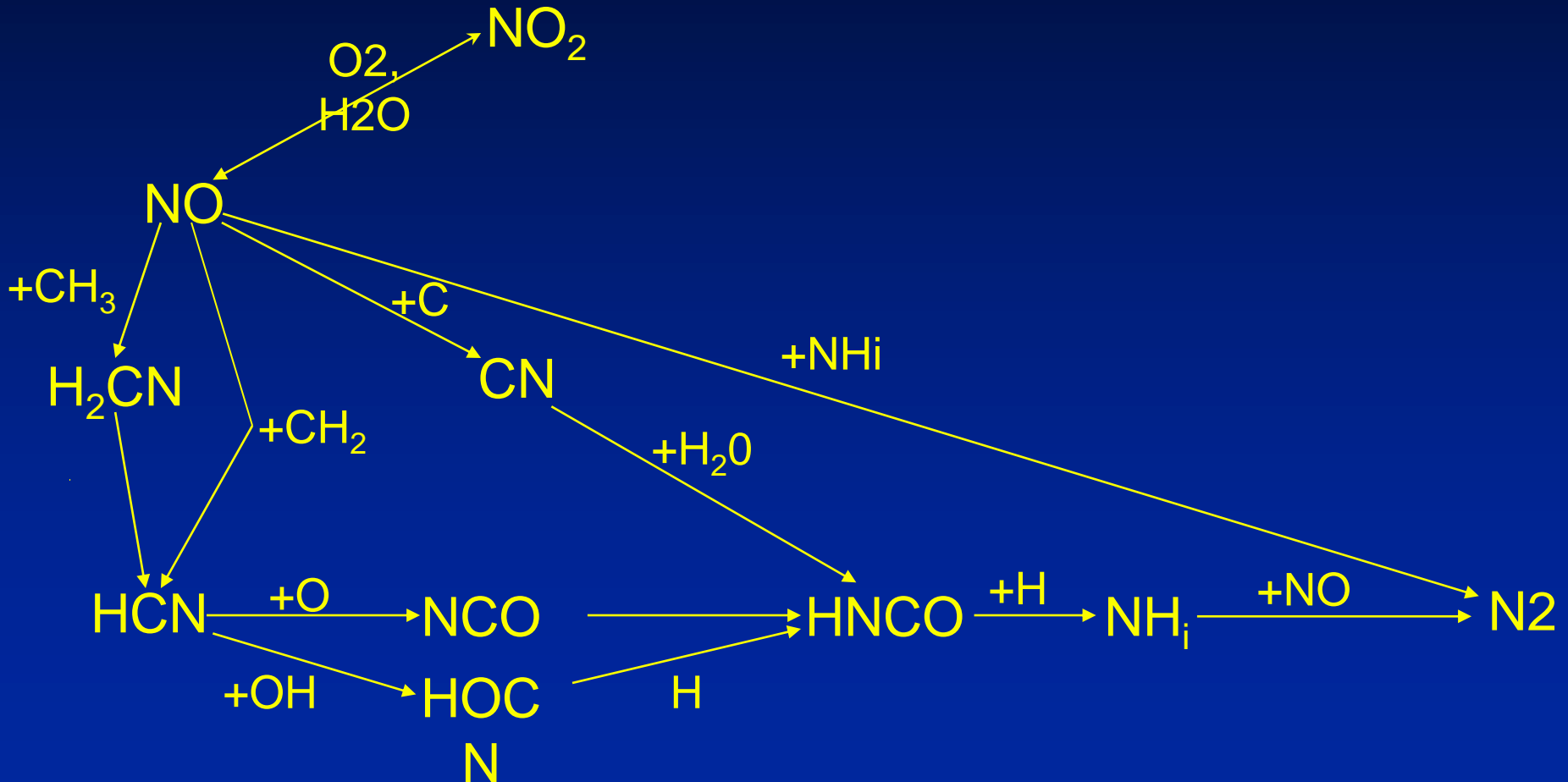


**NOx
Creation**

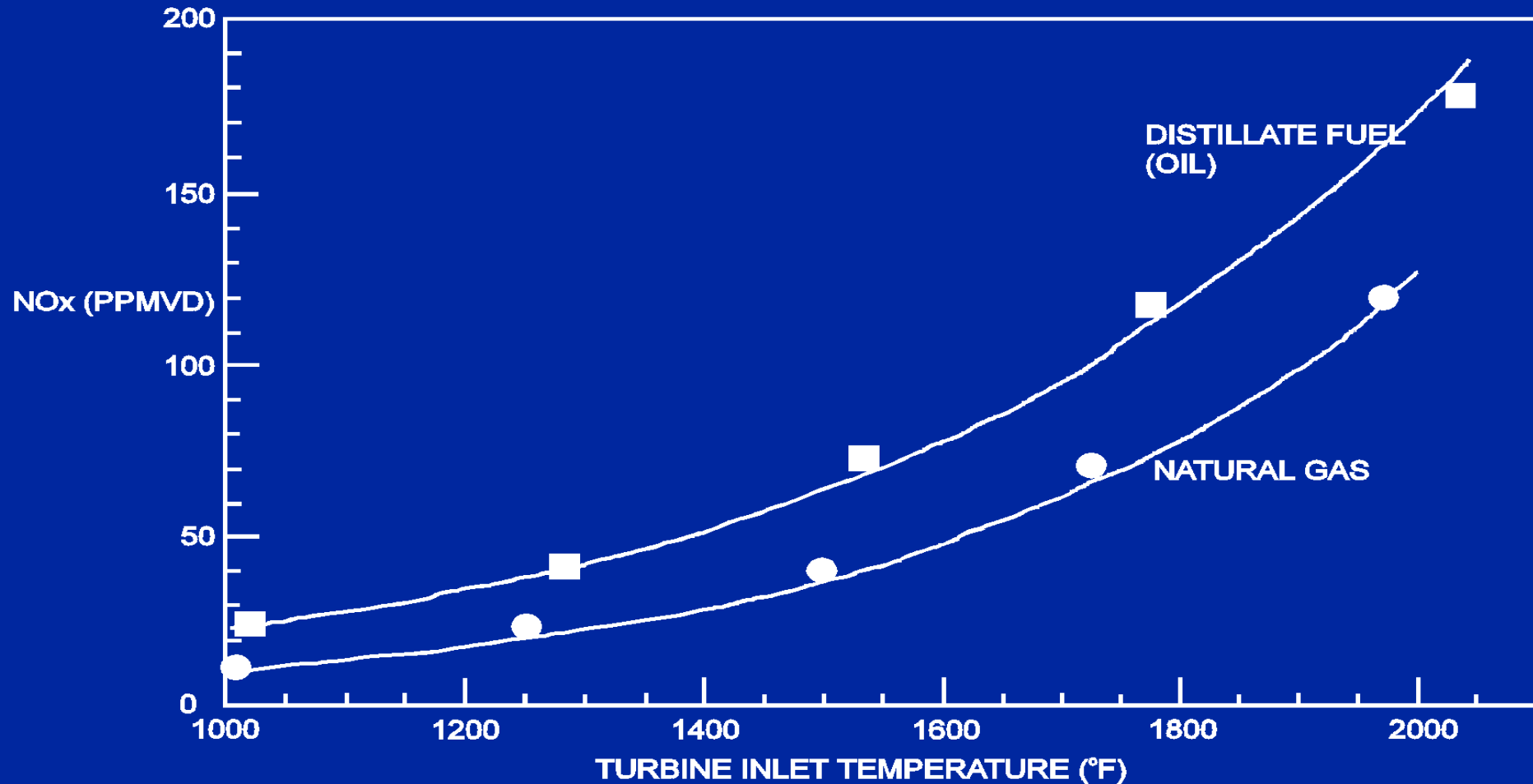
Prompt NOx



PROMPT NOx



NOx vs. Turbine Inlet Temperature



Thermal NOx vs. Equivalence Ratio

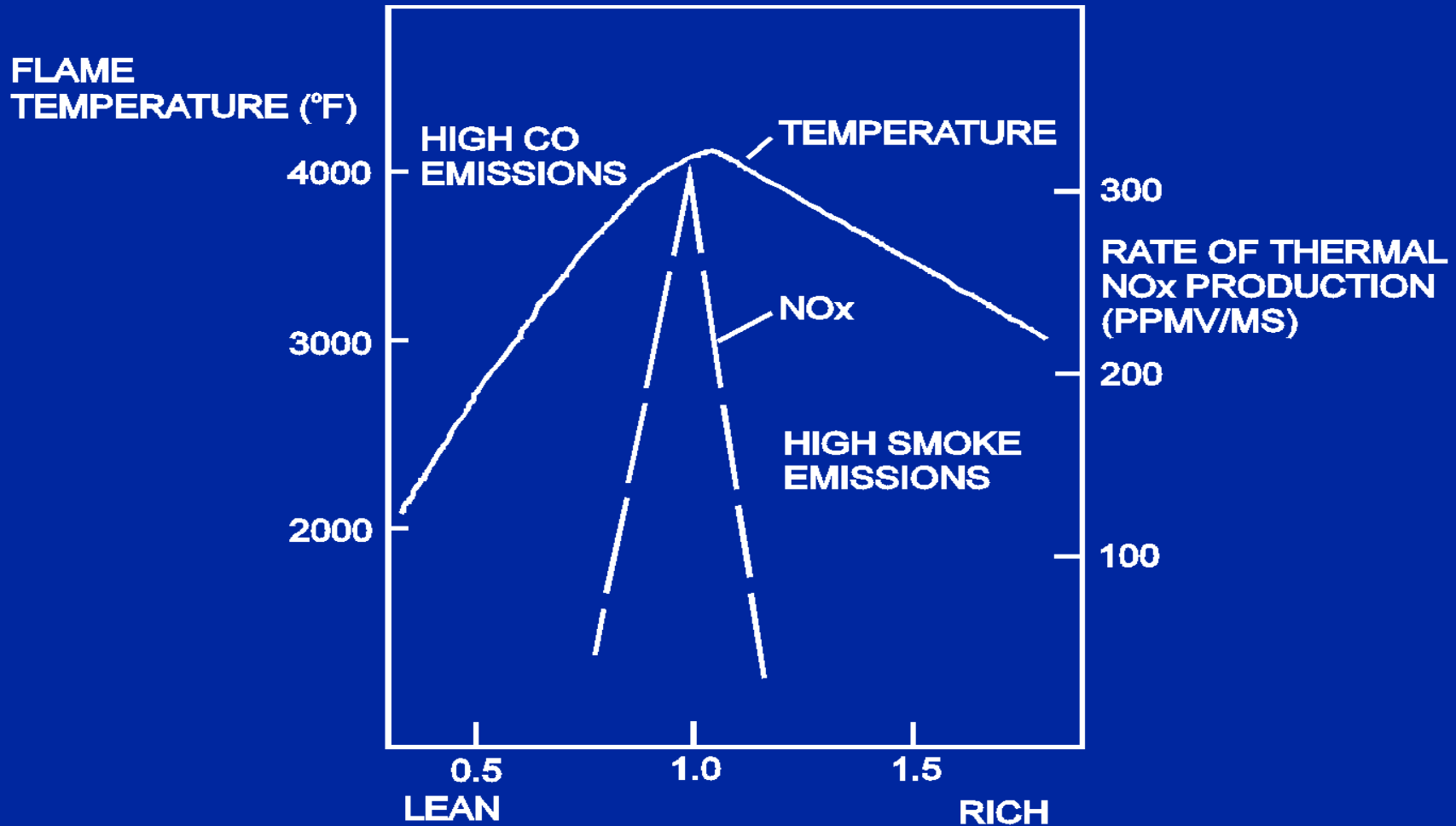
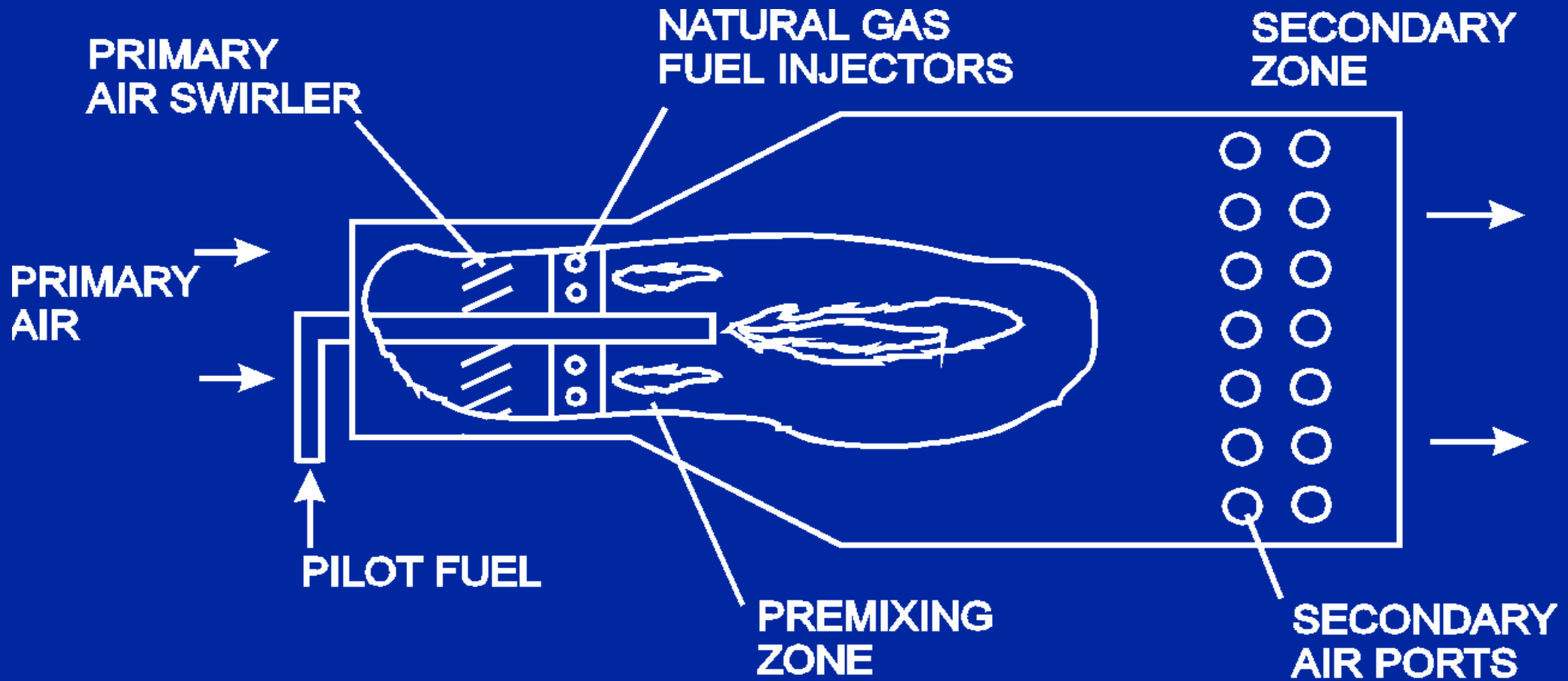
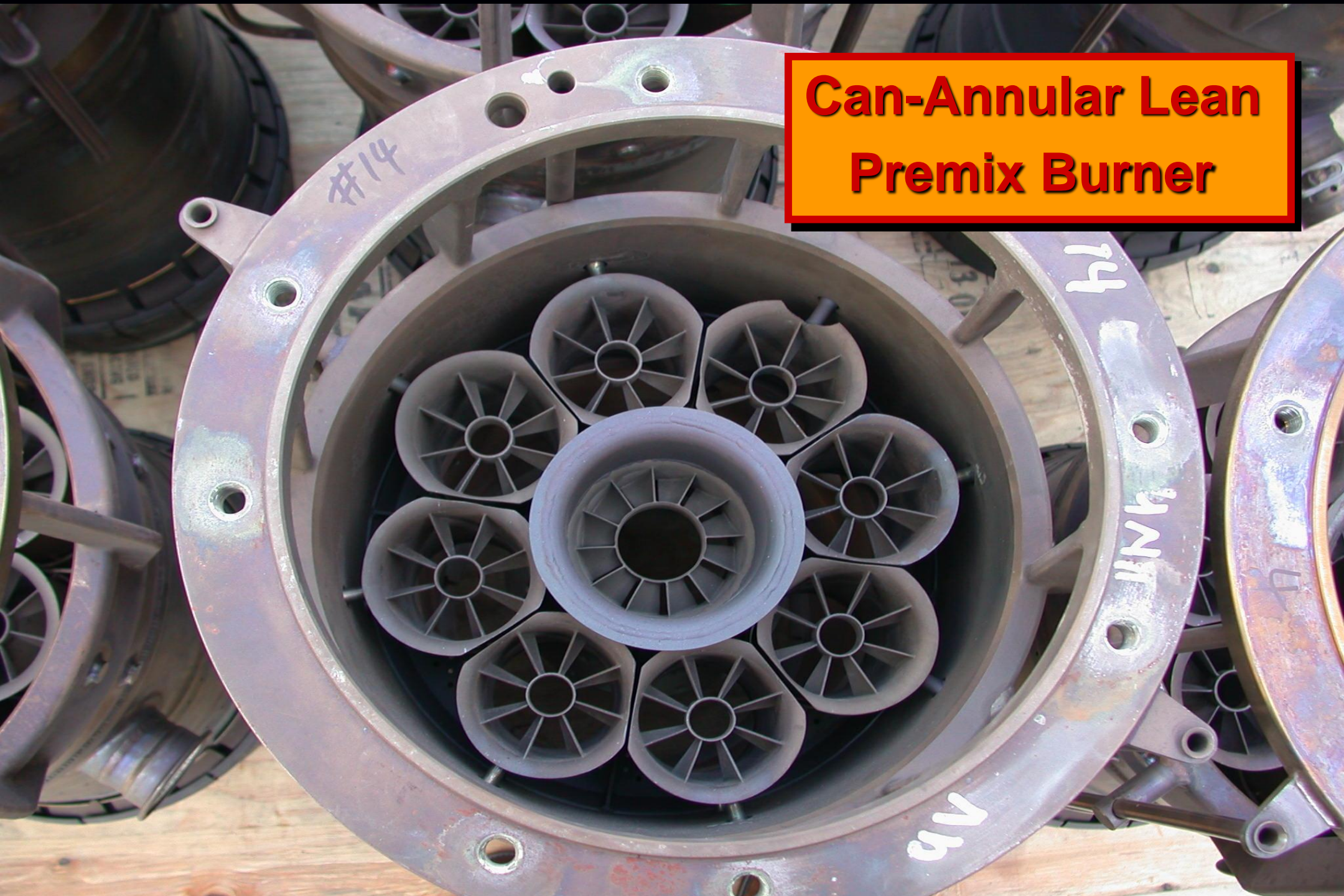


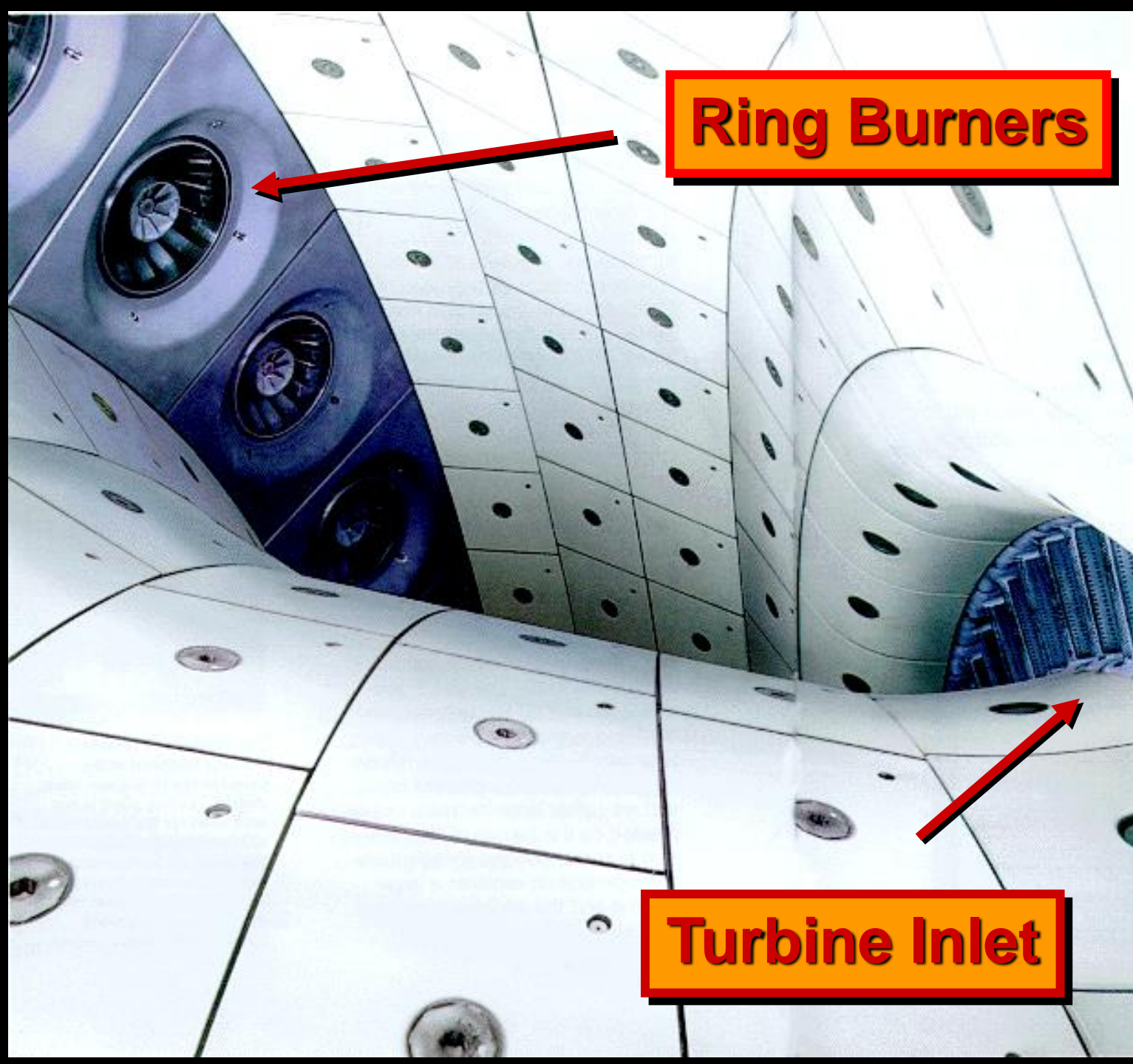
Figure 301.2

Lean Premix Combustor



**Can-Annular Lean
Premix Burner**





Ring Burners

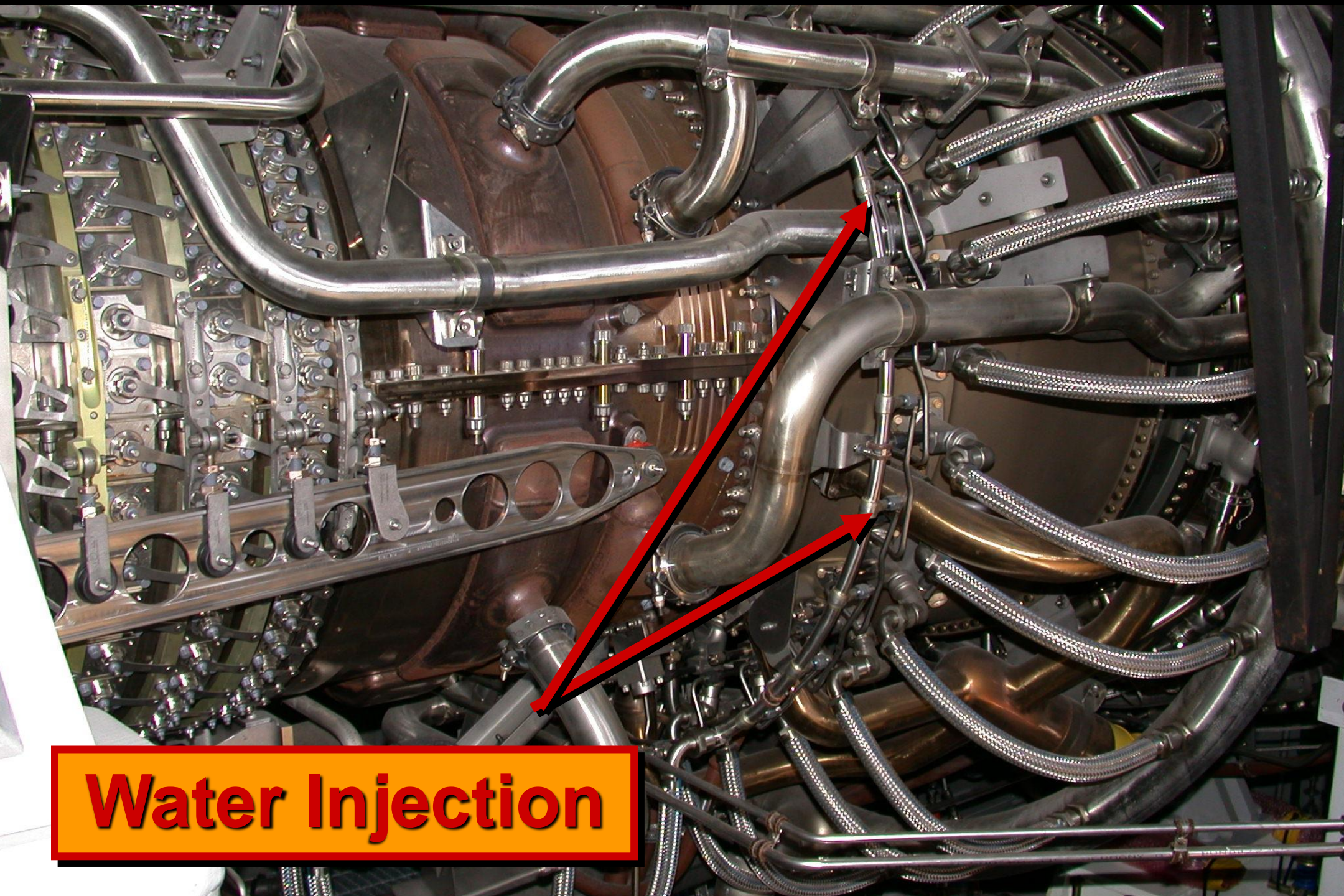
**Siemens
Hybrid
Burner
Ring
Combustor**

Turbine Inlet

**Graphic Courtesy
of Siemens**



Let's Discuss Steam/Water Injection



Water Injection

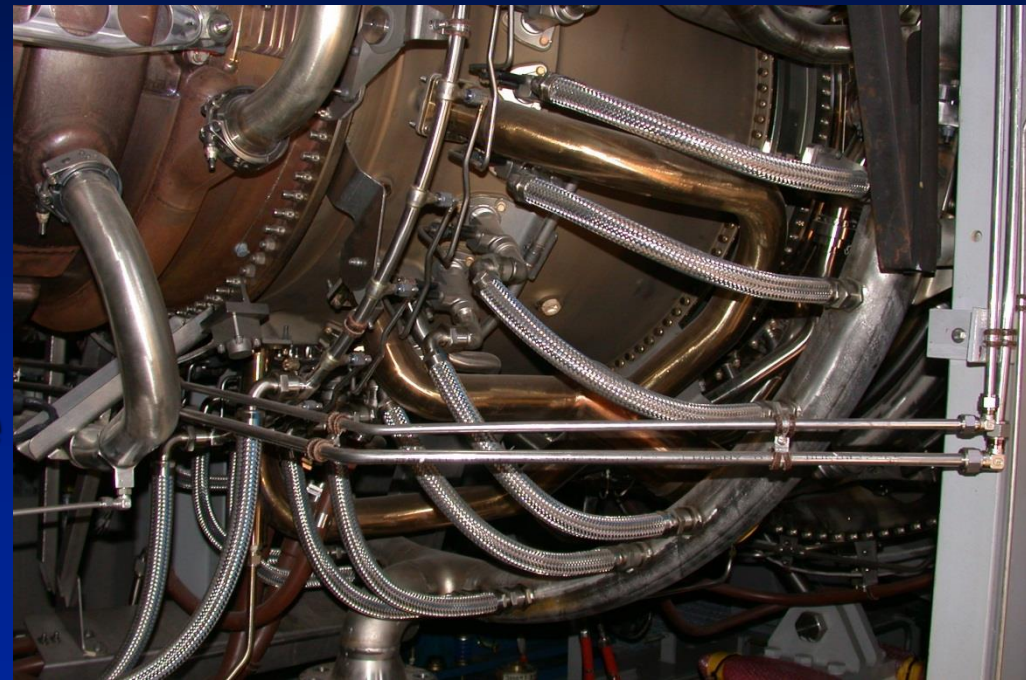
Water & Steam Injection NOx Control

◆ Advantages

- Reduces NOx
- Increases power output

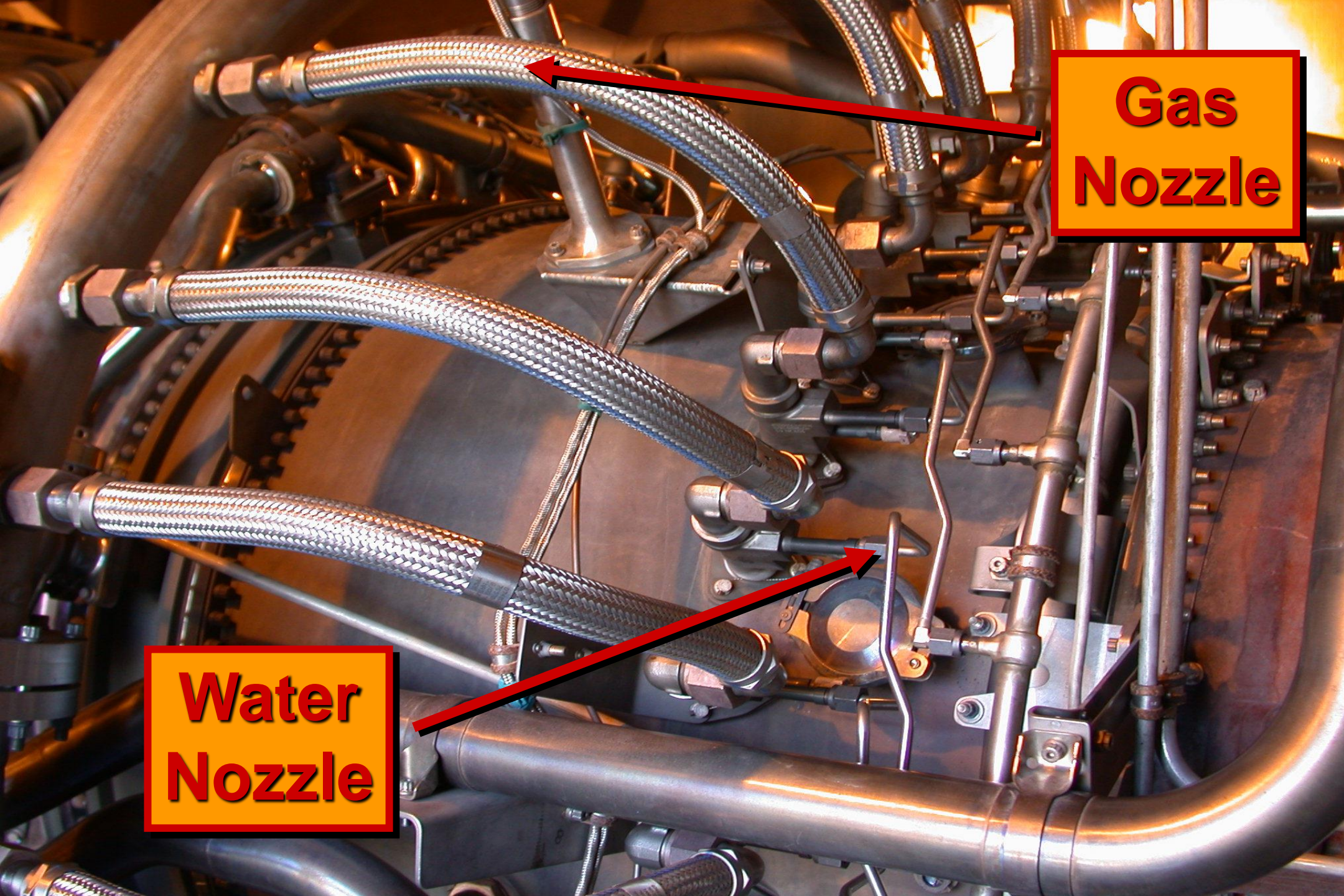
◆ Disadvantages

- Water treatment expense
- Increased fuel use
- Increases HC
- Increases CO
- Increased wear & maintenance



**Gas
Nozzle**

**Water
Nozzle**

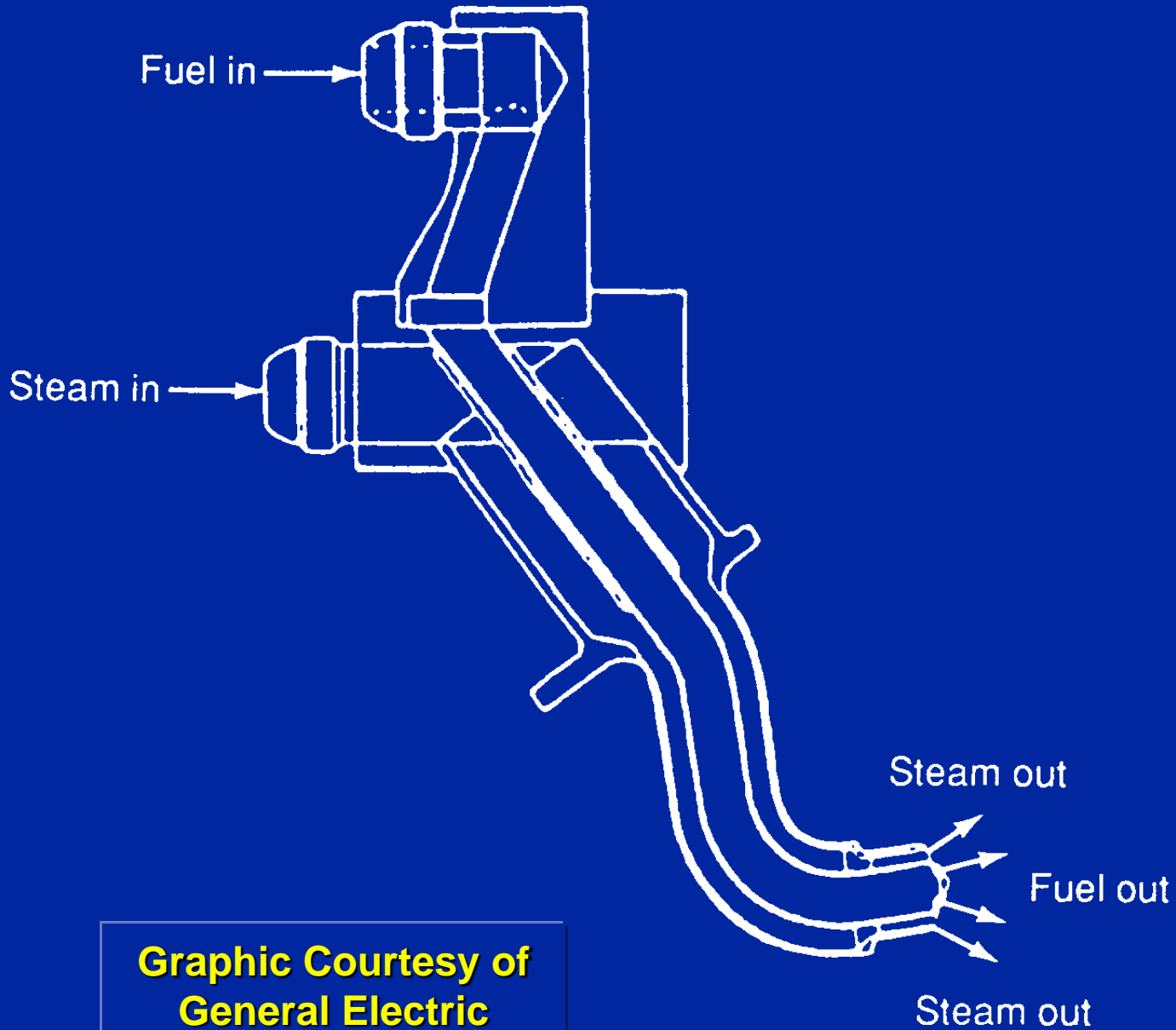




Water Treatment

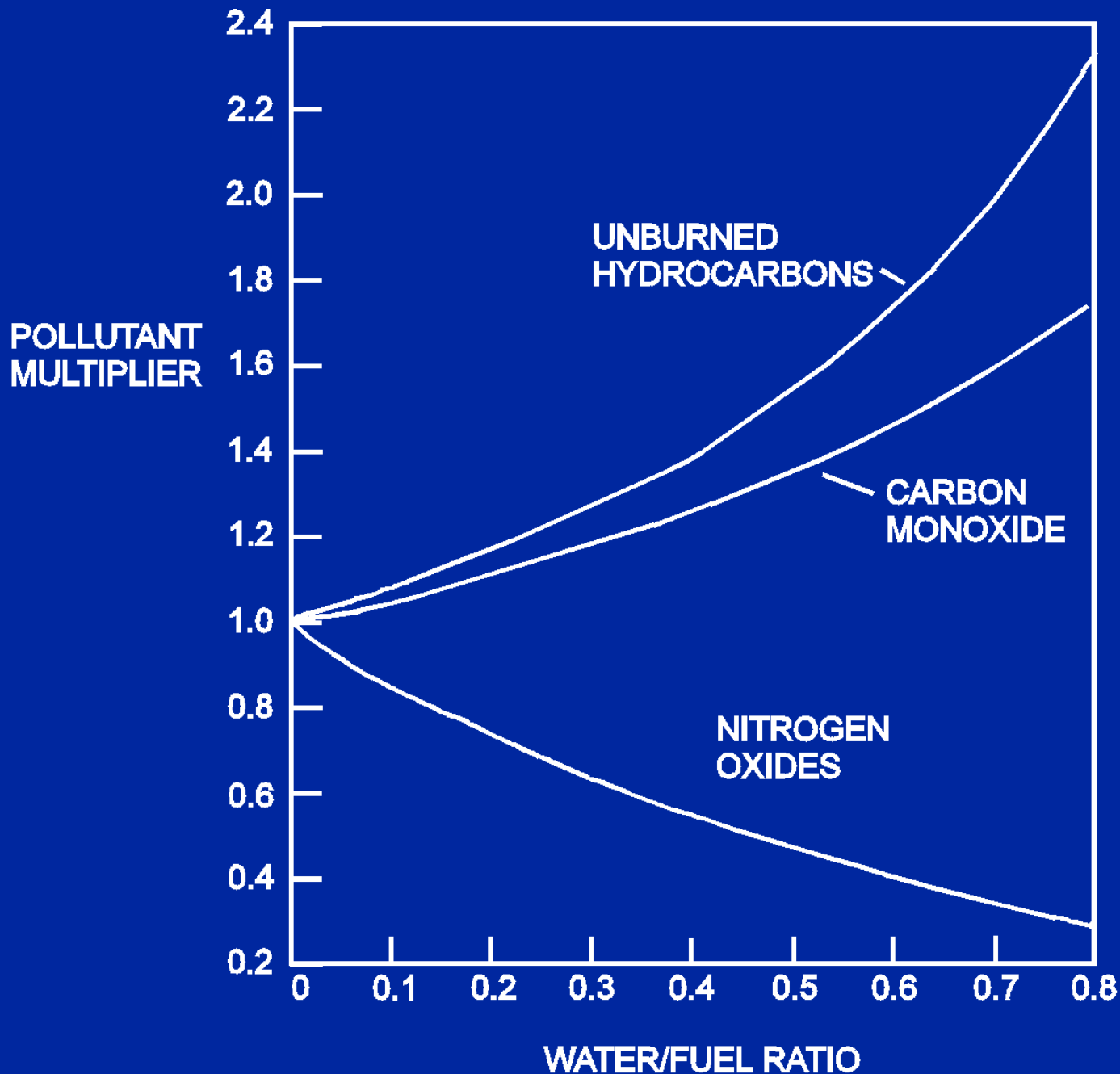
A large industrial stainless steel tank, likely a reverse osmosis membrane tank, is the central focus. It has a corrugated upper section and a smooth lower section. Several pipes are connected to the tank, with two prominent circular access ports. To the left, a grey electrical control box is mounted on a vertical pipe, featuring a small digital display and a yellow label that reads "AQUATECH". To the right, another grey electrical box is mounted on the floor, labeled "B4005". In the background, a vertical black pipe with a red valve and a silver chain are visible against a white wall. The floor is concrete, and the overall lighting is warm and industrial.

Water Treatment De-Min. Process



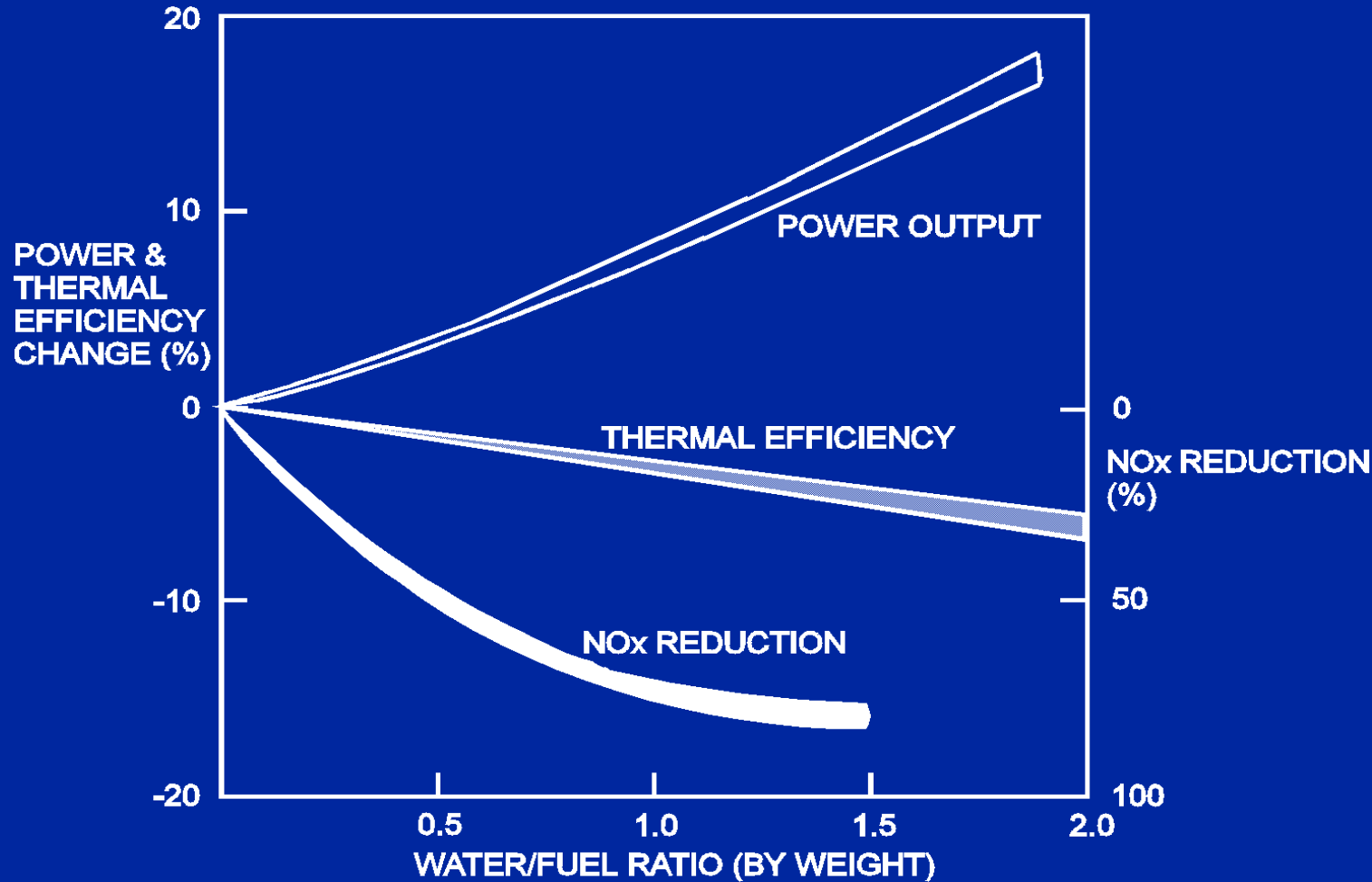
Gas/Steam Fuel Nozzle

Graphic Courtesy of
General Electric

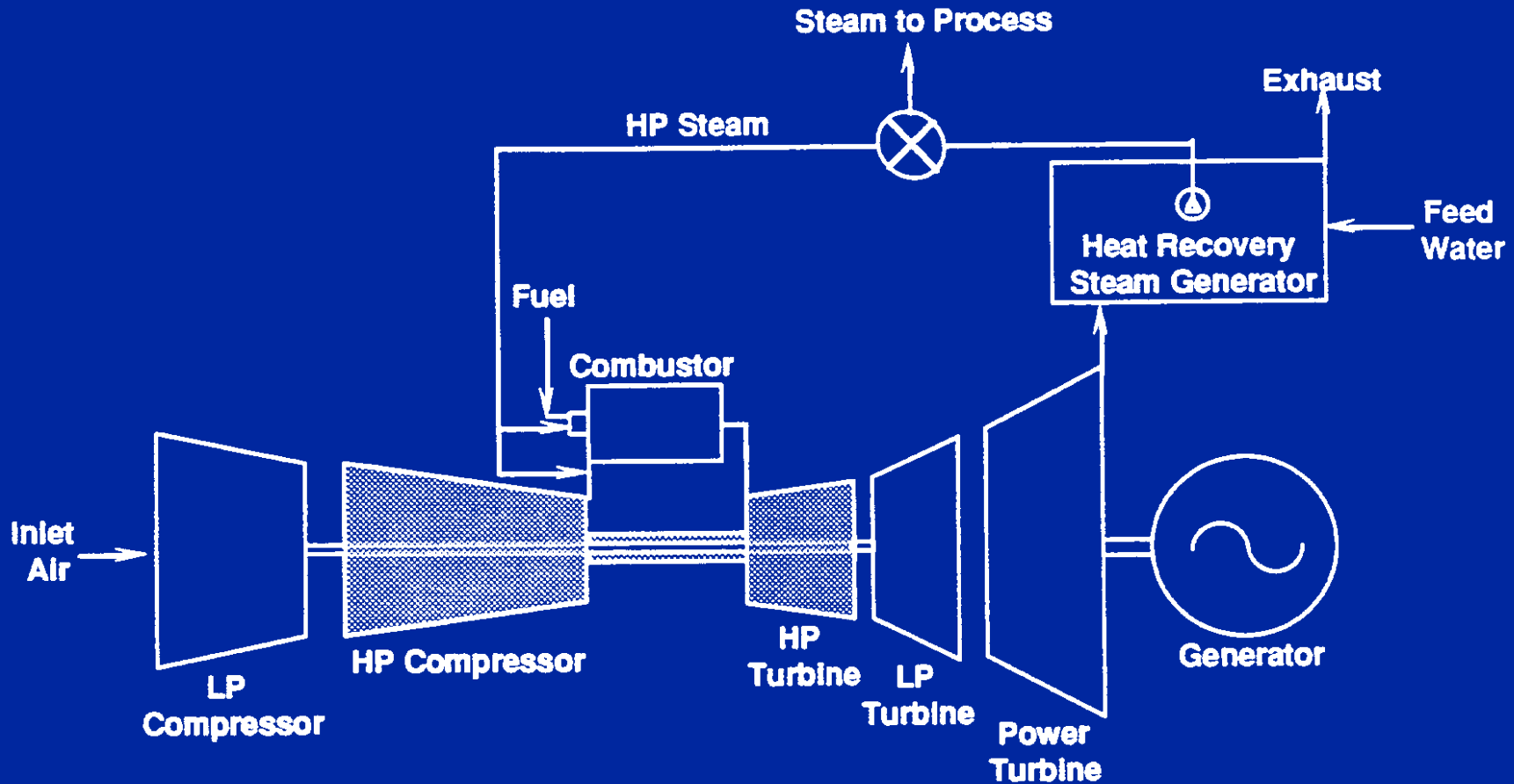


**NOx,
CO,
and
Unburned
HC
vs.
Water
Injection**

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

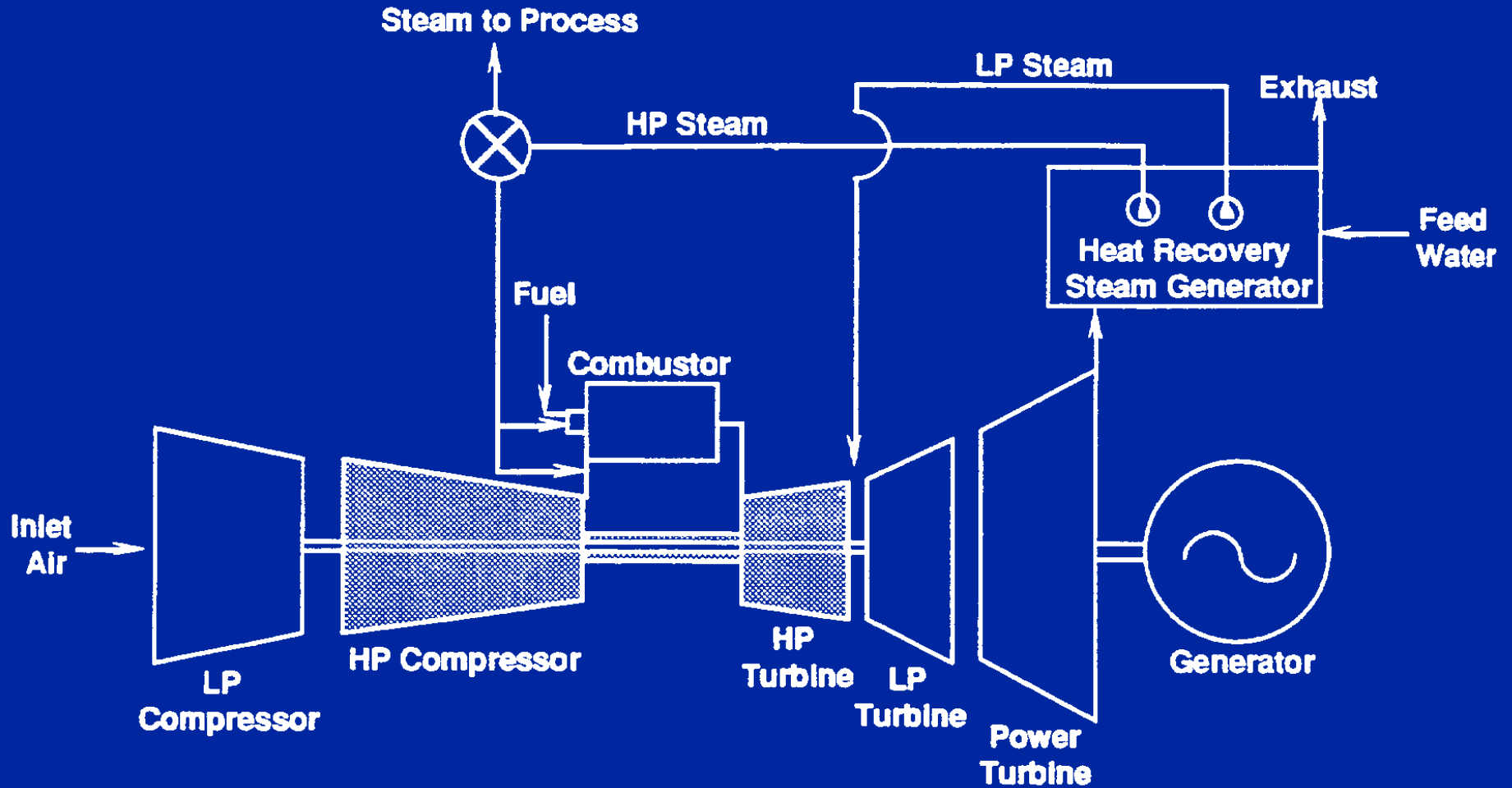


Partial STIG



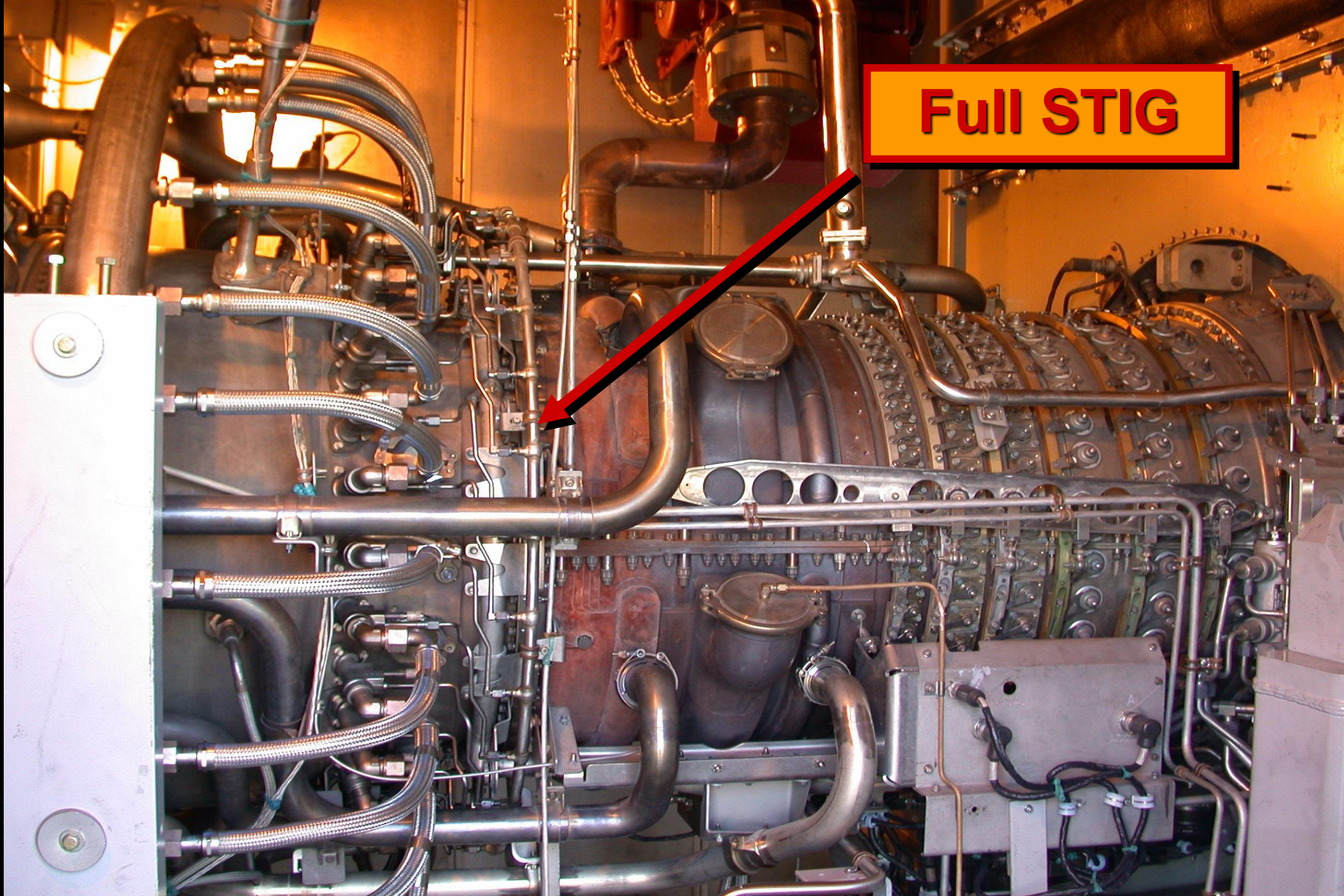
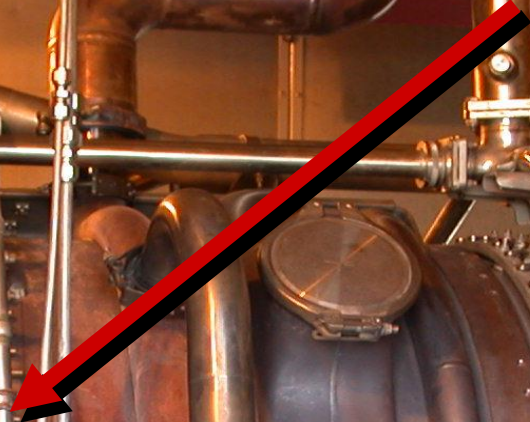
Graphic Courtesy of General Electric

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

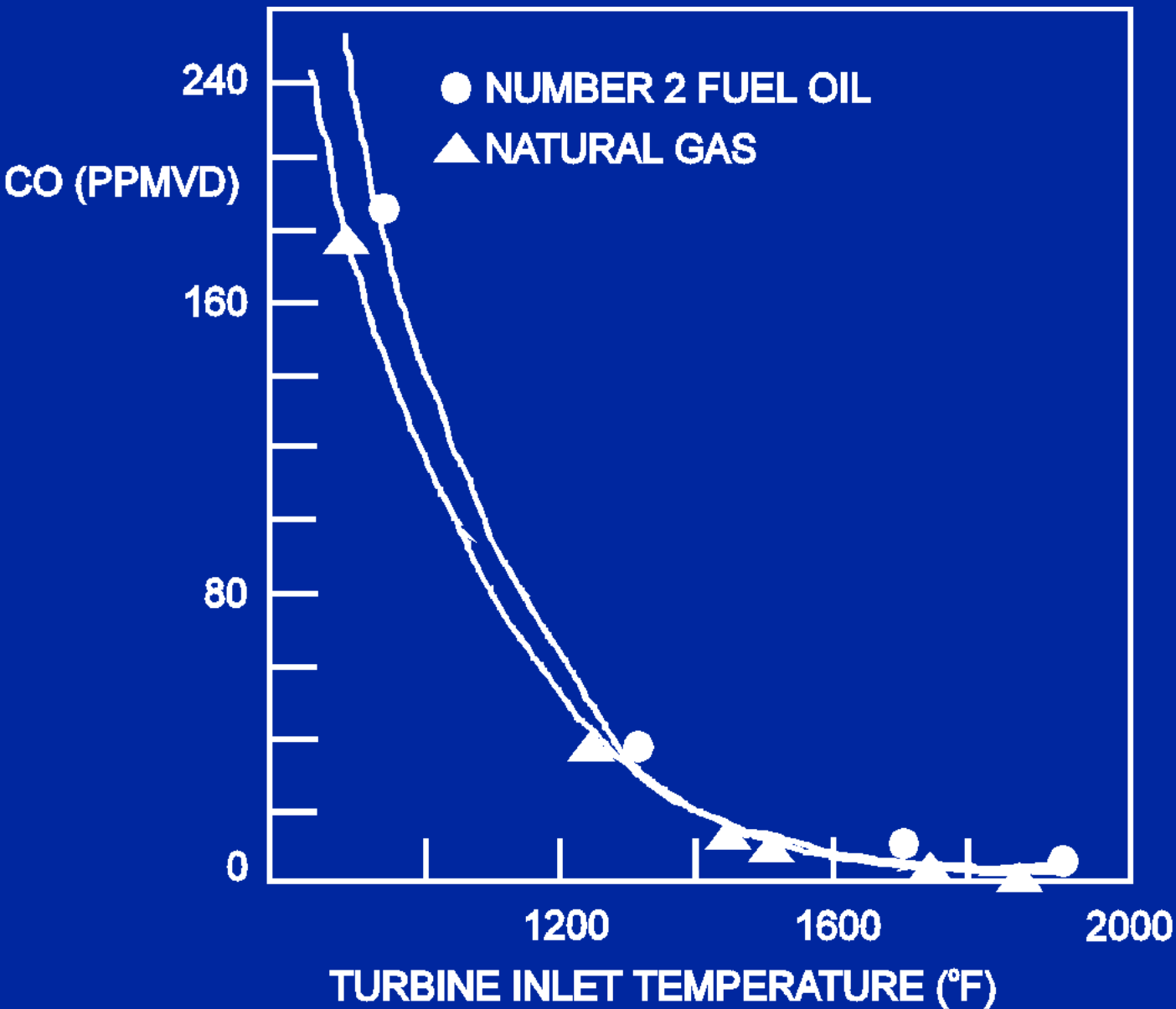




Catalytic Conversion

- ◆ CO is oxidized → CO₂ Oxidation catalyst
- ◆ NO_x is reduced → N₂ Reduction catalyst





**CO
vs.
Turbine
Inlet
Temp**



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. H₂O
- ◆ Problems
 - Expensive
 - High maintenance
 - Catalyst replacement & disposal

CO Catalyst





Let's Discuss Selective Catalytic Reduction (SCR)

Selective Catalytic Reduction (SCR)

◆ NO_x control thru ammonia (NH₃) injection



◆ 90-95% control

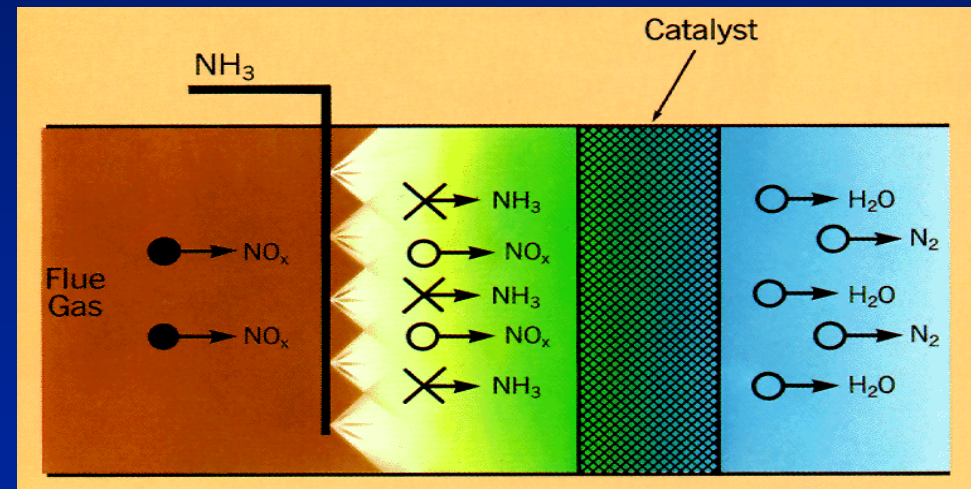
◆ Problems

– Expensive

– High maintenance

– Ammonia “slip”

– Catalyst replacement & disposal





NH₃ Storage Tank



NH₃ Lines

↑ AMMONIA ↑

↑ AMMONIA

↑ AMMONIA

↑ AMMONIA

↑ AMMONIA

↑ AMMONIA

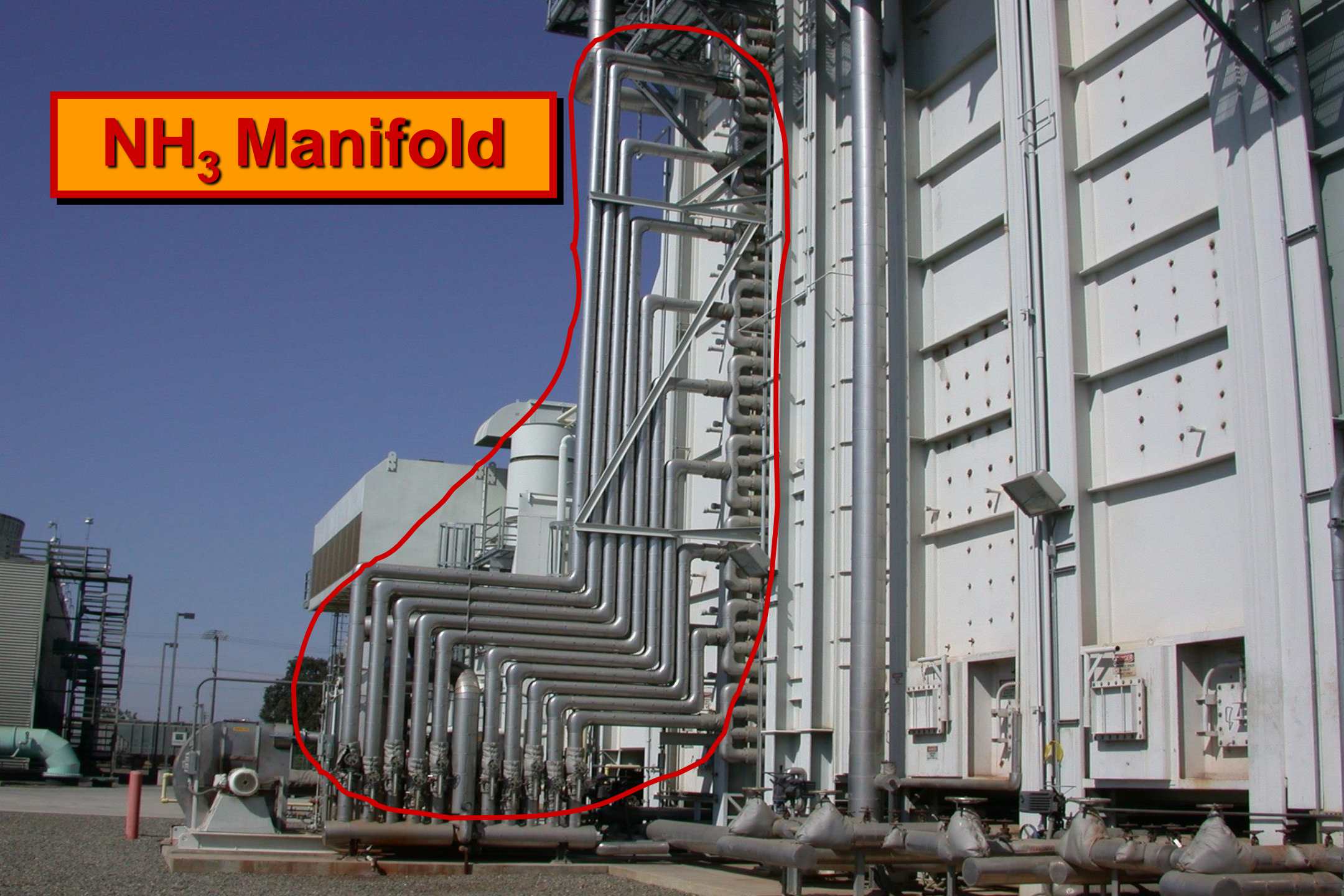
↑ AMMONIA

↑ AMMONIA

↑ AMMONIA

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37010 BASSANO DEL GRAPPA (VI)
ITALY
TEL. +39 0445 4341
FAX +39 0445 4342
E-MAIL: info@frigeron.it
www.frigeron.it

NH₃ Manifold





NH₃ Lines

The image shows a complex industrial structure with numerous vertical pipes, ladders, and walkways. A red arrow points from the 'NH₃ Lines' label to a set of vertical pipes in the center. On the right, a large cylindrical tank is visible, and a red arrow points from the 'HRSG' label to a section of the structure below it.

HRSG

NH₃ Injection Tube



Catalyst System Installation



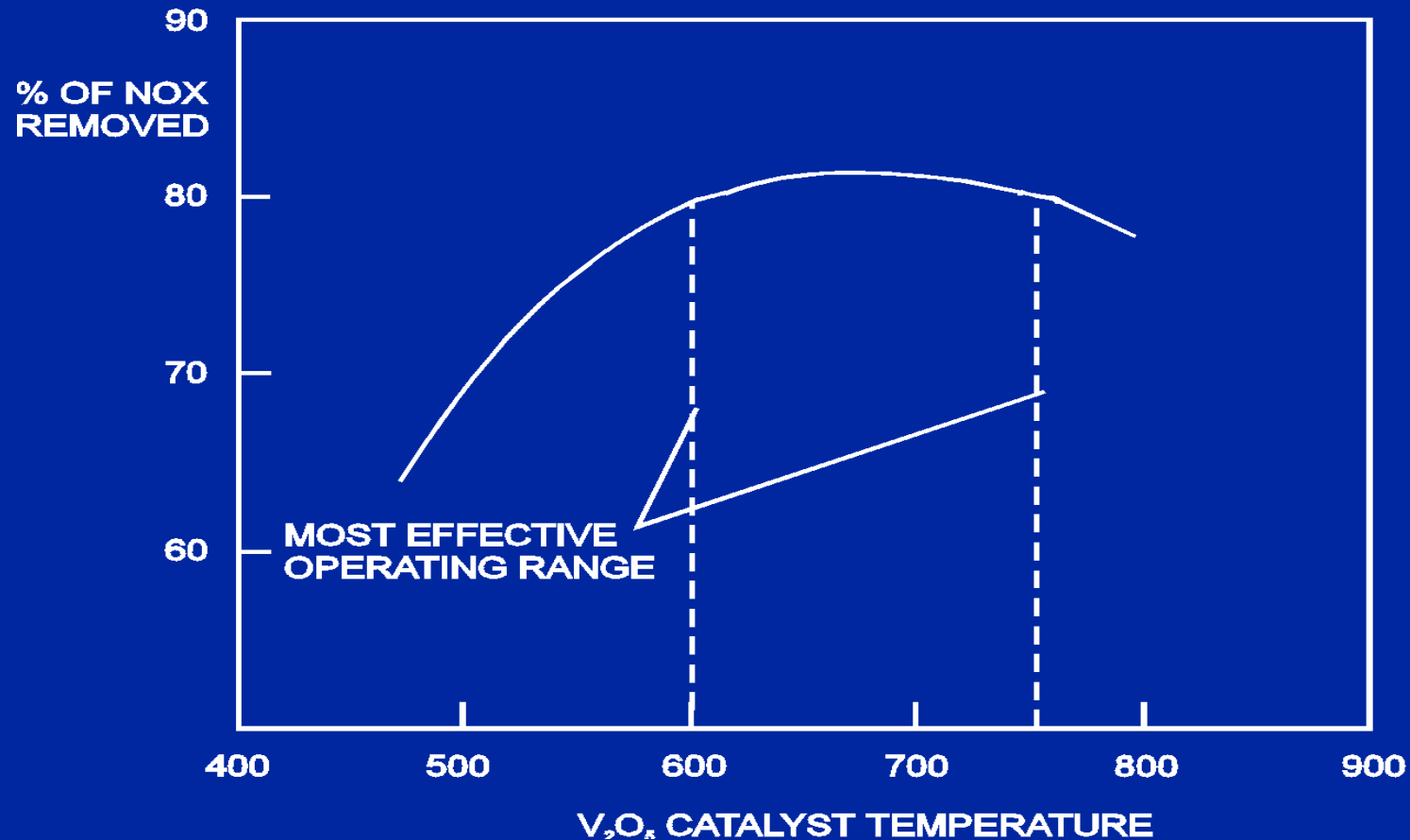


**SCR Catalyst &
NH₃ Tubes**

SCR Catalyst



% NOx Removed vs. Vanadium Pentoxide Catalyst Temperature



A wide-angle landscape photograph of a mountain valley. The scene is dominated by massive, grey granite cliffs that rise steeply from a dense forest of green coniferous trees. The sky is filled with large, billowing white and grey clouds, with patches of blue visible. The lighting suggests a bright day with some overcast areas. At the bottom of the image, there is a prominent orange rectangular box with a black border containing the text "Regulatory Requirements" in a bold, red, sans-serif font.

Regulatory Requirements



Regulatory Requirements

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





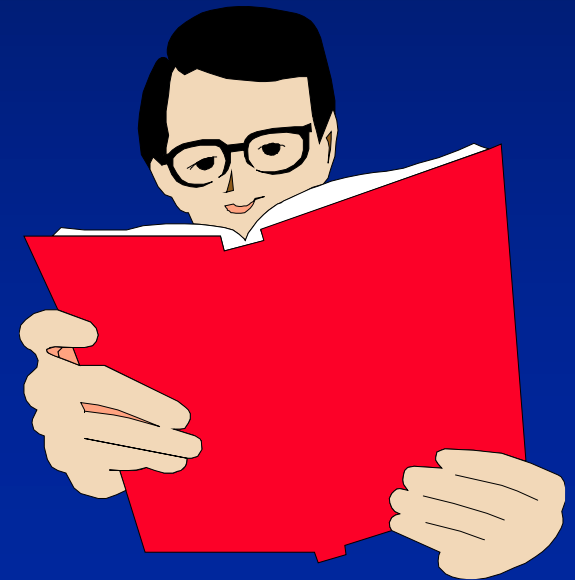
Turbine Regulations

- ◆ 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 – $(150 \times 14.4/Y) + F$ ppm _{vd} @15%O ₂ Large – $(75 \times 14.4/Y) + F$ ppm _{vd} @15%O ₂	0.8% by weight	150 ppm _{vd} @15%O ₂
Subpart KKKK (2005+)	15 to 150 ppm _{vd} @15%O ₂ 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%O ₂	

BACT Summary for Stationary Gas Turbines

	NO_x	CO	VOC	PM₁₀	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:

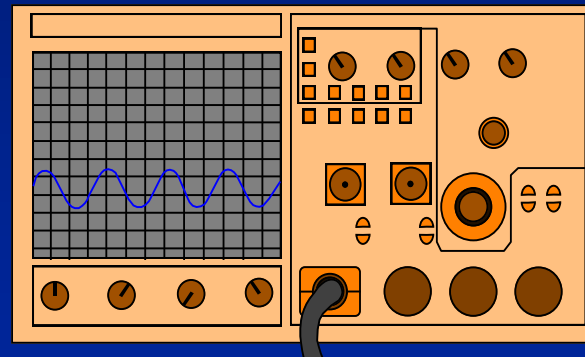
- NO_x

- SO_x

- CO

- O₂

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



A scenic landscape featuring a calm lake in the foreground that perfectly reflects the rugged, rocky mountains in the background. The mountains are illuminated by warm, golden light, likely from the setting or rising sun. The sky is clear and bright. In the lower right corner, there is a prominent yellow rectangular box with a red border containing the word "Inspections" in a bold, red, sans-serif font. The overall scene is peaceful and majestic.

Inspections

Reasons for Inspections



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

Pre-Inspection

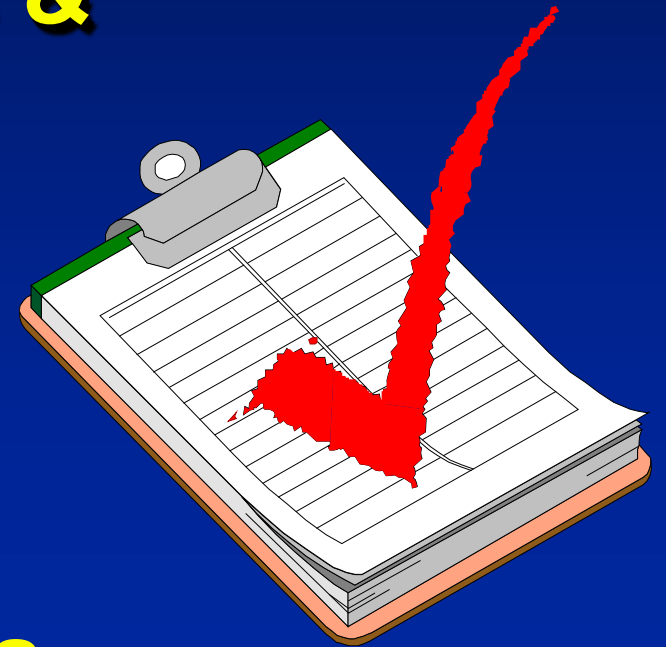
- ◆ Prepare inspection report form
- ◆ File review
- ◆ Regulation review
- ◆ Equipment check
- ◆ Pre-entry & entry
- ◆ Pre-inspection meeting
- ◆ Permit check





Inspection

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



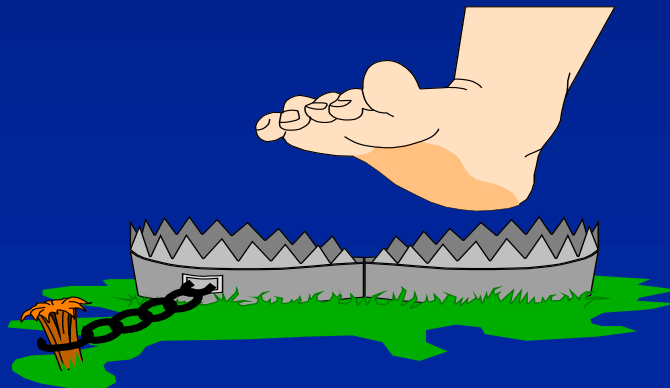


Source Testing & RATA Test



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>



Thank You

**Photo Credits:
www.jasonbranz.com**