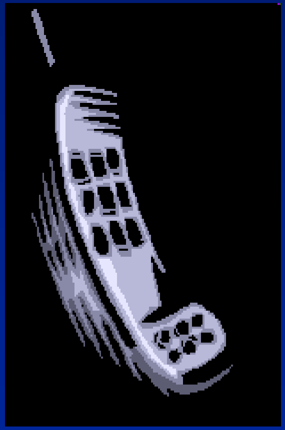
National Training Program

NACT 299

Introduction to Control Devices

House Keeping

- Bathrooms
- Emergency Evacuation
- Cell Phones
- Refreshments
- Questions
- Agenda




♦ Particulate Matter
♦ VOC
♦ SOx - FGD
♦ CO
♦ NOx
Control Equipment

Combustion Considerations

3 T's of Combustion

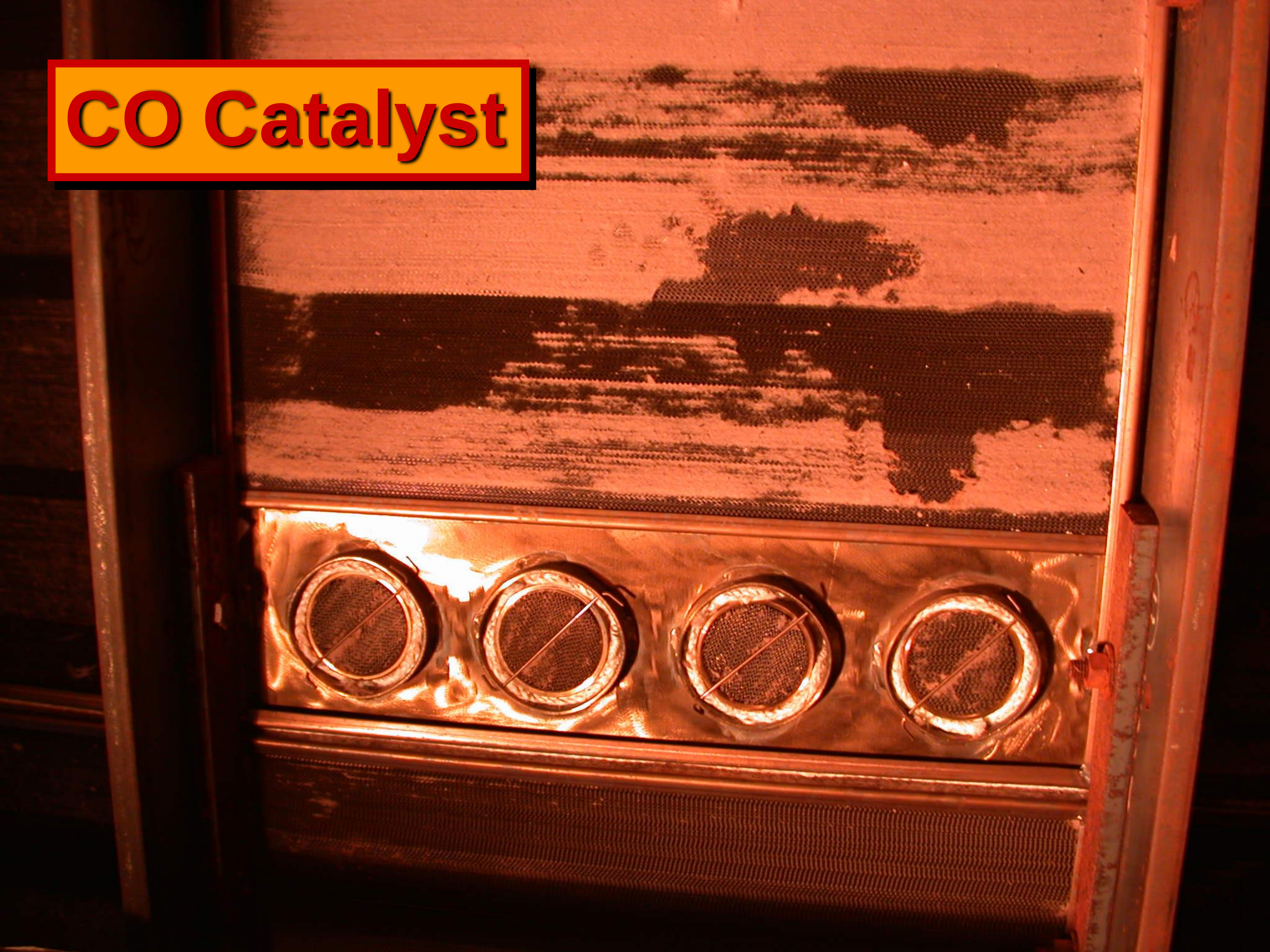
- Time (residence time)
- Temperature
- Turbulence (mixing)
- Increase 3T's > more NOx
- Decrease 3T's > more CO & PICs

Let’s Discuss CO Catalyst

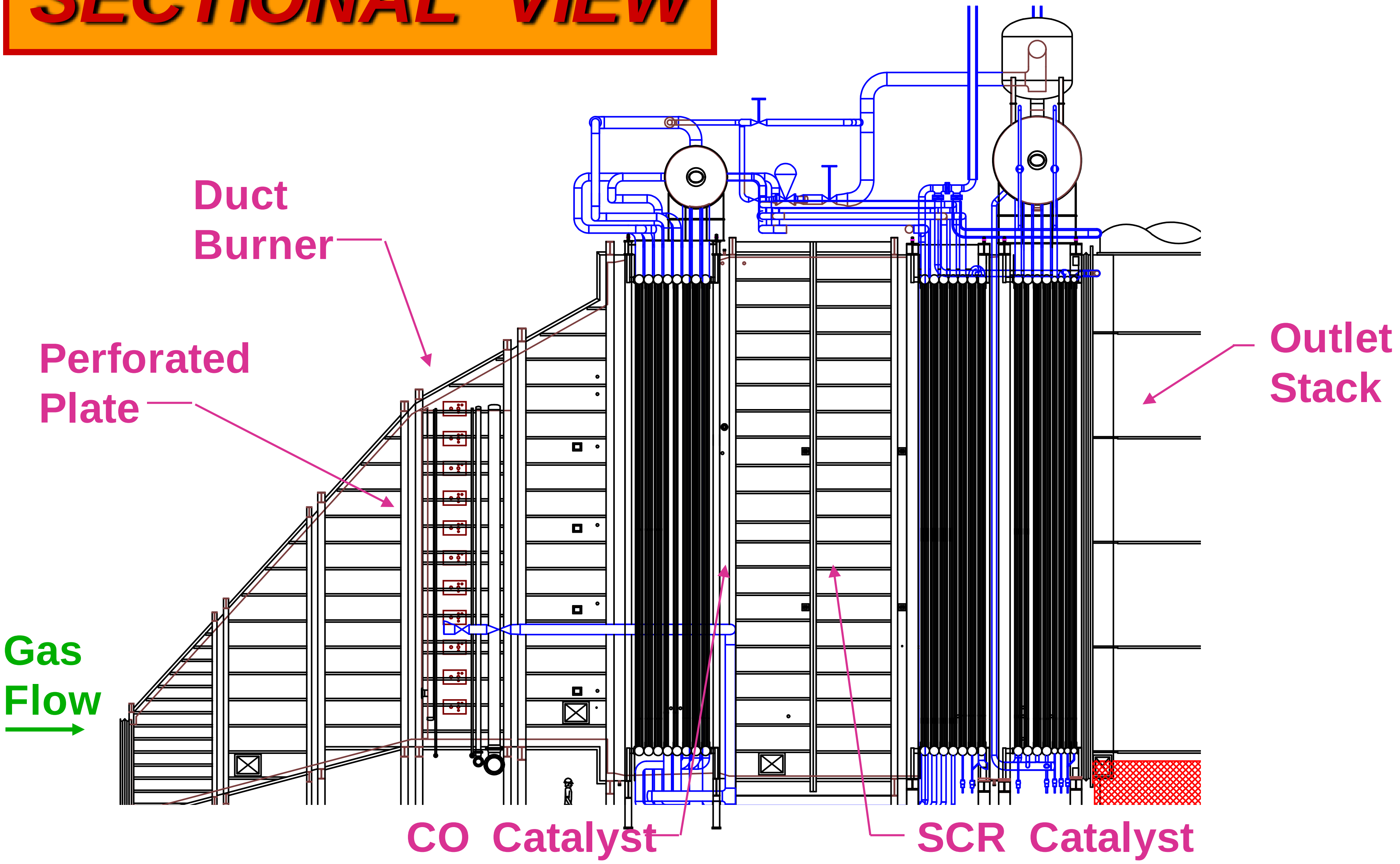
CO Catalyst

- $2CO + O_2 \rightarrow 2CO_2$
- 700 to 1000 ^{o}F operating temp
- 90% plus efficiency
- Pressure drop 1-2 in. H_2O
- Problems
  - Expensive
  - High maintenance
  - Catalyst replacement

CO Catalyst



SECTIONAL VIEW

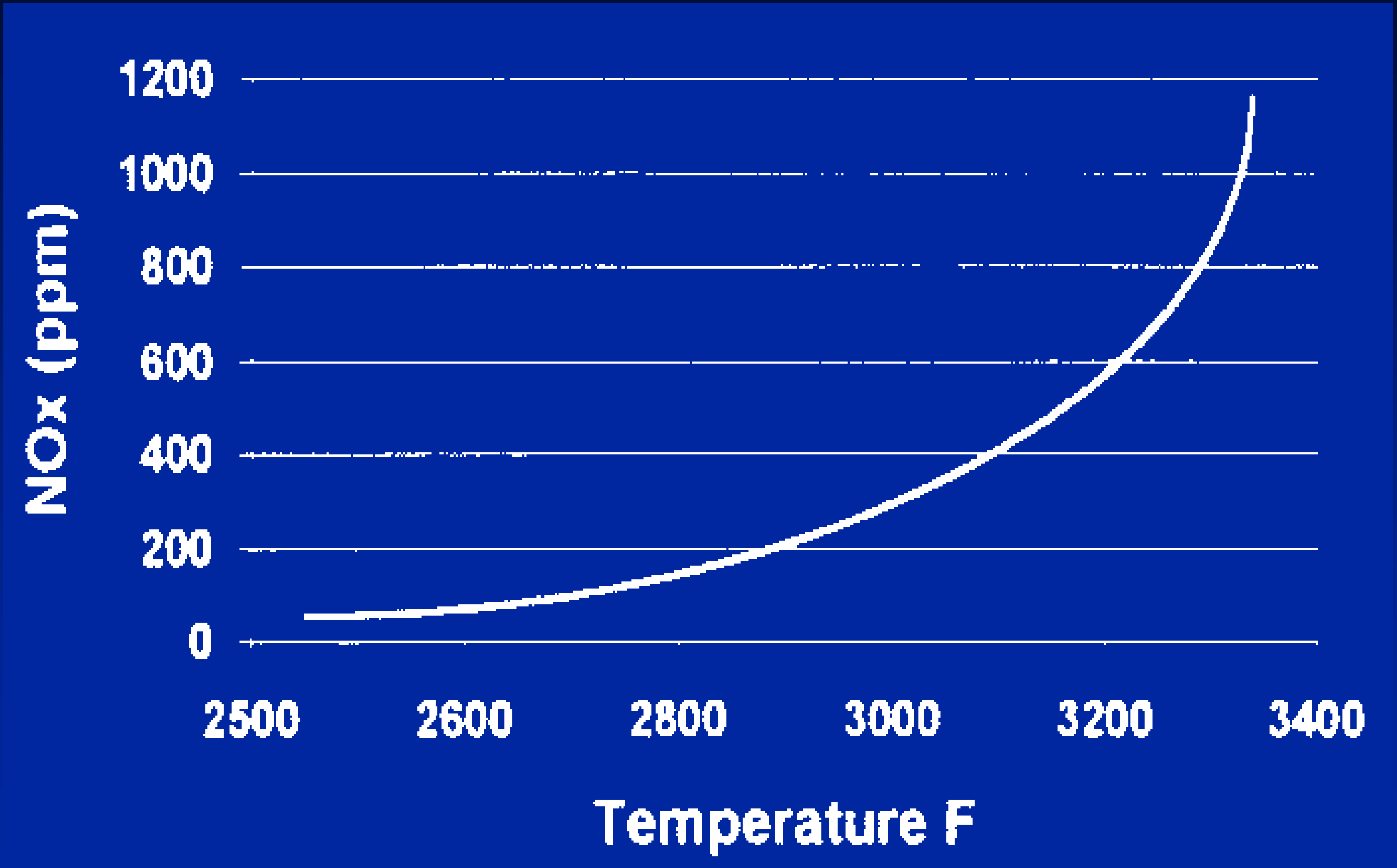


Let's Discuss NOx Control

- Formation of NOx
- Low-NOx combustion techniques
- Ammonia injection (SCR & SNCR)
- Catalytic controls

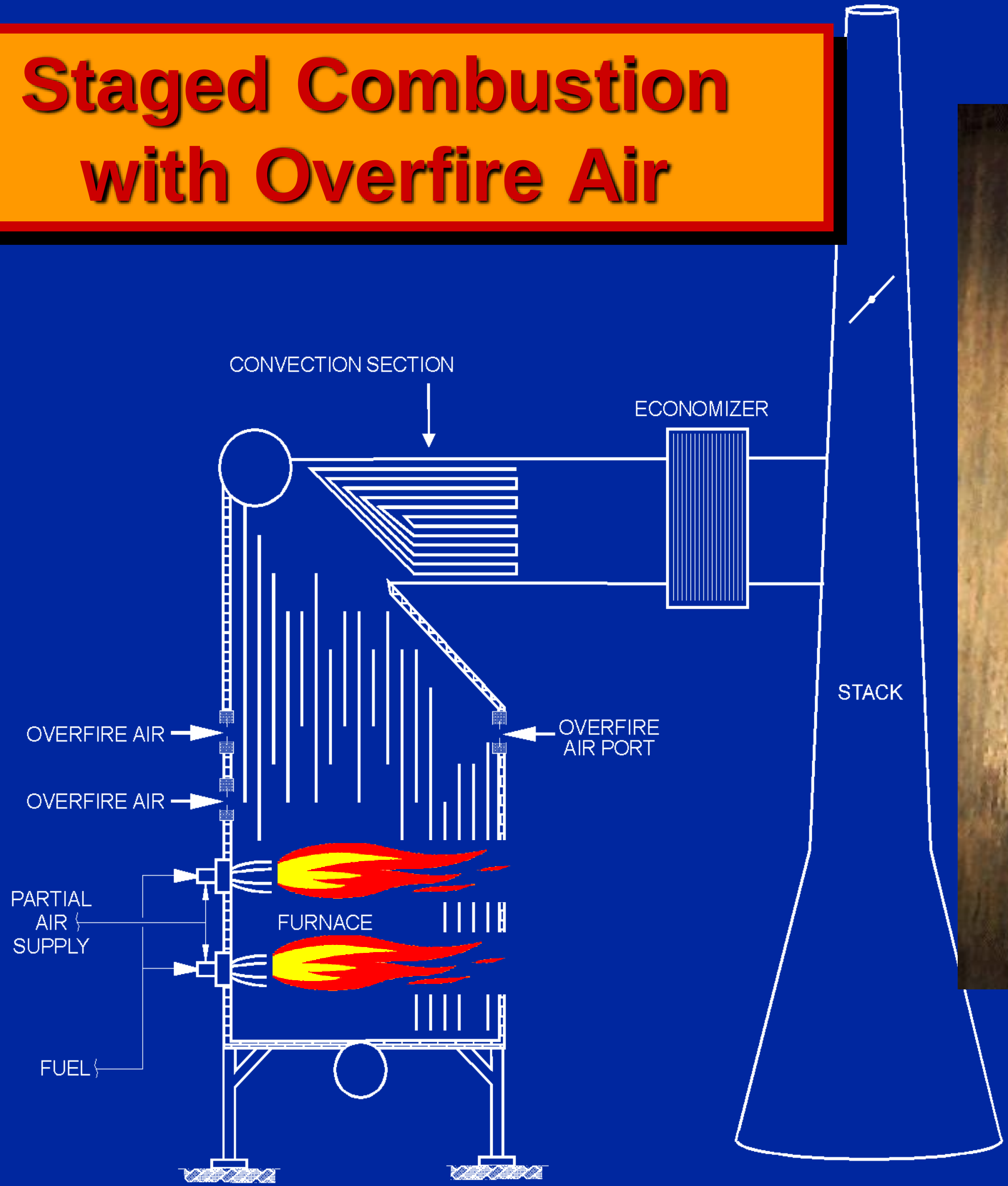
Thermal NOx
Fuel-bound NOx
Prompt NOx
NOx Creation

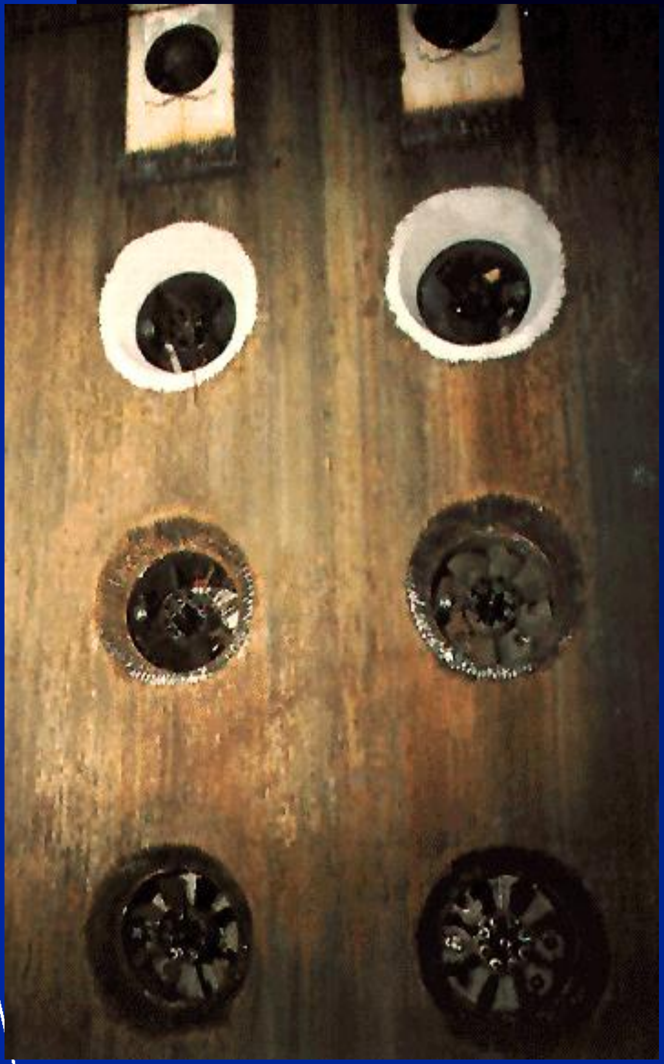
NOx vs. Temperature



Babcock & Wilcox Utility Boiler

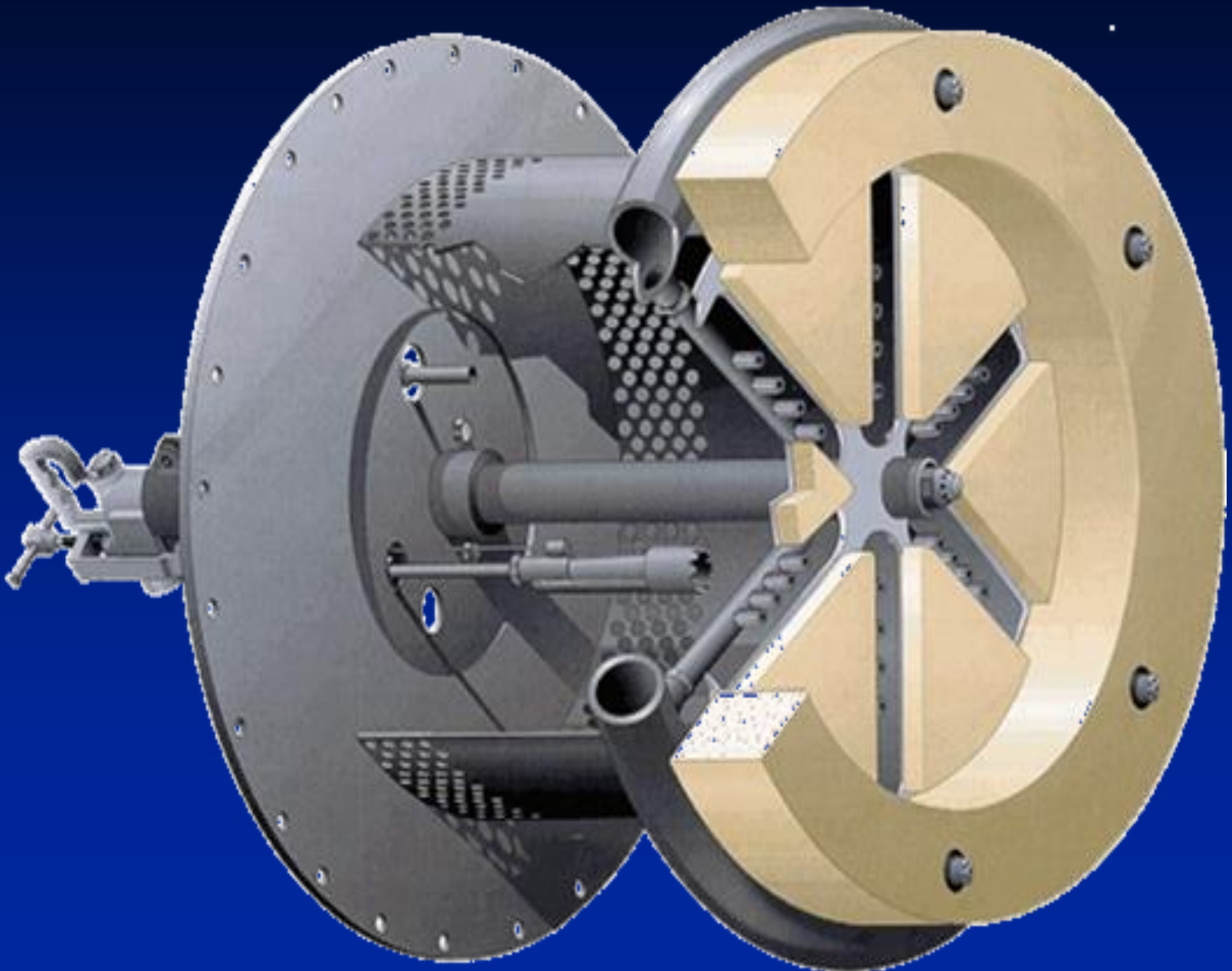
Staged Combustion with Overfire Air



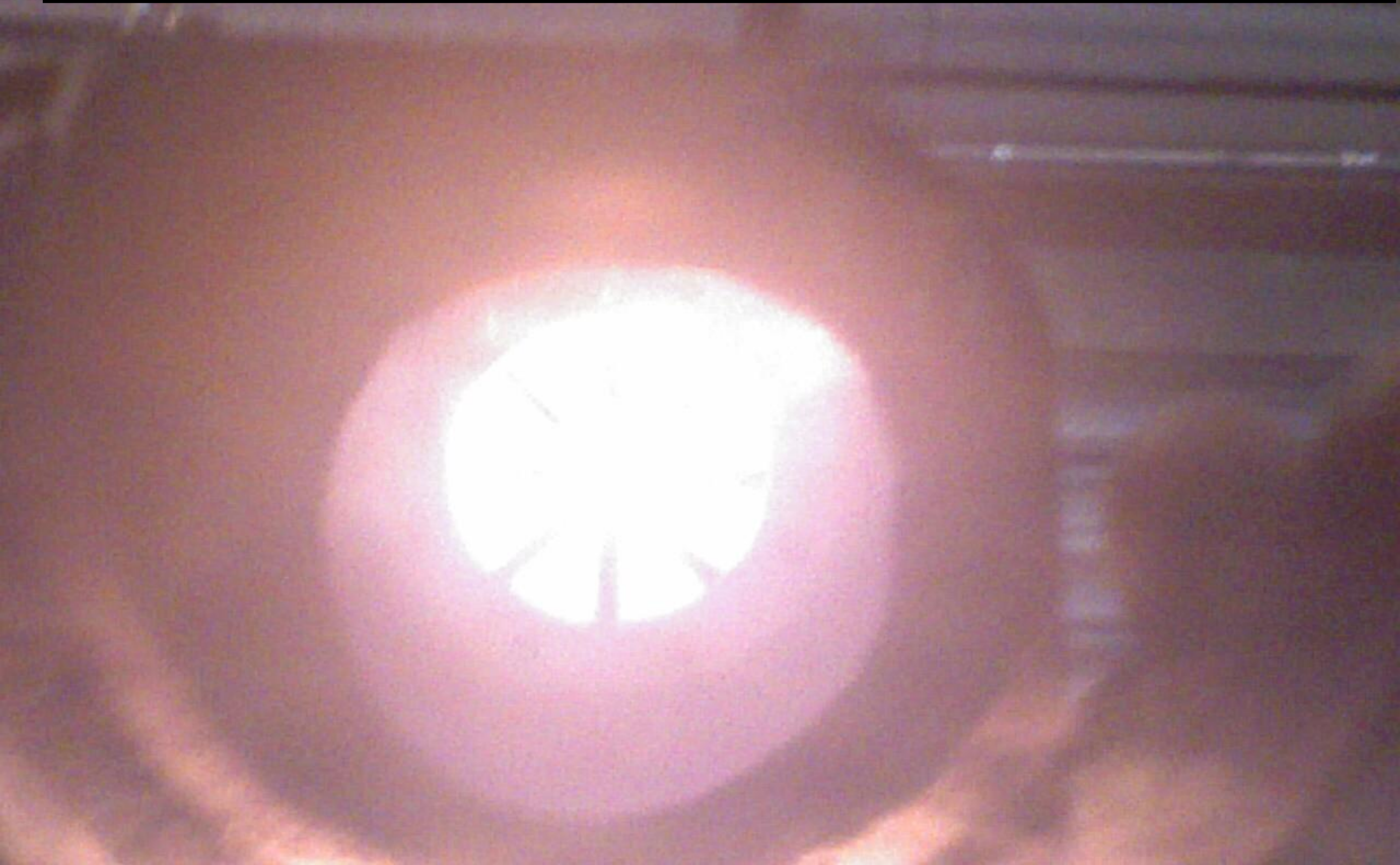



Fire-Tube Boiler

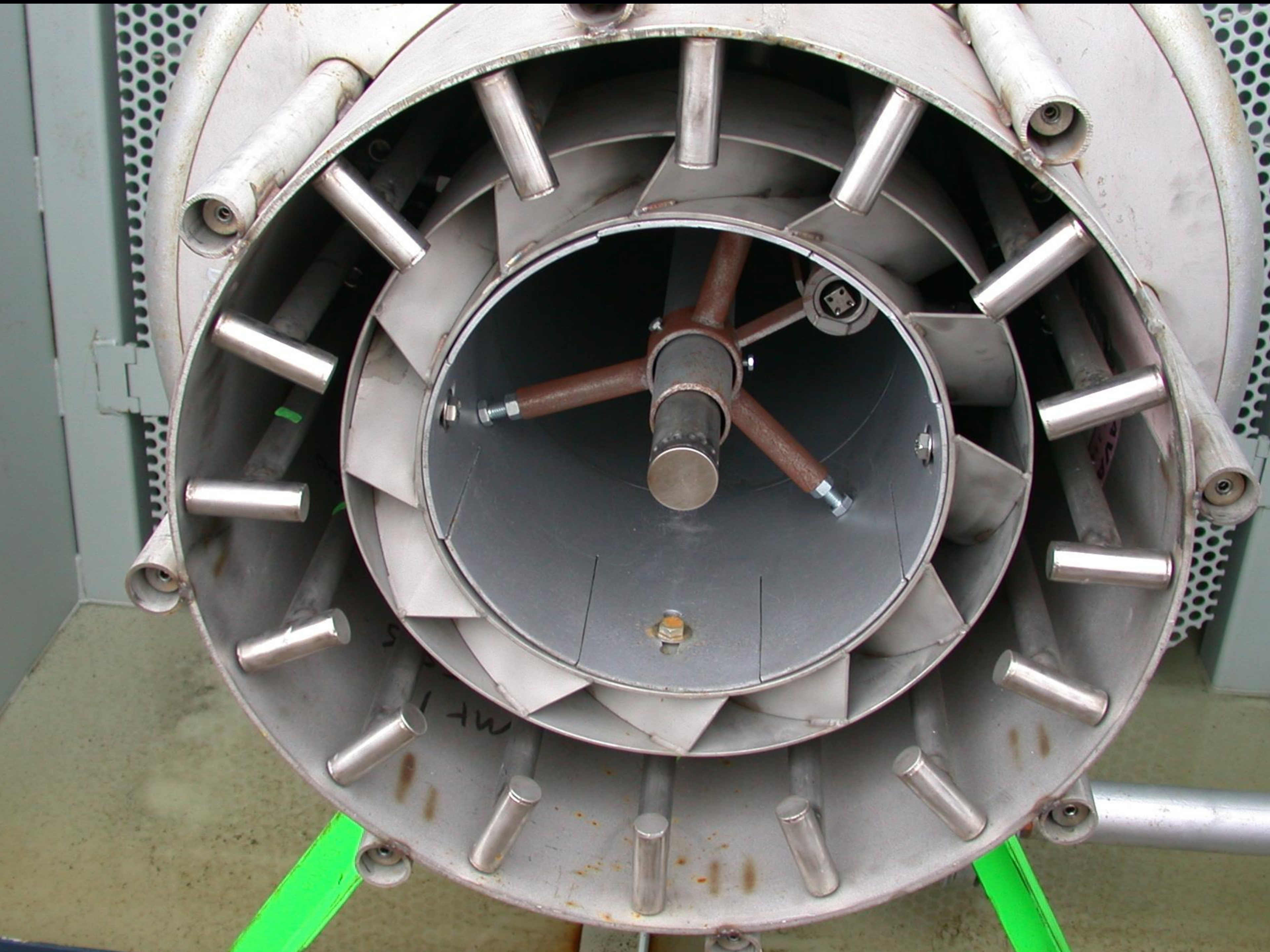
Low-NOx Burner with Staged Fuel



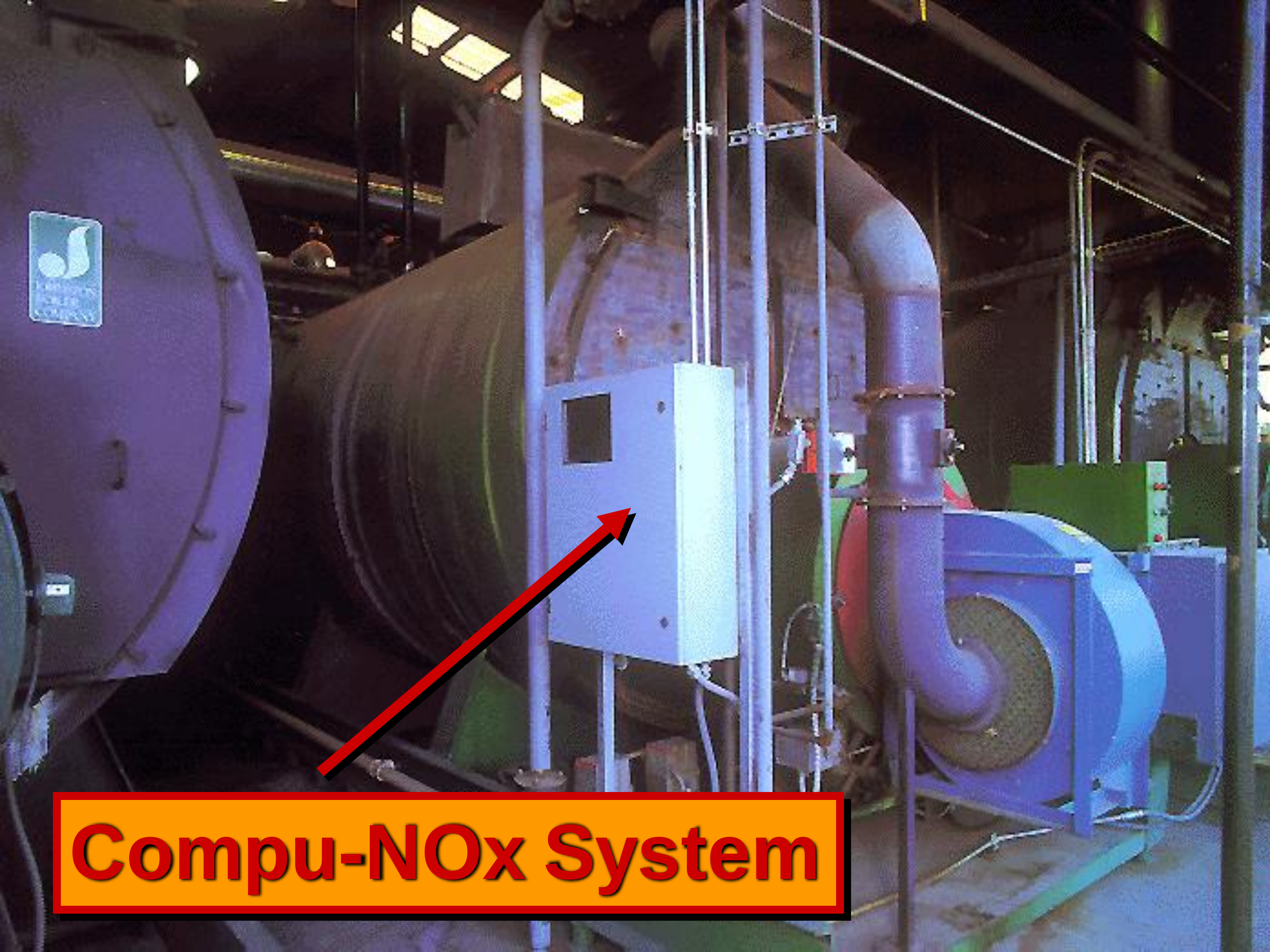
Low-NOx Burner with Staged Fuel



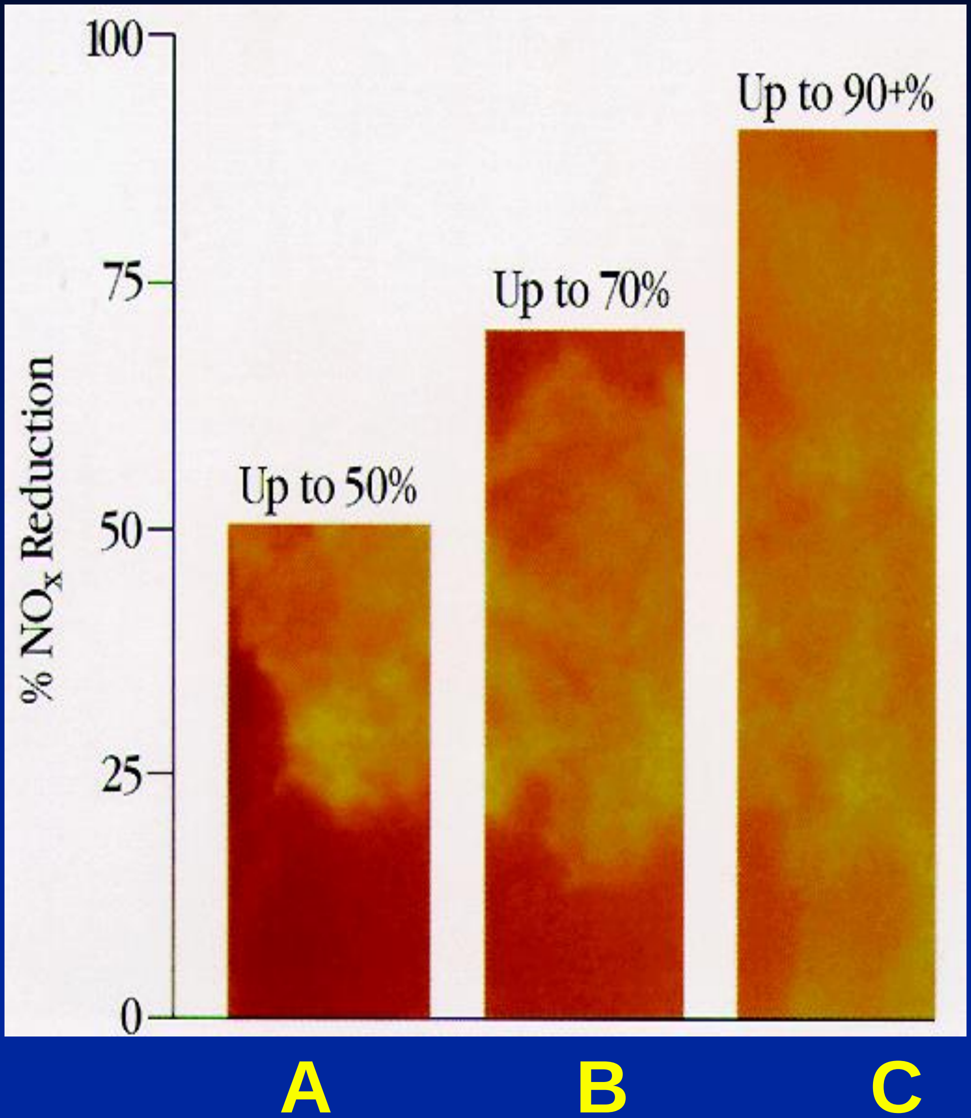
Ultra Low-NOx Burner (9 ppm)




Flue Gas
Recirculation


Compu-NOx System

NOx Reduction by Boiler Configuration



A: Low-NOx burner only, no overfire air (OFA)

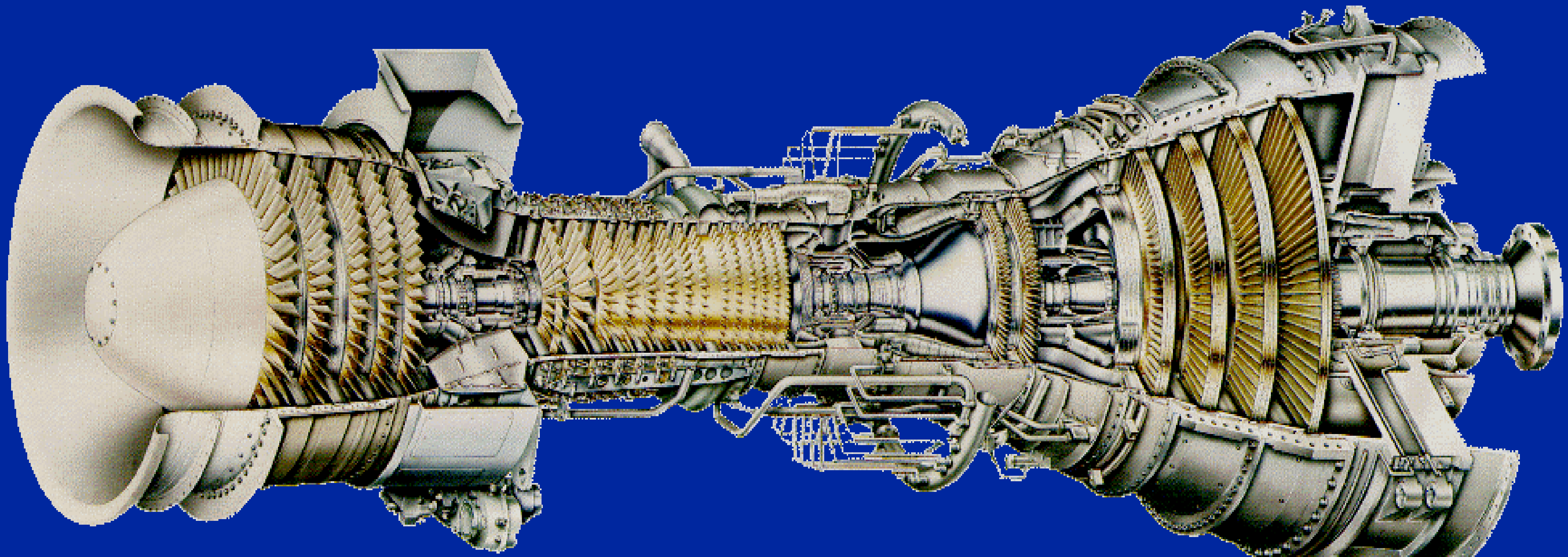
B: Low-NOx burner with OFA

C: Ultra Low-NOx burner with FGR

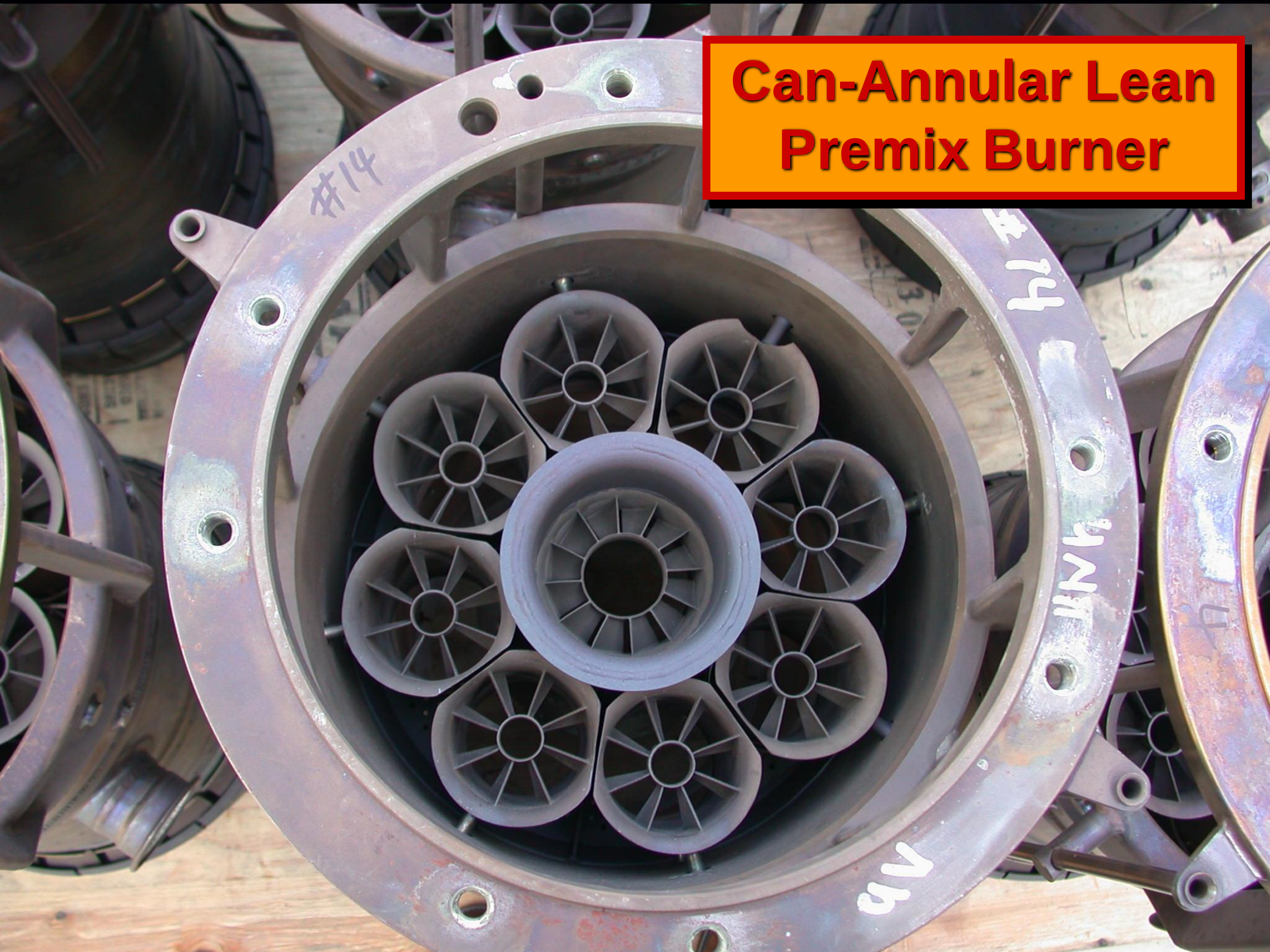
Let's Discuss Gas Turbine Power Plant Controls

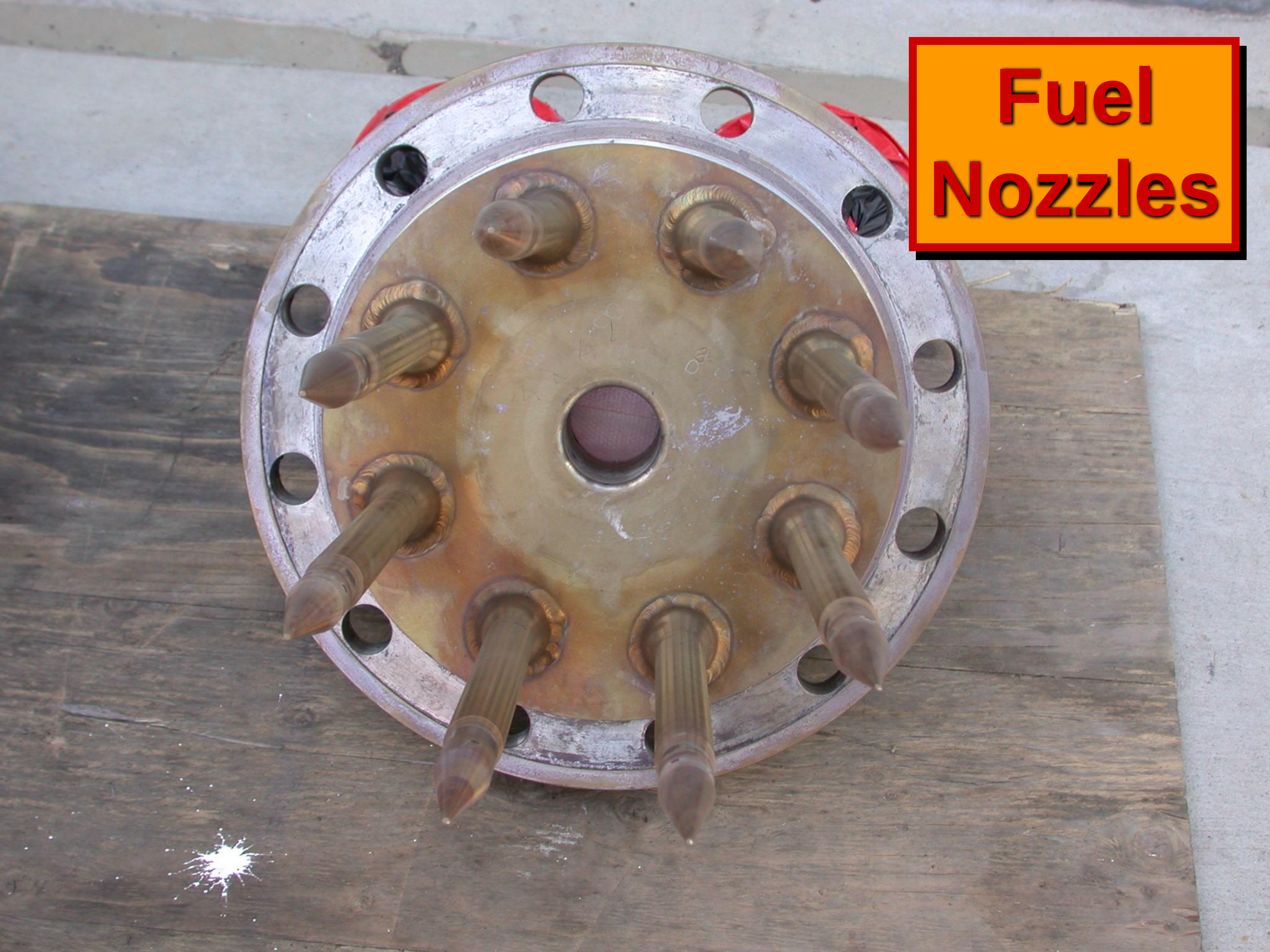

Gas Turbine
Power Plant

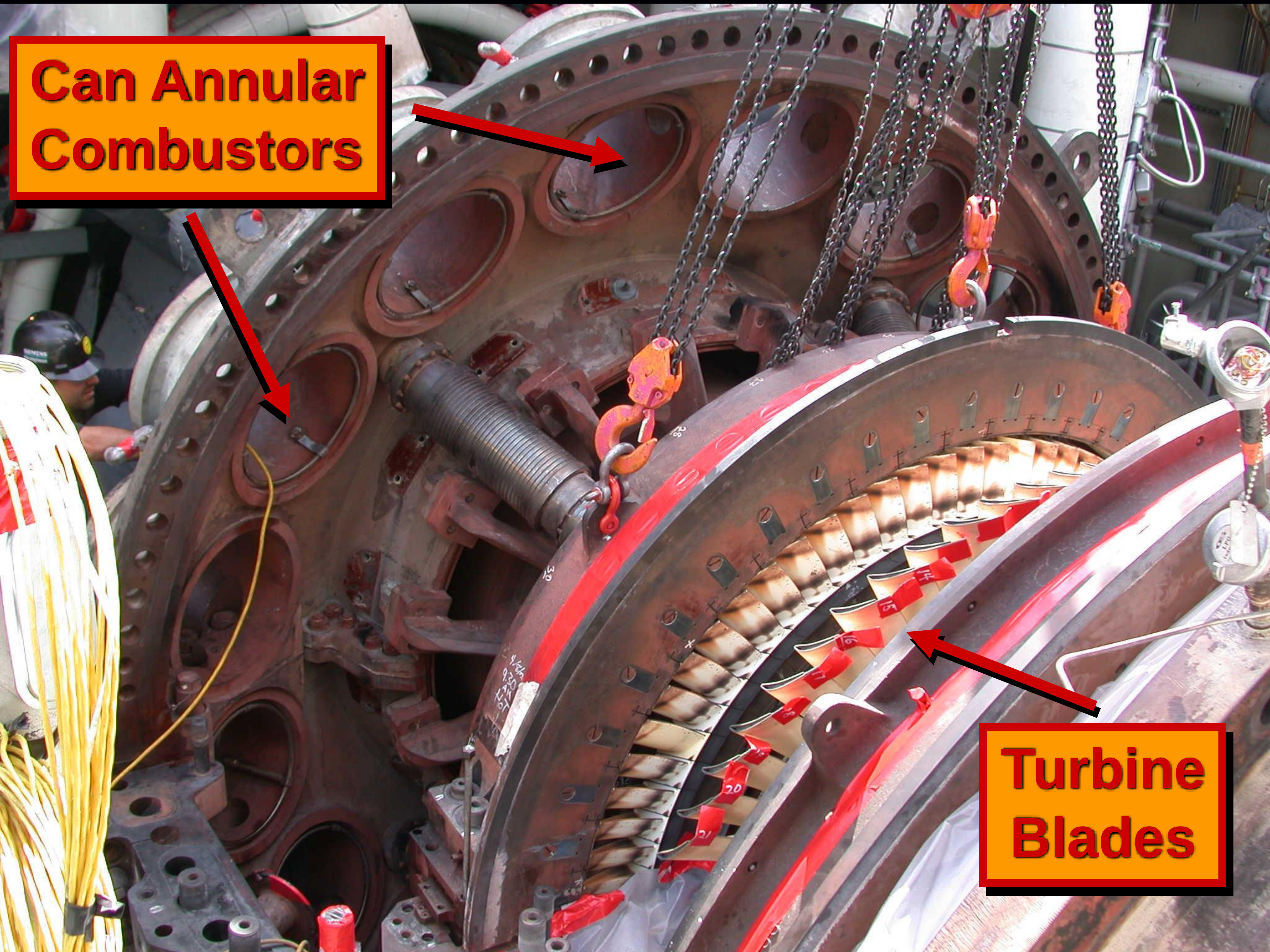
GE LM6000 Gas Turbine

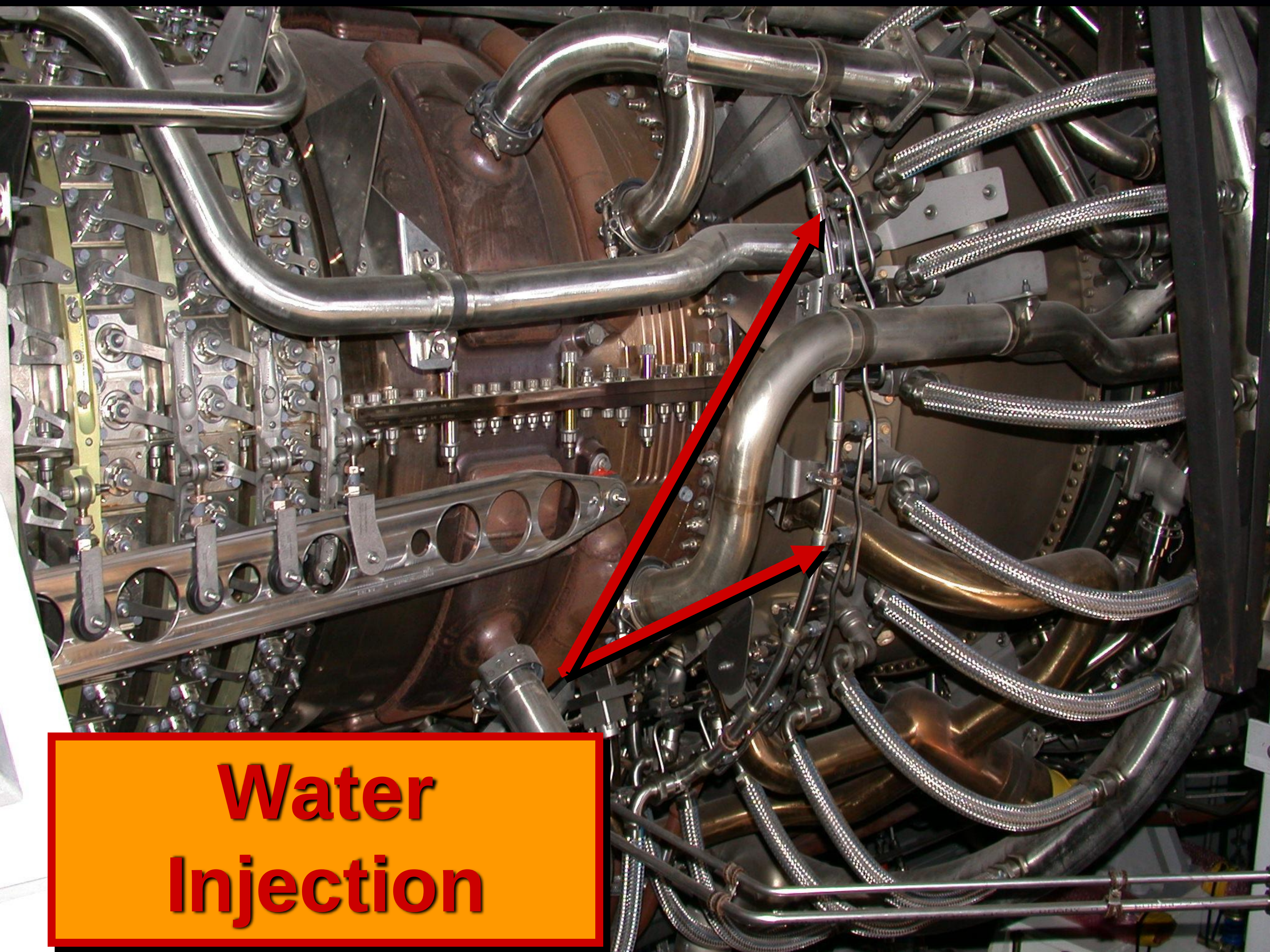


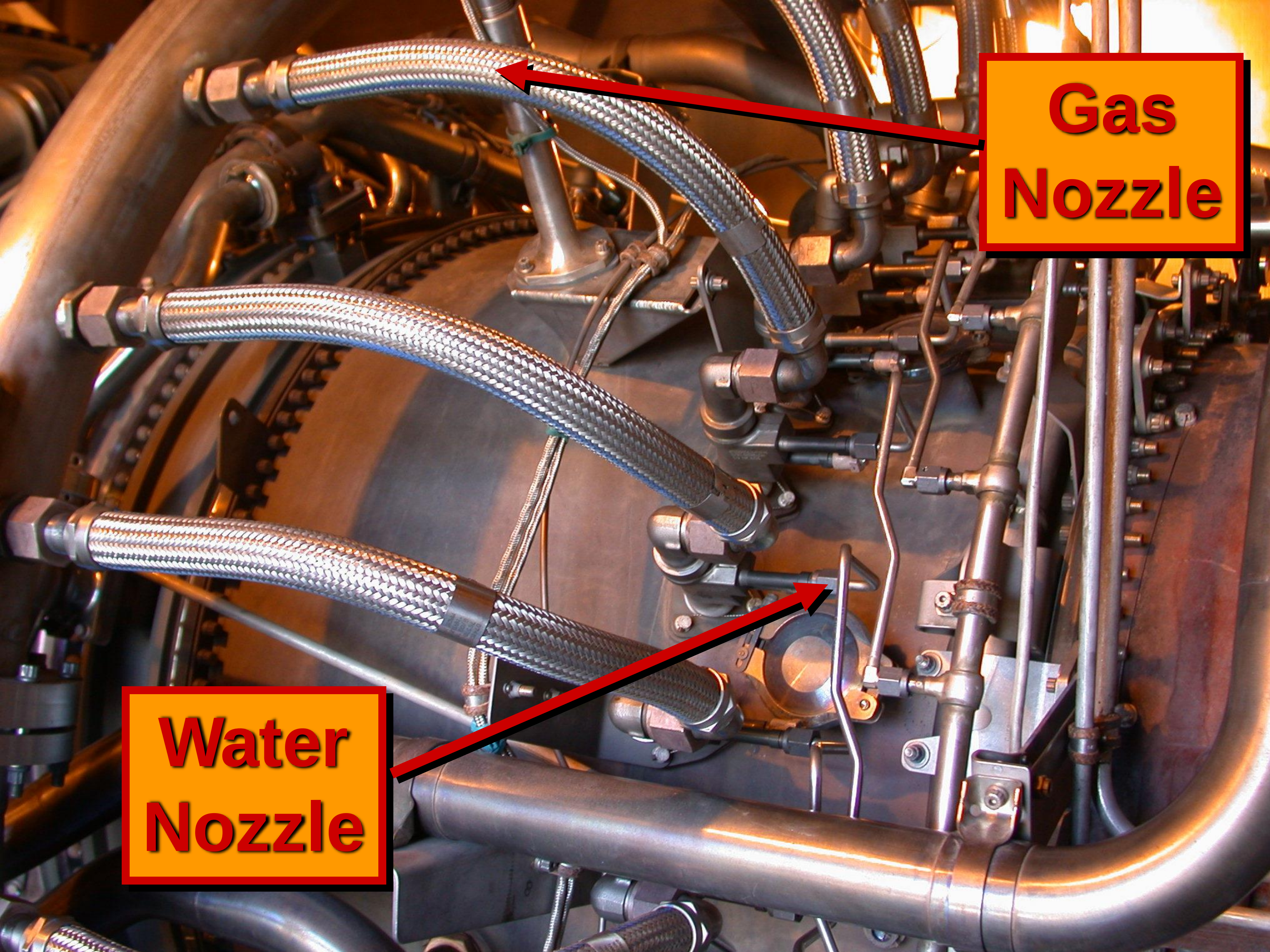
Can-Annular Lean Premix Burner

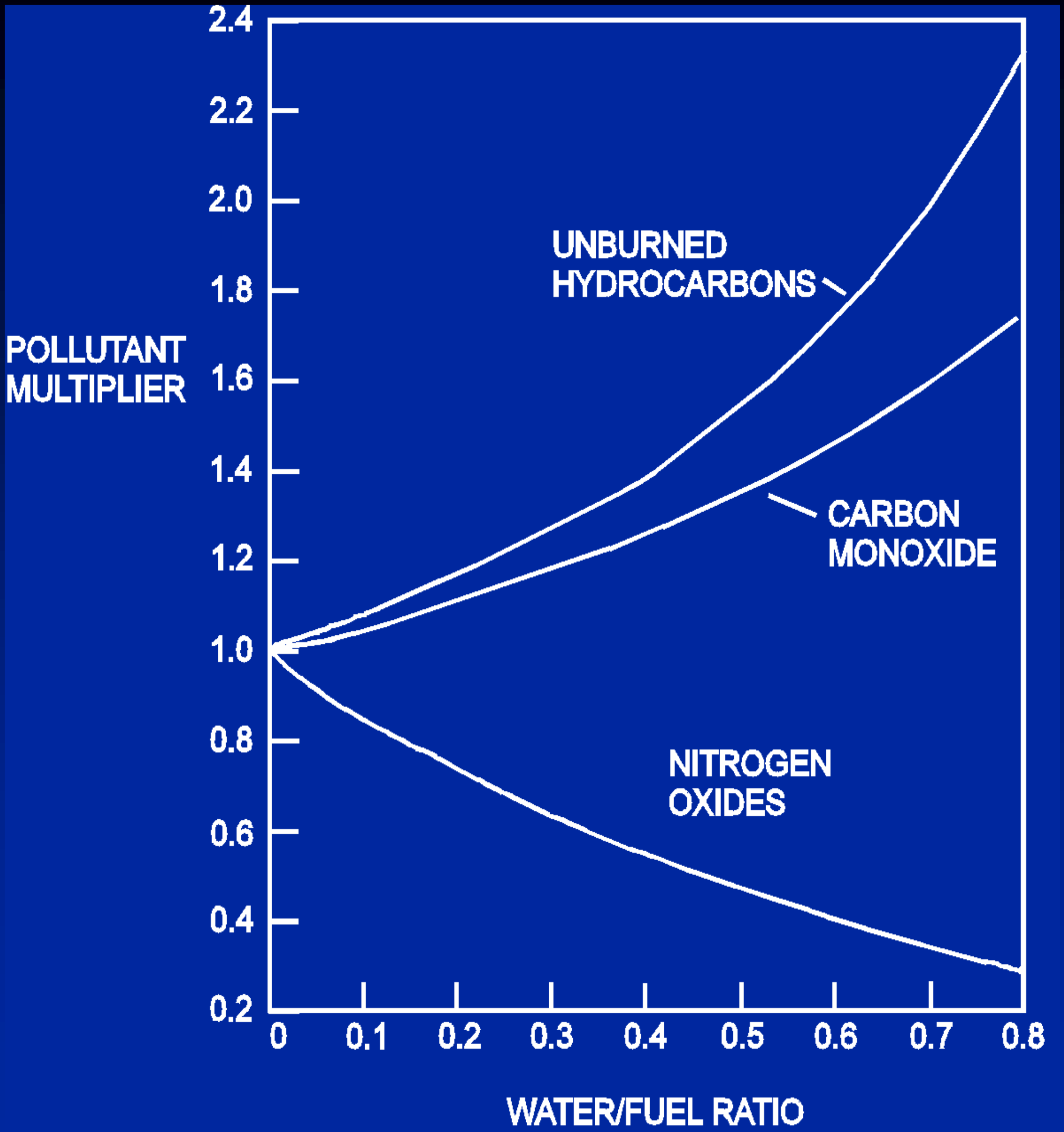



Fuel Nozzles


Can Annular Combustors
Turbine Blades

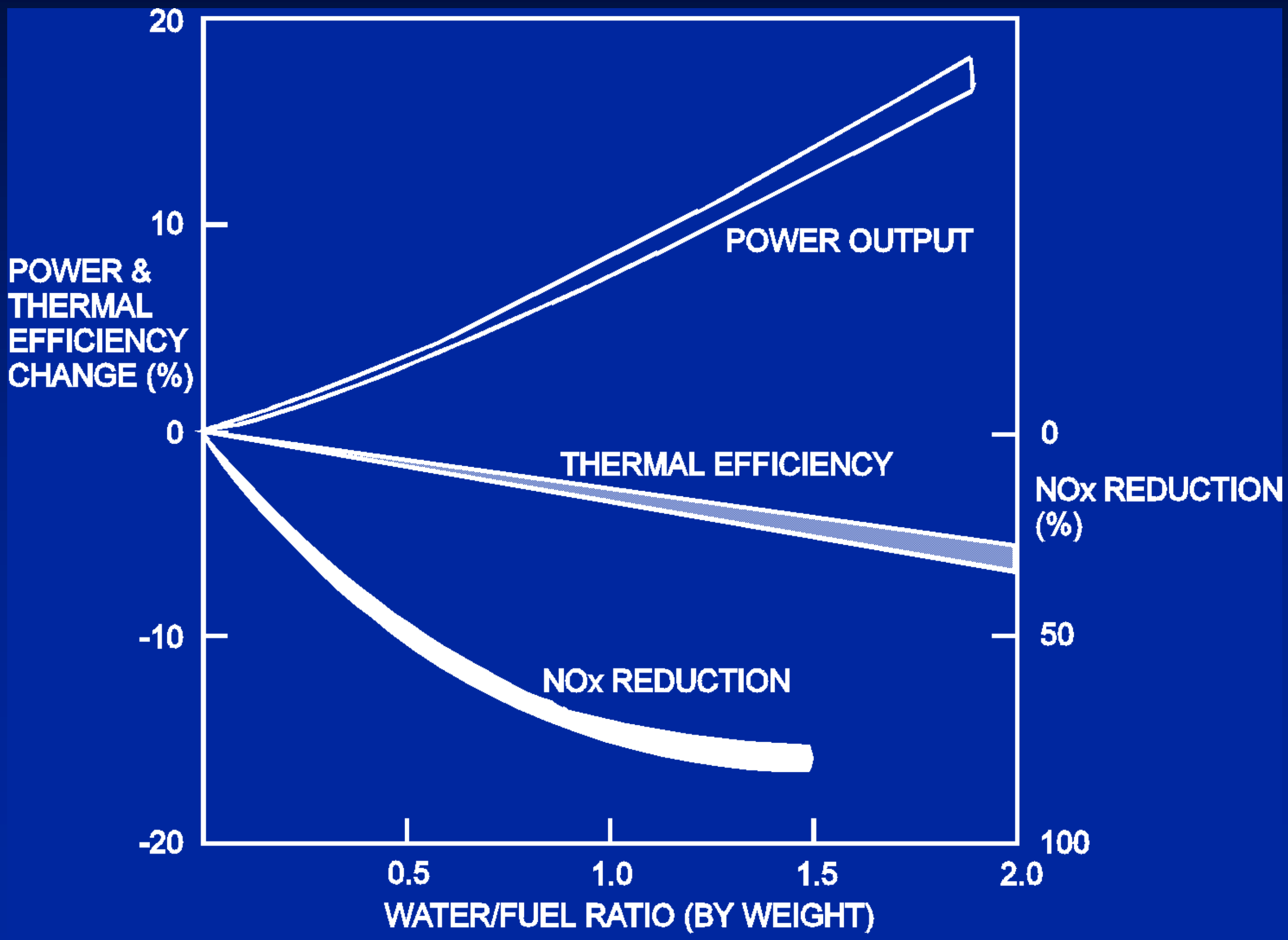

Water Injection


Gas
Nozzle
Water
Nozzle



NOx, CO, and Unburned HC vs. Water Injection

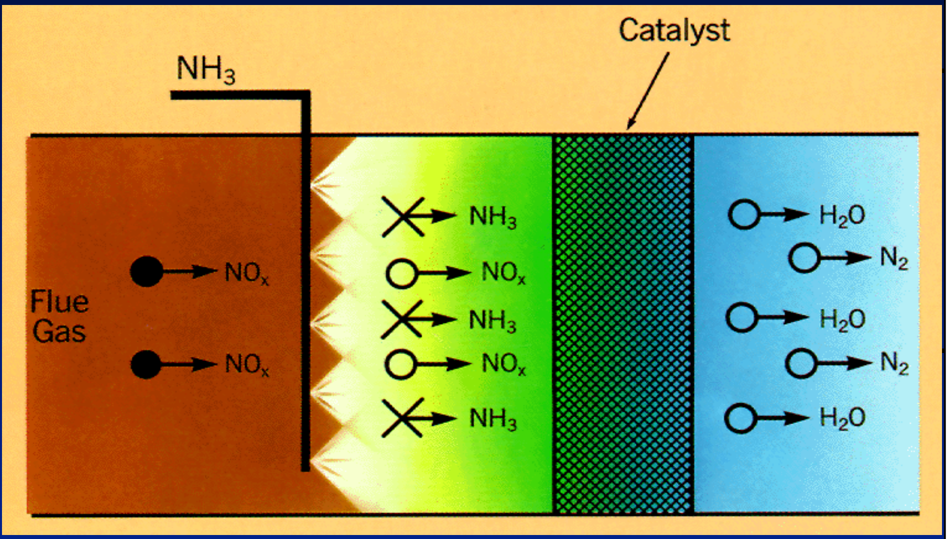
Effect of Water/Fuel Ratio on NOx, Thermal Efficiency, and Power Output

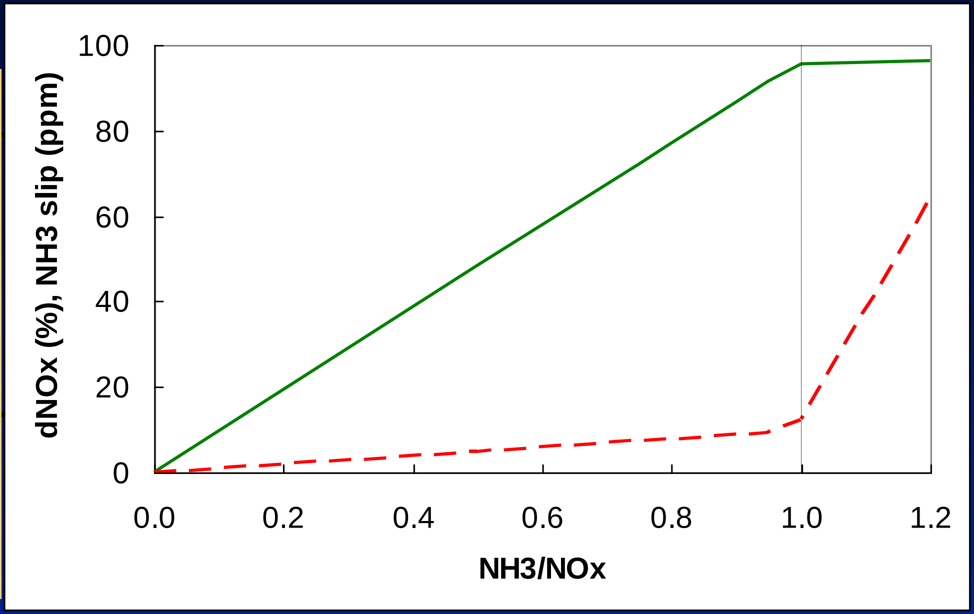



Let’s Discuss SCR

SCR - Introduction

Overview of the SCR Process





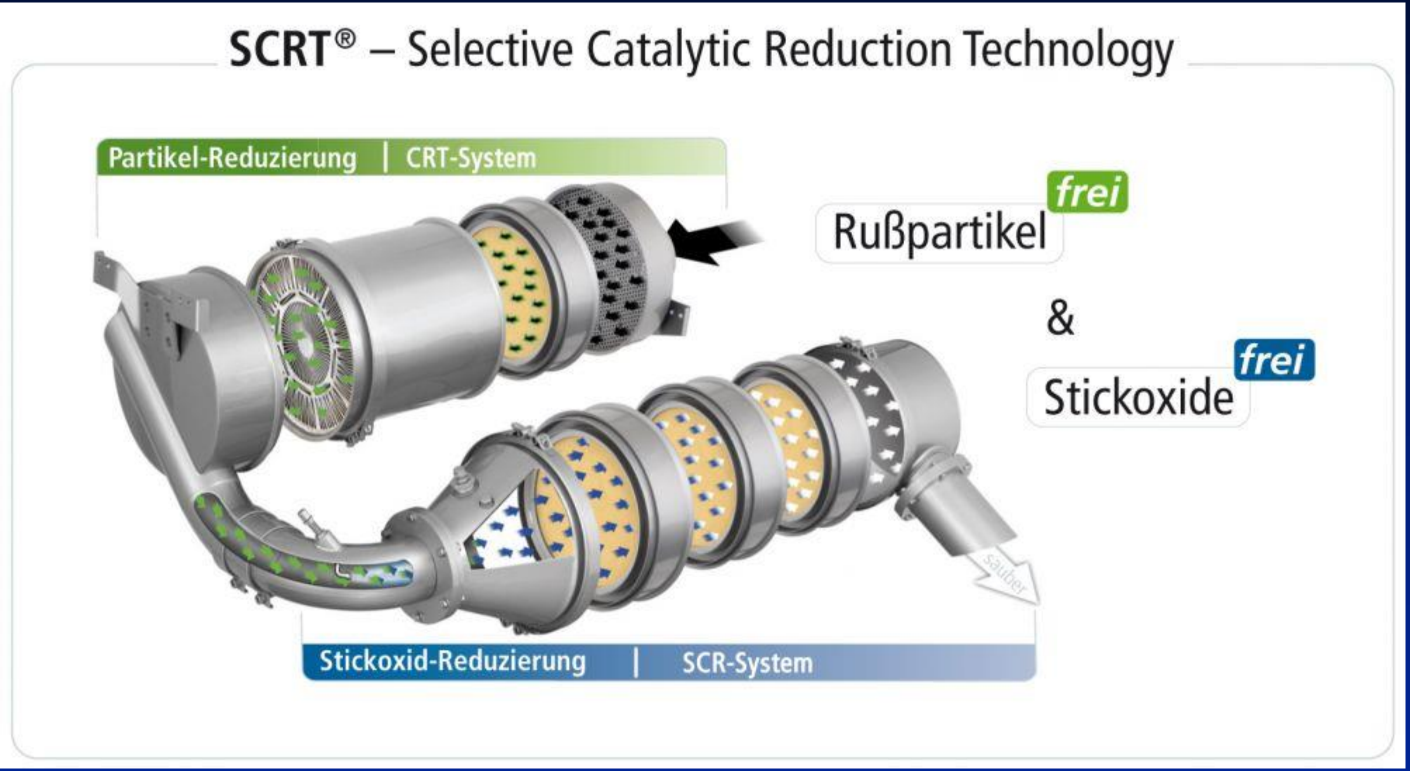
$NO + NH_3 + \frac{1}{4} O_2 \rightarrow N_2 + 1.5H_2O$ (1)*

$6NO_2 + 8NH_3 \rightarrow 7N_2 + 6H_2O$ (2)

$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$ (3)

* The vast majority of NO_x is in the form of NO, so reaction (1) dominates

SCRT®
Johnson Matthey



$$2\ NH_3 + NO + NO_2 \rightarrow 2\ N_2 + 3\ H_2O$$

Selective Catalytic Reduction (SCR)

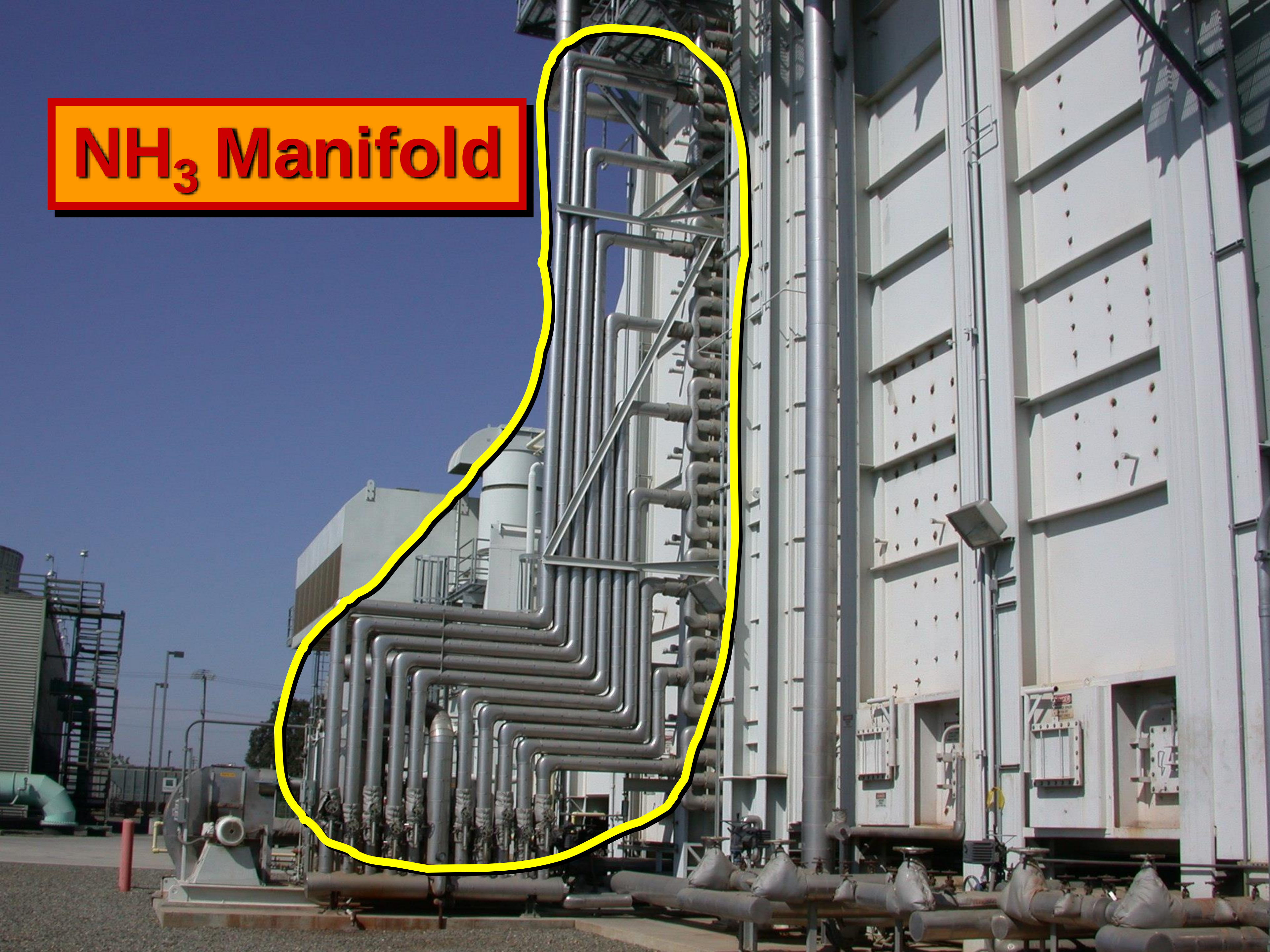
- 65-90% control
- Problems
  - Expensive
  - High maintenance
  - Ammonia “slip”
  - Catalyst replacement & disposal

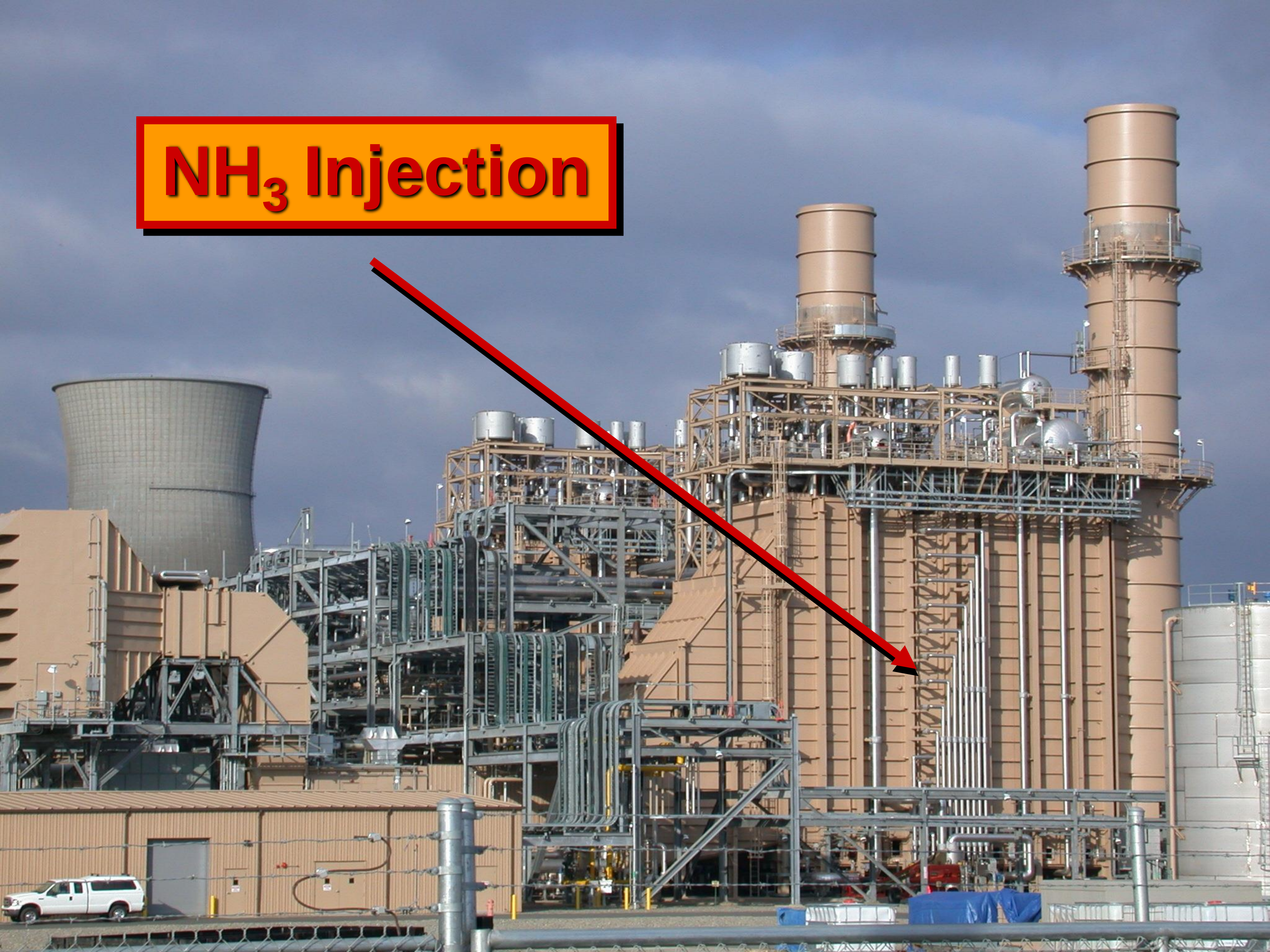
SCR – Where is it Used?

- Widespread Use
  - Coal and Gas Fired Utility Boilers
  - Gas Turbine Electric Generators (Simple and Combined Cycle)
- More Recently
  - Refinery Combustion Systems
  - Smaller Industrial Boilers (Gas, Biomass Fired)
  - Mobile Diesel Engines

Combined Cycle Power Plant w/SCR


Small Boiler
with SCR

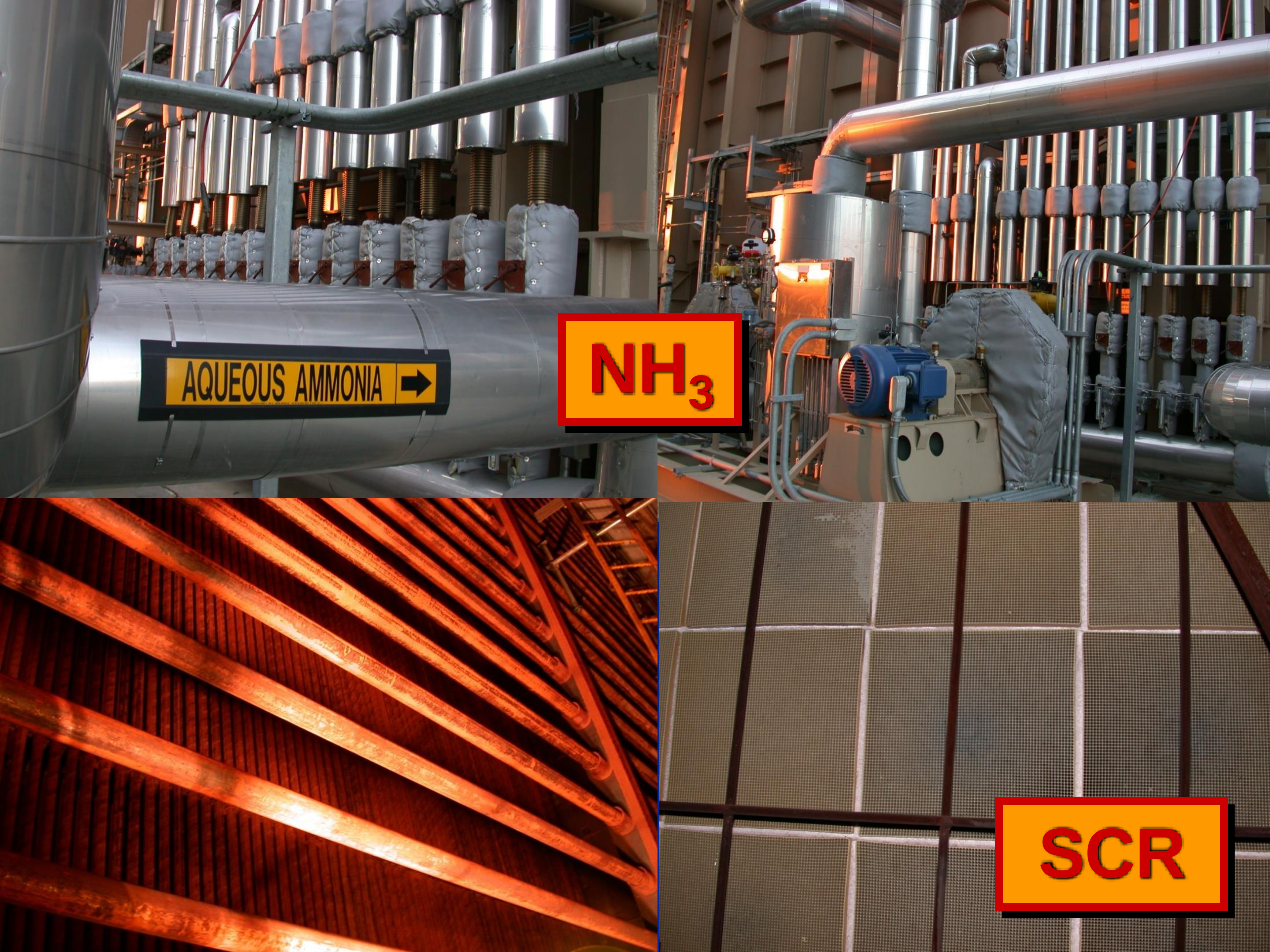

NH_3 Manifold


NH$_3$ Injection


SCR &
NH_3 Tubes


ANHYDROUS
AMMONIA
AIR
PRODUCTS
STOCKTON COGEN FACILITY
CHEMICAL/AMMONIA TRUCK UNLOADING POLICIES
1) YOU MUST WEAR A HARD HAT AND SAFETY GLASSES WHEN OUTSIDE OF YOUR TRUCK.
2) CHOCK YOUR TRAILER WHEELS BEFORE UNLOADING.
3) STAY WITH YOUR TRUCK WHILE UNLOADING.
4) IF THE ALARM HORN SOUNDS, SECURE YOUR TRUCK AND WAIT FOR INSTRUCTIONS FROM AN AIR PRODUCTS EMPLOYEE.
5) NO SMOKING ON THE PLANT SITE EXCEPT IN DESIGNATED AREAS.
7) PLEASE BUCKLE UP!
3
1
0
DANGER
NO SMOKING, MATCHES OR OPEN LIGHTS
WARNING
ANHYDROUS
AMMONIA

Ammonia Storage Tank

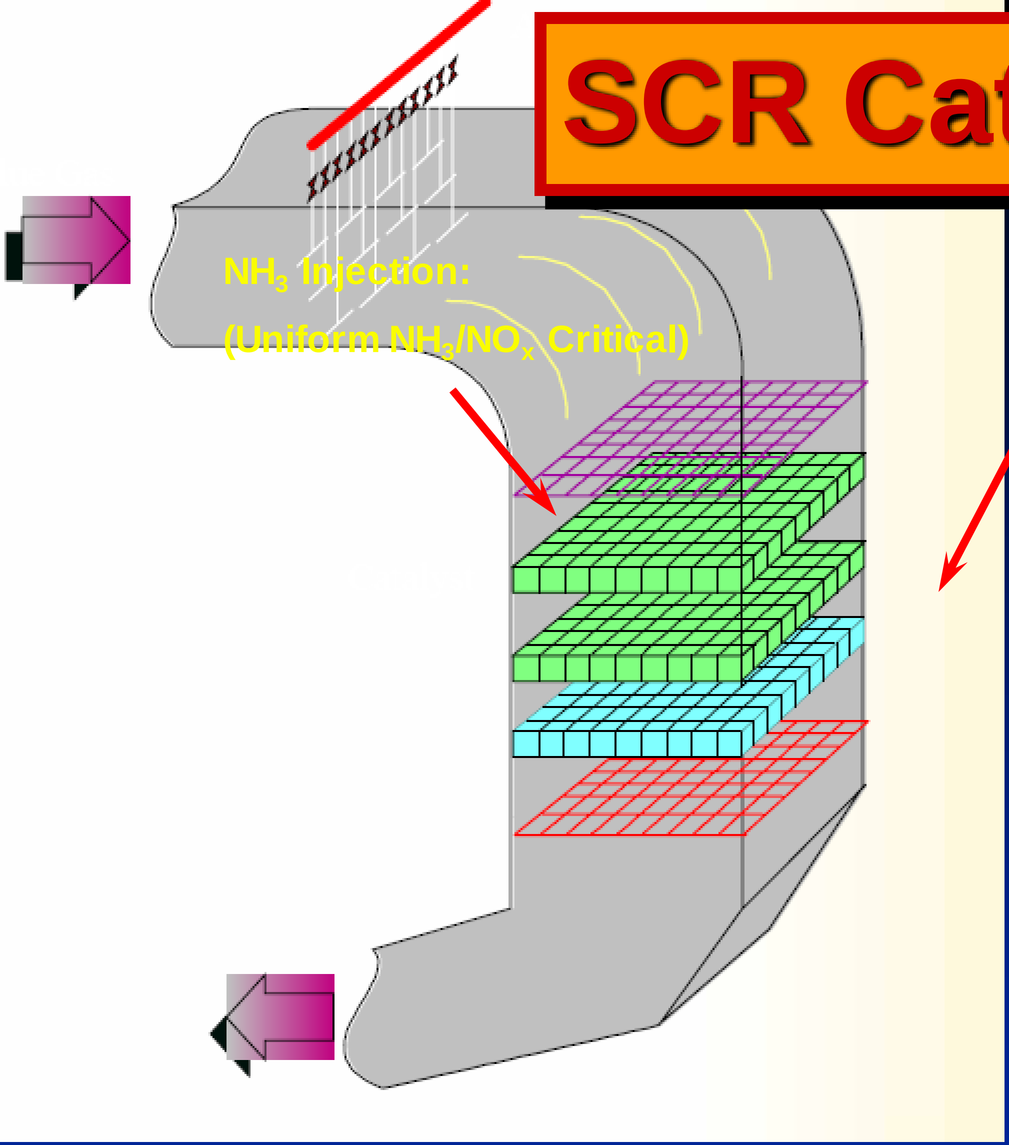

AQUEOUS AMMONIA
NH3
SCR


SCR Catalyst &
NH3 Tubes


SCR Catalyst


Utility Boiler with SCR

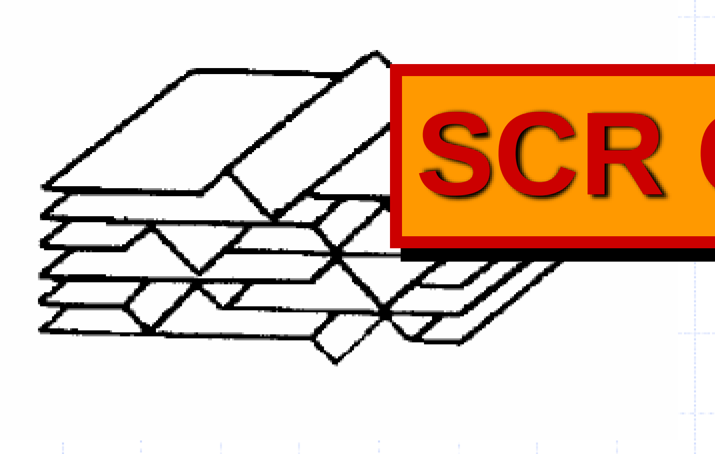
SCR Catalyst

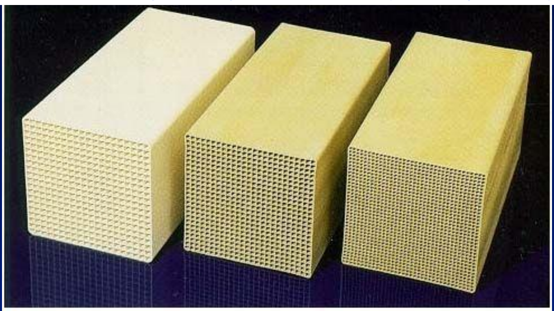


Turning Vanes to give uniform Velocity across the Catalyst

Catalyst Layer(s)

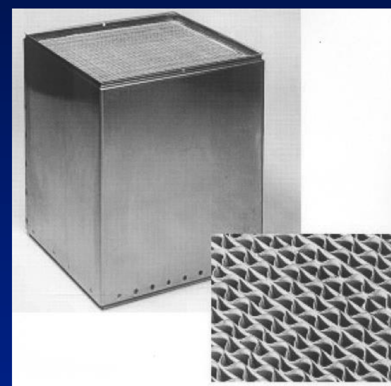
SCR Catalyst Types





Corrugated

(Haldor-Topsoe)



Plate

Composition

- Vanadium Pentoxide (V2O5)
- Titanium Dioxide (TiO2)
- Molybdenum
- Tungsten

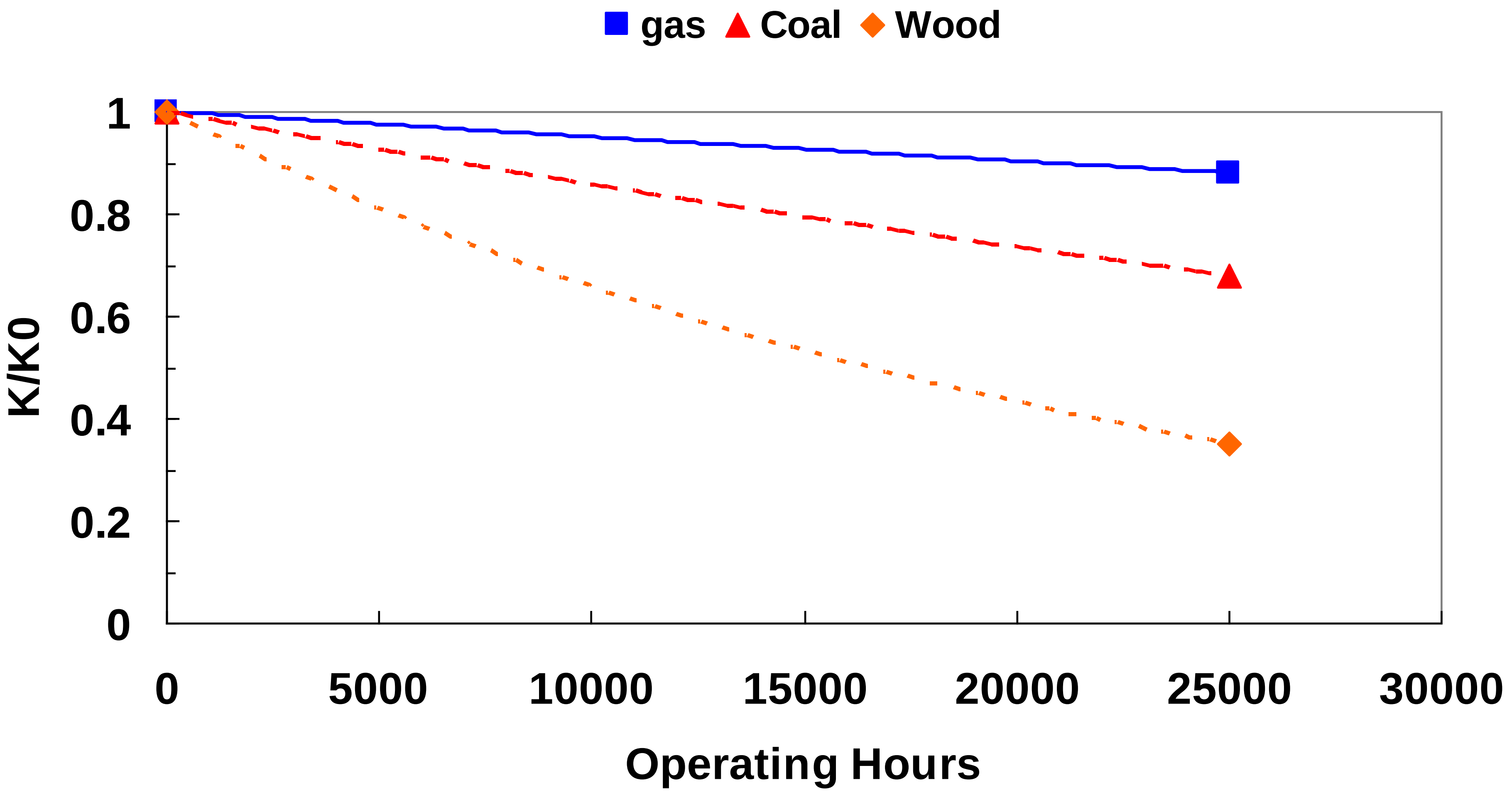

Utility Boiler: ID Fans for SCR

Catalyst Degrade with Time

Reason for Degradation Fuel Dependent

- **Bituminous Coal-Arsenic Poisoning**
- **Other Coal- Calcium sulfate blinding**
- **Potassium & Chlorine Poisoning**

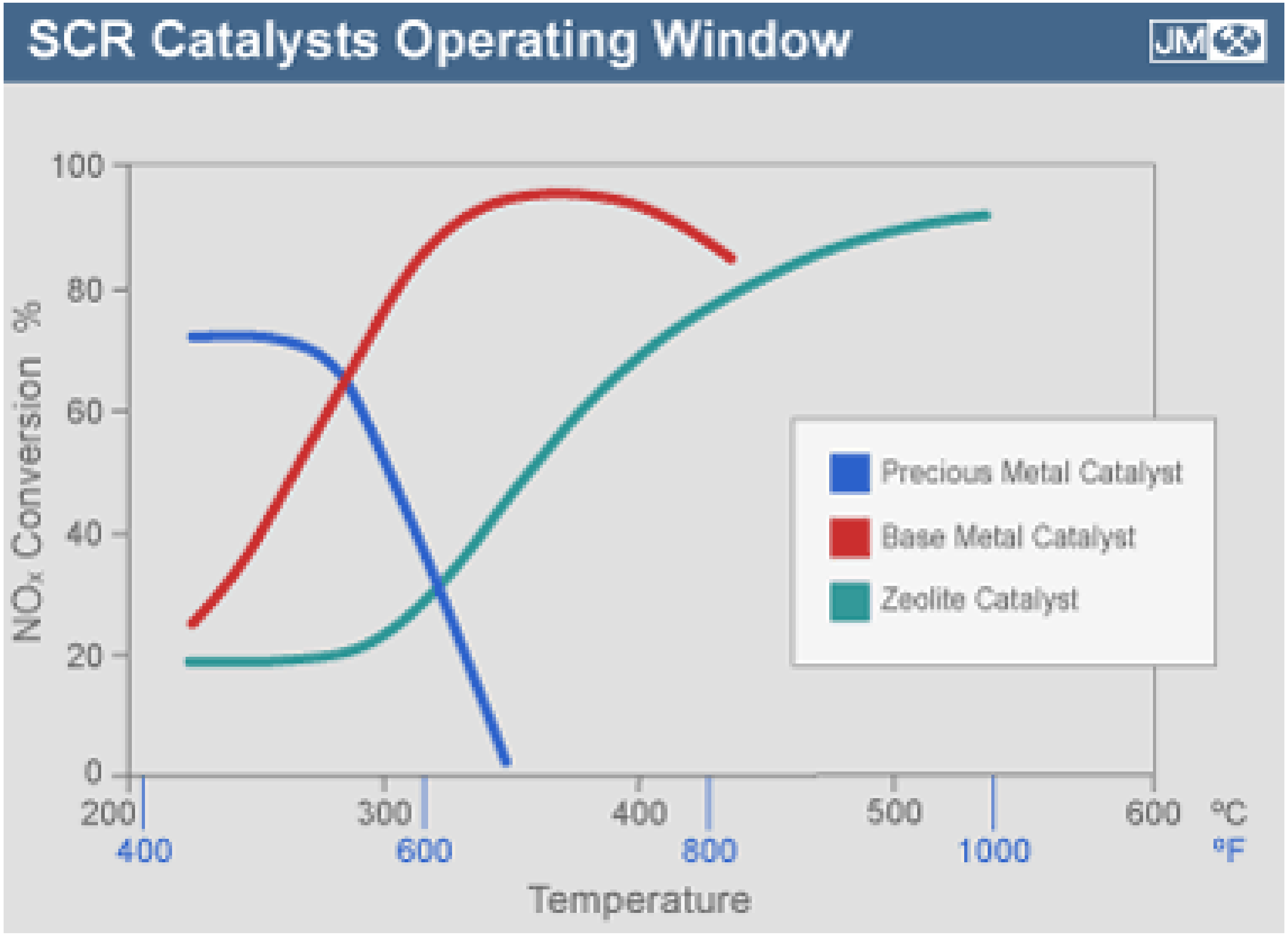
Typical Catalyst Deactivation Rates



NO_x Control Techniques – Selective Catalytic Reduction

- Factors affecting efficiency
  - Catalyst activity
  - Masking or poisoning
  - Space velocity (gas flow rate divided by bed volume)
  - Excess ammonia or urea slip

Typical SCR Catalysts Operating Windows

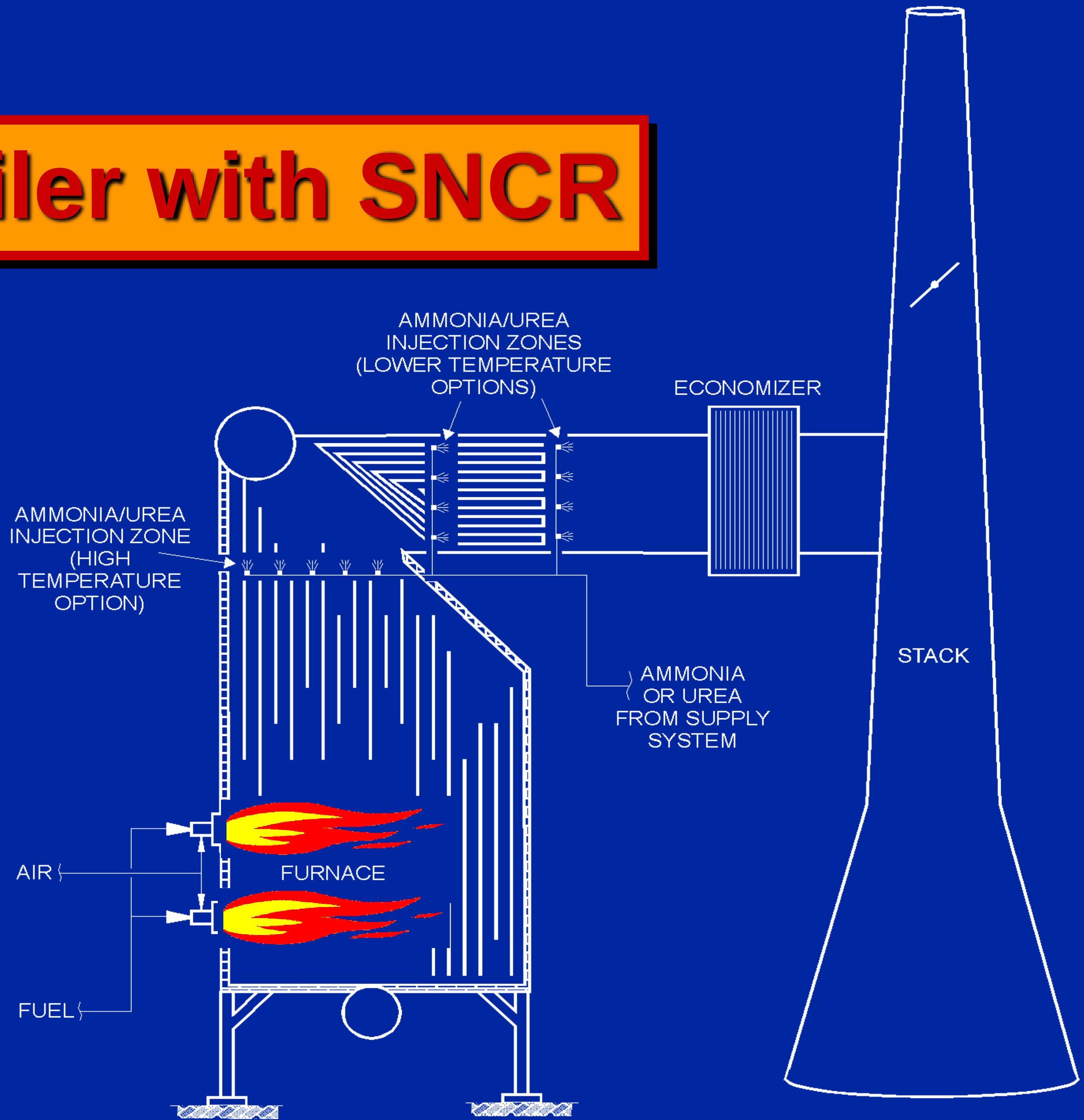


NOx Control Techniques – Selective Catalytic Reduction

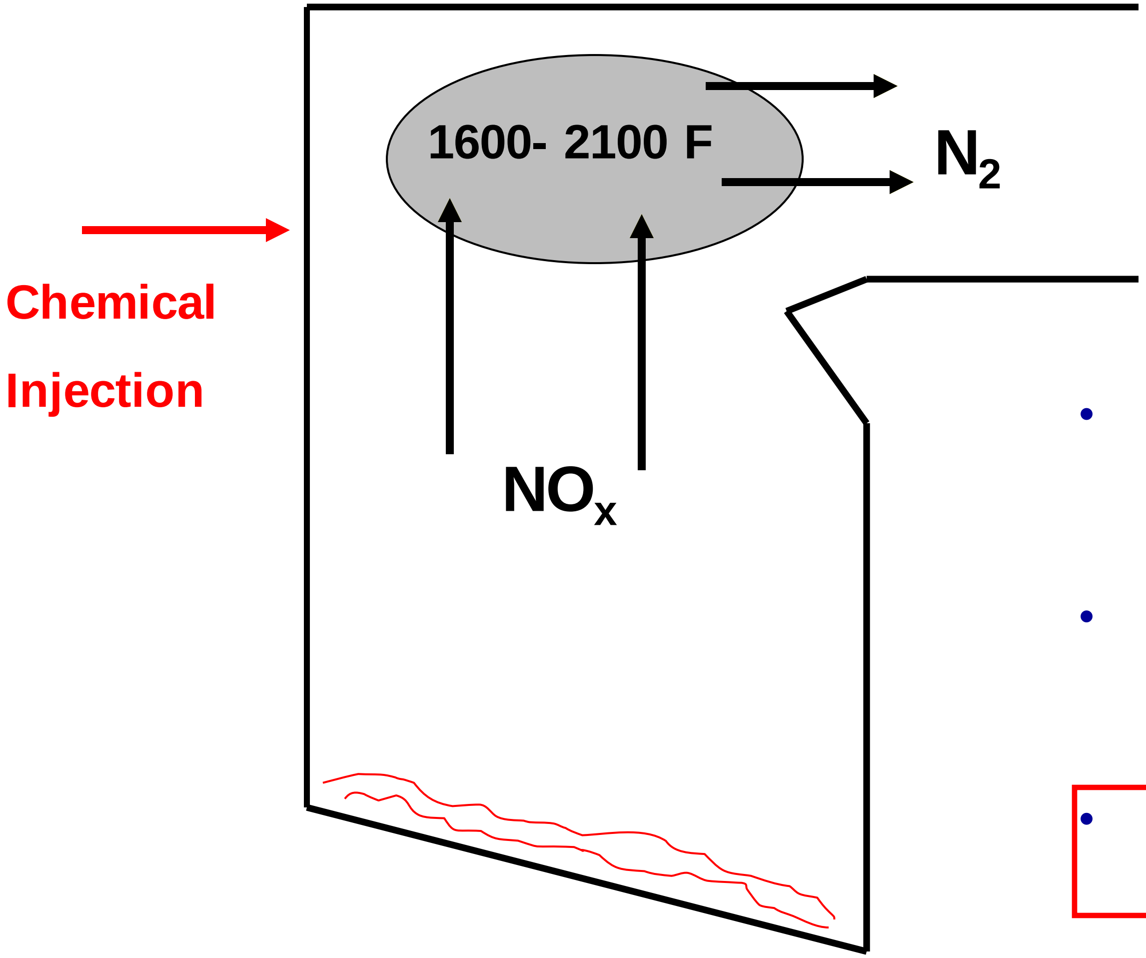
- Performance indicators
  - Inlet and Outlet NOx concentration
  - Ammonia / urea injection rate
  - Catalyst bed inlet temperature
  - Catalyst activity (coupon)
  - Outlet ammonia concentration
  - Inlet gas flow rate
  - Fuel sulfur content
  - Pressure differential across catalyst bed


Let’s Discuss SNCR

Boiler with SNCR



SNCR Process



- Gas Phase Reaction Between the Injected Chemical and NOx
- Reactions Occur in the Temperature Region of 1600-2100 F
- Furnace is the Chemical Reactor

Selective Non-Catalytic Reduction

- NOx control through ammonia injection
- No catalyst necessary
- Temperature range 1600 ^{o}F – 2100 ^{o}F
- Injected upstream of convection section
- 20% - 50% control under normal conditions
- Problems:
  - Changing flue temperatures with changing load
  - Formation of ammonium salts
  - Ammonia slip

Selective Non-Catalytic Reduction

Ammonia

NH_3

$NH_3 + OH$ $NH_2 + H_2O$

$NH_2 + NO$ $N_2 + H_2O$

N_2

Urea

NH_2CONH_2

$NH_3 + HNCO$

$HNCO + OH$ $NCO + H_2O$

$NCO + NO$ $N_2O + CO$

$N_2O + H$ $N_2 + OH$

$N_2O + OH$ $N_2 + HO_2$

$N_2O + M$ $N_2 + ...$

N_2O

Detailed SNCR Mechanism

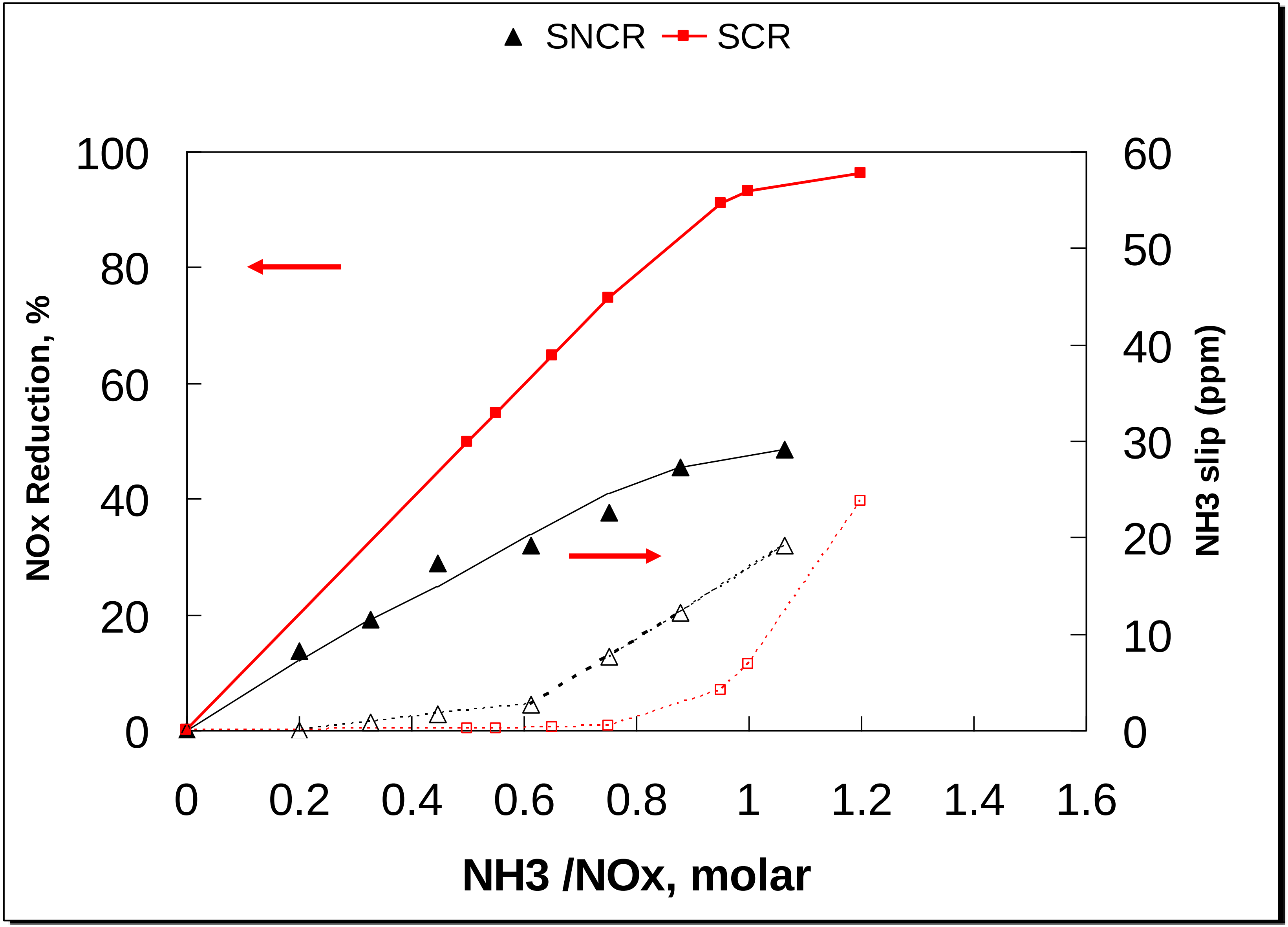
```
C2H2+C2H2=C4H3+H          0.200E+13  0.000  45900.000
C4H3+M=C4H2+H+M           0.100E+17  0.000  59700.000
CH2(S)+C2H
C4H2+O=C3
C2H2+O2=H
C2H2+M=C2
C2H4+M=C2
C2H4+M=C2
H2+O2=2OH                 0.170E+14  0.000  47780.000
OH+H2=H2O+H               0.117E+10  1.300   3626.000
O+OH=O2+H                 0.400E+15 -0.500      0.000
O+H2=OH+H                 0.506E+05  2.670   6290.000
H+O2+M=HO2+M              0.361E+18 -0.720      0.000
  H2O/18.6/ CO2/4.2/ H2/2.86/ CO/2.11/ N2/1.26/
OH+HO2=H2O+O2             0.750E+13  0.000      0.000
H+HO2=2OH                 0.140E+15  0.000   1073.000
O+HO2=O2+OH               0.140E+14  0.000   1073.000
2OH=O+H2O                 0.600E+09  1.300      0.000
H+H+M=H2+M                0.100E+19 -1.000      0.000
 H2/0.0/ H2O/0.0/ CO2/0.0/
H+H+H2=H2+H2              0.920E+17 -0.600      0.000
H+H+H2O=H2+H2O            0.600E+20 -1.250      0.000
H+H+CO2=H2+CO2            0.549E+21 -2.000      0.000
H+OH+M=H2O+M              0.160E+23 -2.000      0.000
  H2O/5/
H+O+M=OH+M                0.620E+17 -0.600      0.000
  H2O/5/
O+O+M=O2+M                0.189E+14  0.000  -1788.000
H+HO2=H2+O2               0.125E+14  0.000      0.000
HO2+HO2=H2O2+O2           0.200E+13  0.000      0.000
H2O2+M=OH+OH+M            0.130E+18  0.000  45500.000
H2O2+H=HO2+H2             0.160E+13  0.000   3800.000
H2O2+OH=H2O+HO2           0.100E+14  0.000   1800.000
CH+N2=HCN+N               0.200E+12  0.000  13600.000
CN+N=C+N2                 0.104E+16 -0.500      0.000
CH2+N2=HCN+NH             0.100E+14  0.000  74000.000
H2CN+N=N2+CH2             0.200E+14  0.000      0.000
H2CN+M=HCN+H+M            0.300E+15  0.000  22000.000
C+NO=CN+O                 0.660E+14  0.000      0.000
CH+NO=HCN+O               0.110E+15  0.000      0.000
CH2+NO=HCNO+H             0.139E+13  0.000  -1100.000
CH3+NO=HCN+H2O            0.100E+12  0.000  15000.000
CH3+NO=H2CN+OH            0.100E+12  0.000  15000.000
HCCO+NO=HCNO+CO           0.200E+14  0.000      0.000
CH2(S)+NO=HCN+OH          0.200E+14  0.000      0.000
HCNO+H=HCN+OH             0.100E+15  0.000  12000.000
CH2+N=HCN+H               0.500E+14  0.000      0.000
CH+N=CN+H                 0.130E+14  0.000      0.000
CO2+N=NO+CO               0.190E+12  0.000   3400.000
HCCO+N=HCN+CO             0.500E+14  0.000      0.000
CH3+N=H2CN+H              0.300E+14  0.000      0.000
C2H3+N=HCN+CH2            0.200E+14  0.000      0.000
C3H3+N=HCN+C2H2           0.100E+14  0.000      0.000

CN+N2O=NCO+N2             0.100E+14  0.000      0.000
C2N2+O=NCO+CN             0.457E+13  0.000   8880.000
C2N2+OH=HOCN+CN           0.186E+12  0.000   2900.000
HO2+NO=NO2+OH             0.211E+13  0.000   -479.000
NO2+H=NO+OH               0.350E+15  0.000   1500.000
NO2+O=NO+O2               0.100E+14  0.000    600.000
NO2+M=NO+O+M              0.110E+17  0.000  66000.000
NCO+H=NH+CO               0.500E+14  0.000      0.000
NCO+O=NO+CO               0.200E+14  0.000      0.000
NCO+N=N2+CO               0.200E+14  0.000      0.000
NCO+OH=NO+CO+H            0.100E+14  0.000      0.000
NCO+M=N+CO+M              0.310E+17 -0.500  48000.000
NCO+NO=N2O+CO             0.100E+14  0.000   -390.000
NCO+H2=HNCO+H             0.858E+13  0.000   9000.000
HNCO+H=NH2+CO             0.200E+14  0.000   3000.000
NH+O2=HNO+O               0.100E+14  0.000  12000.000
NH+O2=NO+OH               0.760E+11  0.000   1530.000
NH+NO=N2O+H               0.240E+16 -0.800      0.000
N2O+OH=N2+HO2             0.200E+13  0.000  10000.000
N2O+H=N2+OH               0.760E+14  0.000  15200.000
N2O+M=N2+O+M              0.160E+15  0.000  51600.000
N2O+O=N2+O2               0.100E+15  0.000  28200.000
N2O+O=NO+NO               0.100E+15  0.000  28200.000
NH+OH=HNO+H               0.200E+14  0.000      0.000
NH+OH=N+H2O               0.500E+12  0.500   2000.000
NH+N=N2+H                 0.300E+14  0.000      0.000
  NH+H=N+H2               0.100E+15  0.000      0.000
NH2+O=HNO+H               0.663E+15 -0.500      0.000
NH2+O=NH+OH               0.675E+13  0.000      0.000
NH2+OH=NH+H2O             0.400E+07  2.000   1000.000
NH2+H=NH+H2               0.692E+14  0.000   3650.000
NH2+NO=NNH+OH             0.640E+16 -1.250      0.000
NH2+NO=N2+H2O             0.620E+16 -1.250      0.000
NH3+OH=NH2+H2O            0.204E+07  2.040    566.000
NH3+H=NH2+H2              0.636E+06  2.390  10171.000
NH3+O=NH2+OH              0.210E+14  0.000   9000.000
NNH=N2+H                  0.100E+05  0.000      0.000
NNH+NO=N2+HNO             0.500E+14  0.000      0.000
NNH+H=N2+H2               0.100E+15  0.000      0.000
NNH+OH=N2+H2O             0.500E+14  0.000      0.000
NNH+NH2=N2+NH3            0.500E+14  0.000      0.000
NNH+NH=N2+NH2             0.500E+14  0.000      0.000
NNH+O=N2O+H               0.100E+15  0.000      0.000
HNO+M=H+NO+M              0.150E+17  0.000  48680.000
  H2O/10/ O2/2/ N2/2/ H2/2/
HNO+OH=NO+H2O             0.360E+14  0.000      0.000
HNO+H=H2+NO               0.500E+13  0.000      0.000
HNO+NH2=NH3+NO            0.200E+14  0.000   1000.000
N+NO=N2+O                 0.327E+13  0.300      0.000
N+O2=NO+O                 0.640E+10  1.000   6280.000
N+OH=NO+H                 0.380E+14  0.000      0.000
END
5.18.1989 modified for CHEMKIN I input from CHEMKIN II input
```

Ammonia vs. Urea

Parameter	Ammonia	Urea
Form	High Vapor Pressure Liquid Ammonia/Water Solution	Liquid Solution
Safety	Anhydous/29.4% Aqueous – Safety Issue 19% Aqueous – Fewer Safety Issues	No Safety Issues
Storage	Anhydrous – Pressure Vessel Aqueous – Atmospheric Pressure	Atmospheric Pressure Crystallization at Low Temps.
Injectors	Needs Carrier Gas	Atomizer (Pressure or Twin Fluid)
Temperature	Peak Removal @ 1750° F	Peak Removal @ 1850° F Large Dilute Drops Shield Urea
System Complexity	Relatively Simple	Relatively Simple

SCR vs. SNCR



SNCR
SCR
100
80
60
40
20
0
60
50
40
30
20
10
0
NOx Reduction, %
NH3 slip (ppm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
NH3 /NOx, molar

SCR vs. SNCR

	SNCR	SCR
NOx Reductiuon	20-50%	50-95%
Hardware	Simple	More Complex
Capital Cost	Low (1)	High (5-10)
Reagent Utilization	Typ. 30%	Almost 100%
O&M	Reagent	Reagent/Catalyst
Designability	Poor	Good
NH3 slip	5-20 ppm	<10 ppm

NH_3 Emissions Limits

- Regulatory Limit

- NH_3/SO_3 Reactions
  - Ammonium Bisulfate: $NH_3 + SO_3 \rightarrow NH_4HSO_4$
  - Ammonium Sulfate: $2NH_3 + SO_3 \rightarrow (NH_4)_2SO_4$

- NH_3/Ash Absorption (issue for coal-fired utility units that sell their ash for making cement)

- NH_3/HCl Reactions (detached plume)
  - NH_3/HCl $NH_4Cl(s)$

Comparison of NOx Control Technologies – Gas-Fired Boilers

Technology	Approx. Reduction	Approx. lbs/MMBTU	Approx. ppmv @ 3% O2
Standard burners	Base case	0.14	120
Low NOx burners	60%	0.06	45
Ultra Low NOx Burners – I[st] gen.	80%	0.03	25
Ultra Low NOx Burners – 2[nd] gen.	95%	0.007	6
FGR	55%	0.025	20
Compu- NOx w/ FGR	90%	0.015	12
SNCR	40%	0.033 - 0.085	27 - 70
Catalytic Scrubbing	70%	0.017 - 0.044	14 - 36
SCR	90 – 95%	0.006 - 0.015	5 - 12

Let's Discuss Particulate & NH_3 Controls

Objectives

- Define “particulate matter or PM”
- Identify sources of particulates
- Analyze opacity issues
  - Potassium plumes
  - Ammonium-chloride plumes

What is Particulate Matter??

- It is what the test measurement says it is
- Meaning:
  - Solid particles that are captured on a filter
  - Condensable matter collected in a set of impingers
- What eventually condenses in the atmosphere is also considered as particulate matter along with “solid” particulate in the gas stream


PM

Sources of "Particulate Matter"

- Ash in the fuel
  - Silica and Alumina - generally large particles that are retained or collected in the boiler/precipitator
  - Intrinsic ash - generates the small particles that are more troublesome to control
  - Alkalis - potassium, sodium and calcium
- Condensables (HCl, SO_3, NH_4Cl) which are also considered as "particulates"

Ammonia Slip

- $NH_3 + OH \Rightarrow NH_2 + H_2O$
- $NH_2 + NO \Rightarrow N_2 + H_2O$
- $2NH_3 + OH + NO \Rightarrow 2H_2O + N_2 + NH_3$
- 10 to 25 ppm NH_3 Slip
- Could be higher
- Always have Some NH_3 slip

NH_3 (g) + HCl (g) => NH_4Cl(s)

- NH_3 and HCl released as gases
- Combine and condense into aerosol particles
- Two parallel processes taking place
  - Rate of formation reaction controlled by concentrations
  - Rate of condensation control by temperature
- Both affected by air dilution in the plume

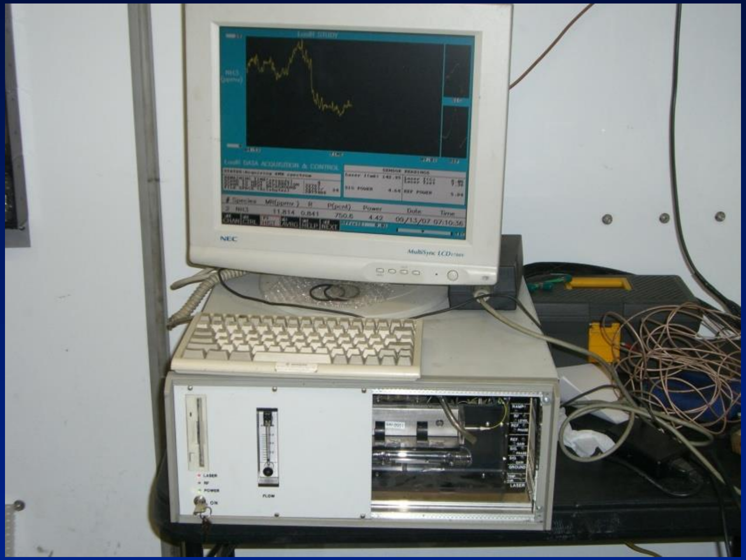
NH_4Cl Formation

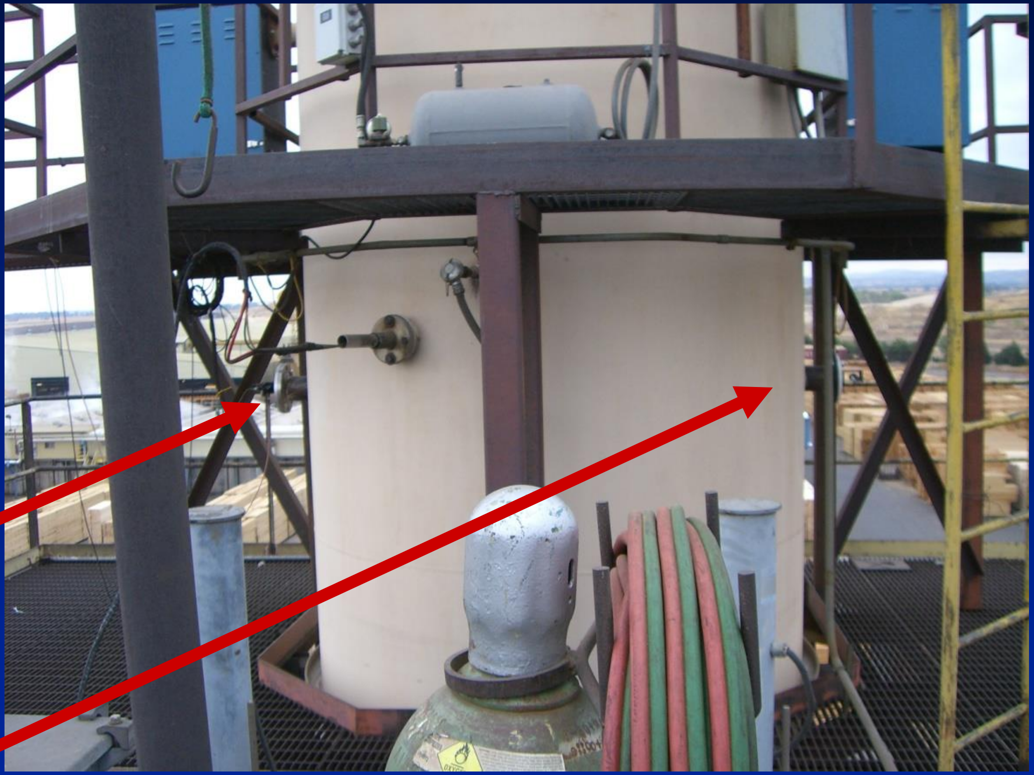
- Function of the concentrations of NH_3 an HCl
- Concentrations decrease as air is mixed into the plume
- Lower concentrations => less NH_4Cl formed
- Therefore: air dilution is good

What Can Be Done??

- Minimize (eliminate Cl) in fuel
- Install acid gas controls
- Minimize NH_3 slip <= monitor
- High stack gas temperatures
- High ambient air temperatures (winter time a problem??)
- Promote rapid gas/air mixing ??
- Install high gas temperature concentric stack annulus ??

Continuous NH3 Analyzer





Laser & Detector

Retro Reflector


Laser & Detector


Retro-reflector

Let’s Discuss VOC Control

- Material Usage Minimization
- Containment
- Absorption
- Adsorption
- Oxidation

Material Usage Minimization

Basic Strategy:

If we optimize the efficiency of the amount of VOC-containing material we use, we also limit VOC emissions

Materials Minimization

We must consider real-world demands

e.g. Spray painted cars look better

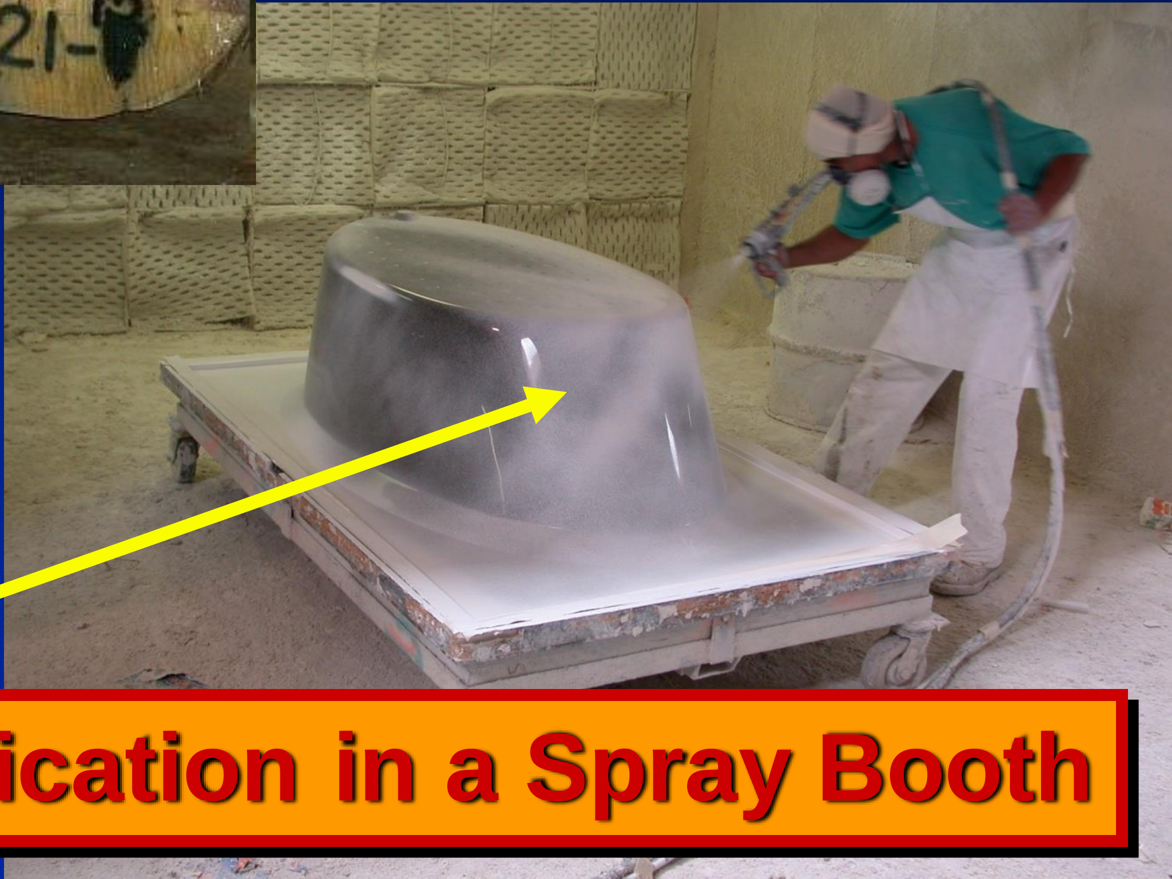
Controlled Coatings Spraying

- Reduces material usage
- Reduces VOC emissions
- Increases transfer efficiency
- Low fluid tip pressure
- Employee gun handling training

Motor Vehicle Coating – High Volume Low Pressure (HVLP) Spray Gun


HVLP
Chopper Gun
VENUS

Chopper Gun



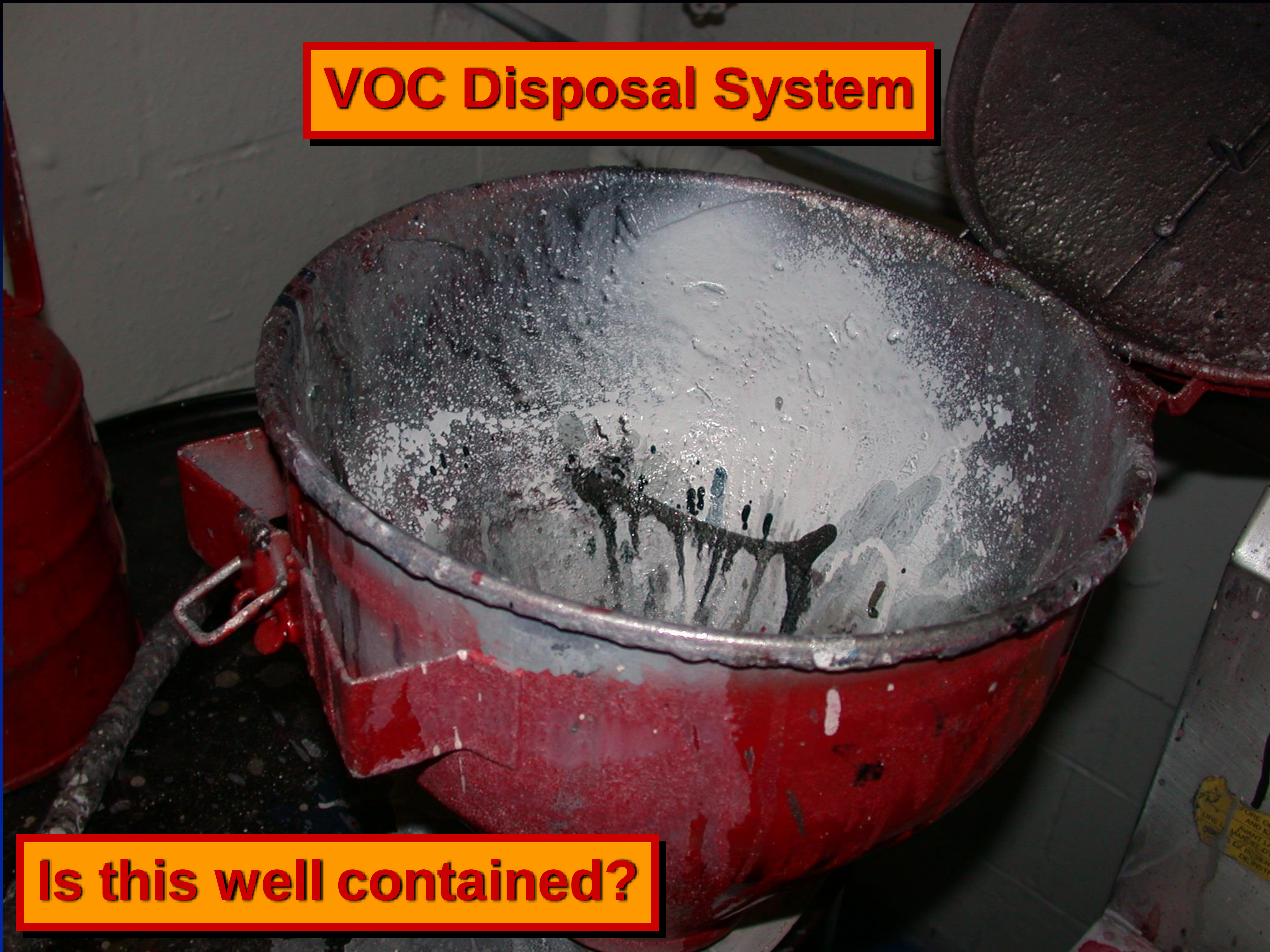
Gel Coat Application in a Spray Booth

Hand Layup of Fiberglass

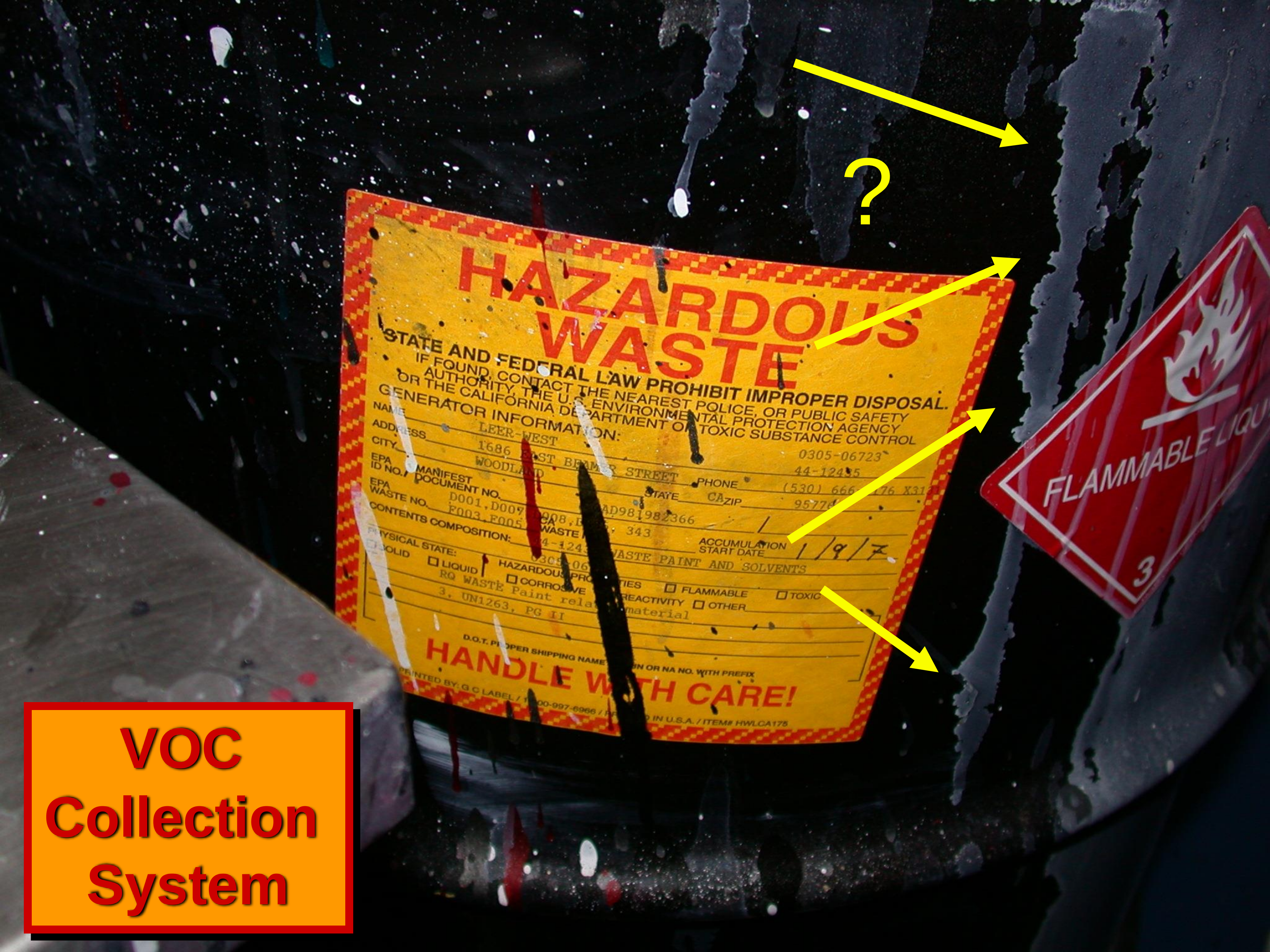
Materials Minimization


Containment Strategy
Solvent Reclaim System

VOC Disposal System



Is this well contained?

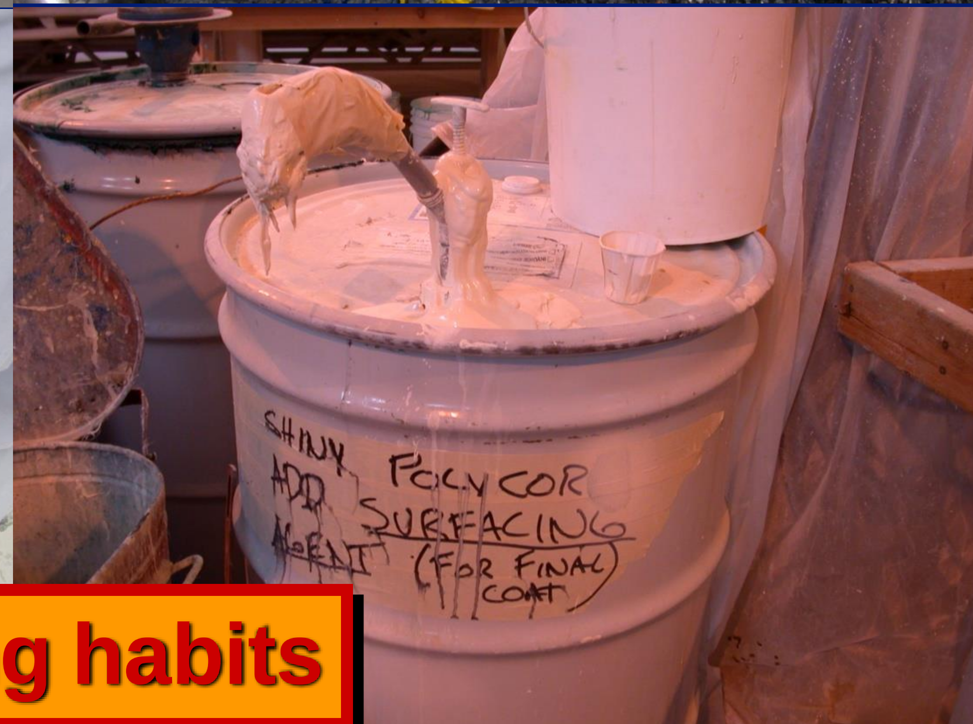


VOC Collection System

Look for housekeeping habits

Look for housekeeping habits

Look for housekeeping habits



Look for housekeeping habits


Capture and Control

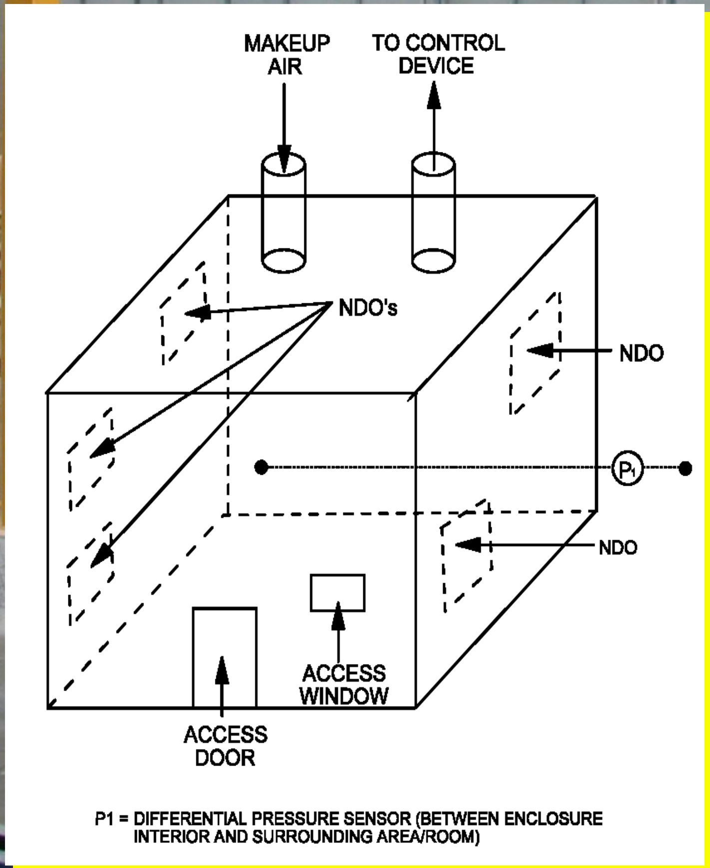
VOC Control Techniques – Capture System

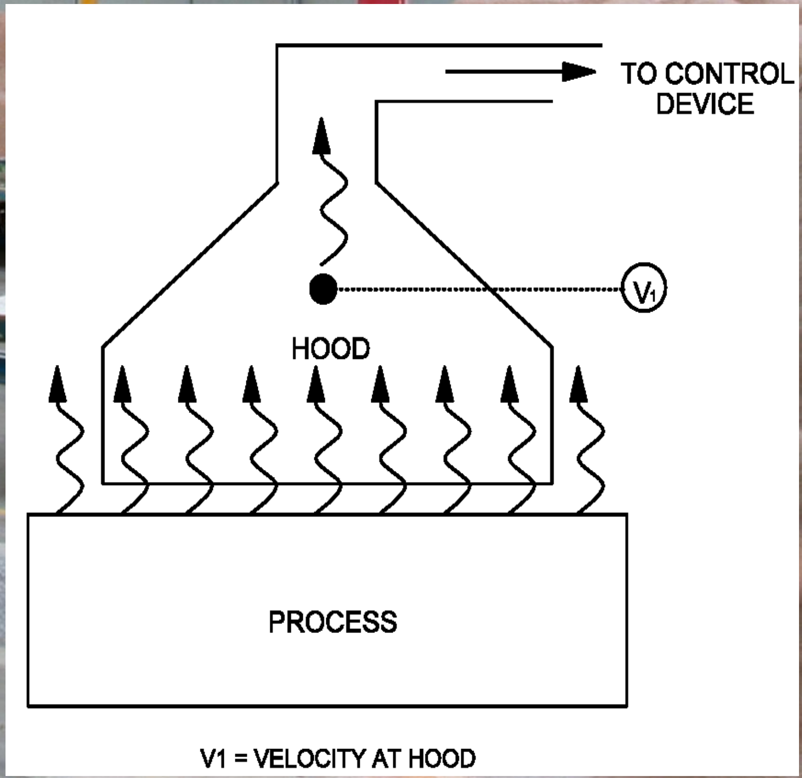
- General description
  - Total efficiency is product of capture and control device efficiencies
  - Two types of systems
    - Enclosures and local exhausts (hoods)

VOC Control Techniques – Capture System

- General description
  - Two types of enclosures
    - Permanent total (M204) – 100% capture efficiency
    - Nontotal or partial – must measure capture efficiency

Capture System Schematic





VOC Control Techniques – Capture System

- Performance indicators
  - Enclosures
    - Face velocity
    - Differential pressure
    - Average face velocity and daily inspections

VOC Control Techniques – Capture System

- Performance indicators (cont.)

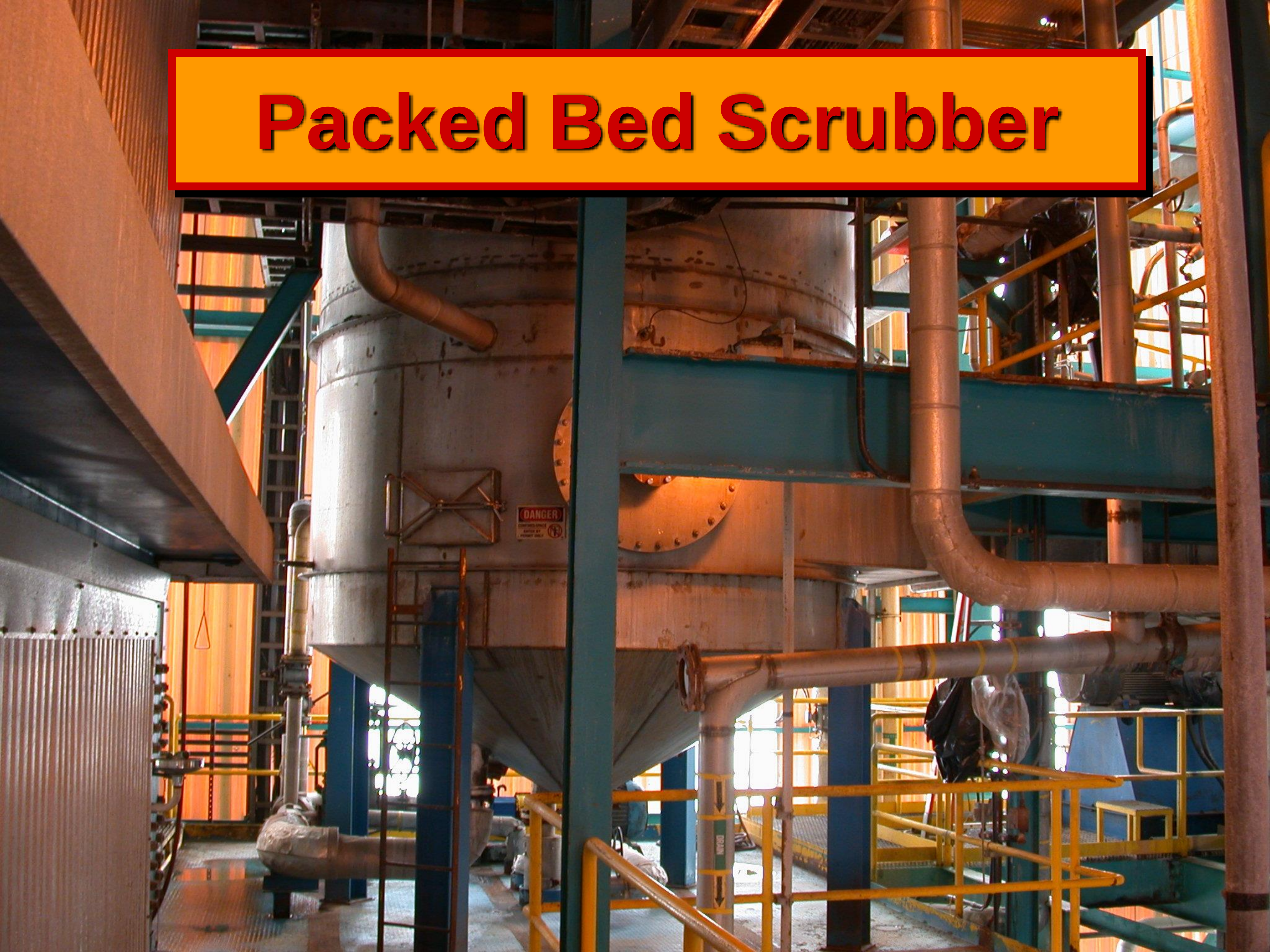
  Exhaust Ventilation

  - Face velocity
  - Exhaust flow rate in duct near hood
  - Hood static pressure

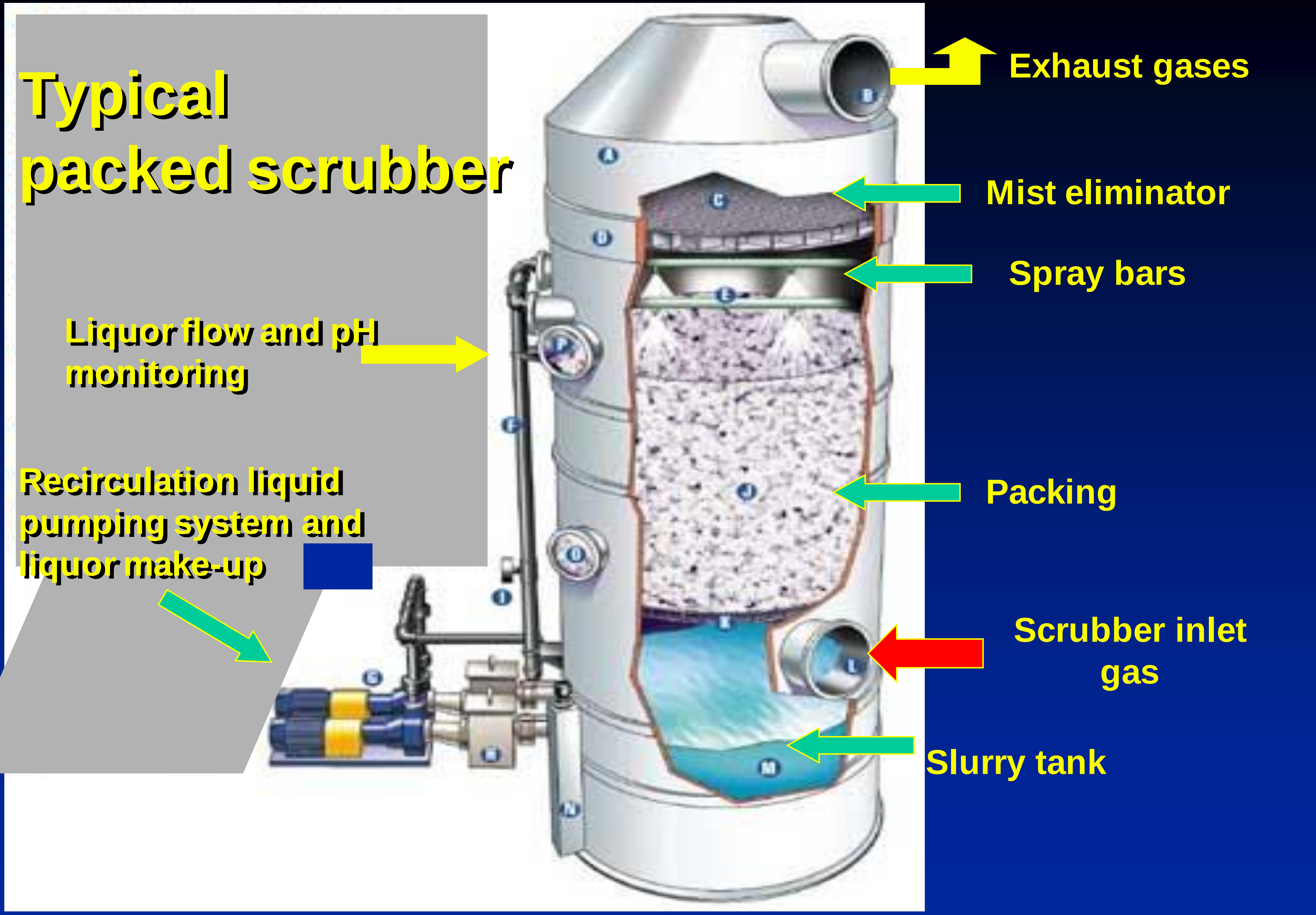
Any Concerns Here?

Let’s Discuss Packed Column Absorbers (a.k.a Scrubbers)

Packed Bed Scrubber



Typical packed scrubber



Typical Packing Material

Atomizing Spray Nozzles

Scrubbers

- Used for a variety of pollutants
  - Both particulates and VOCs
  - Acid gases
  - Odors (e.g. rendering operations)
- Primary indicators
  - Water (liquor) flow rate
  - pH
  - Outlet temperature
- Secondary (longer term) indicators
  - Inlet & water temperatures
  - Gas pressure drop

Monitoring Approach – SO_2

Indicator	Slurry pH	Slurry flow rate
Indicator range	<9.0 - corrective action, reporting	<175 – corrective action, reporting
Measurement location	Recirculation line	Recirculation line
QA/QC	Annual cal.	Annual cal.
Frequency	1/15 minutes	1/15 minutes
Averaging time	hourly	hourly

Compliance Concerns?

Scrubber Leaking Liquor

Compliance Concerns?

Scrubber Liquor Pump

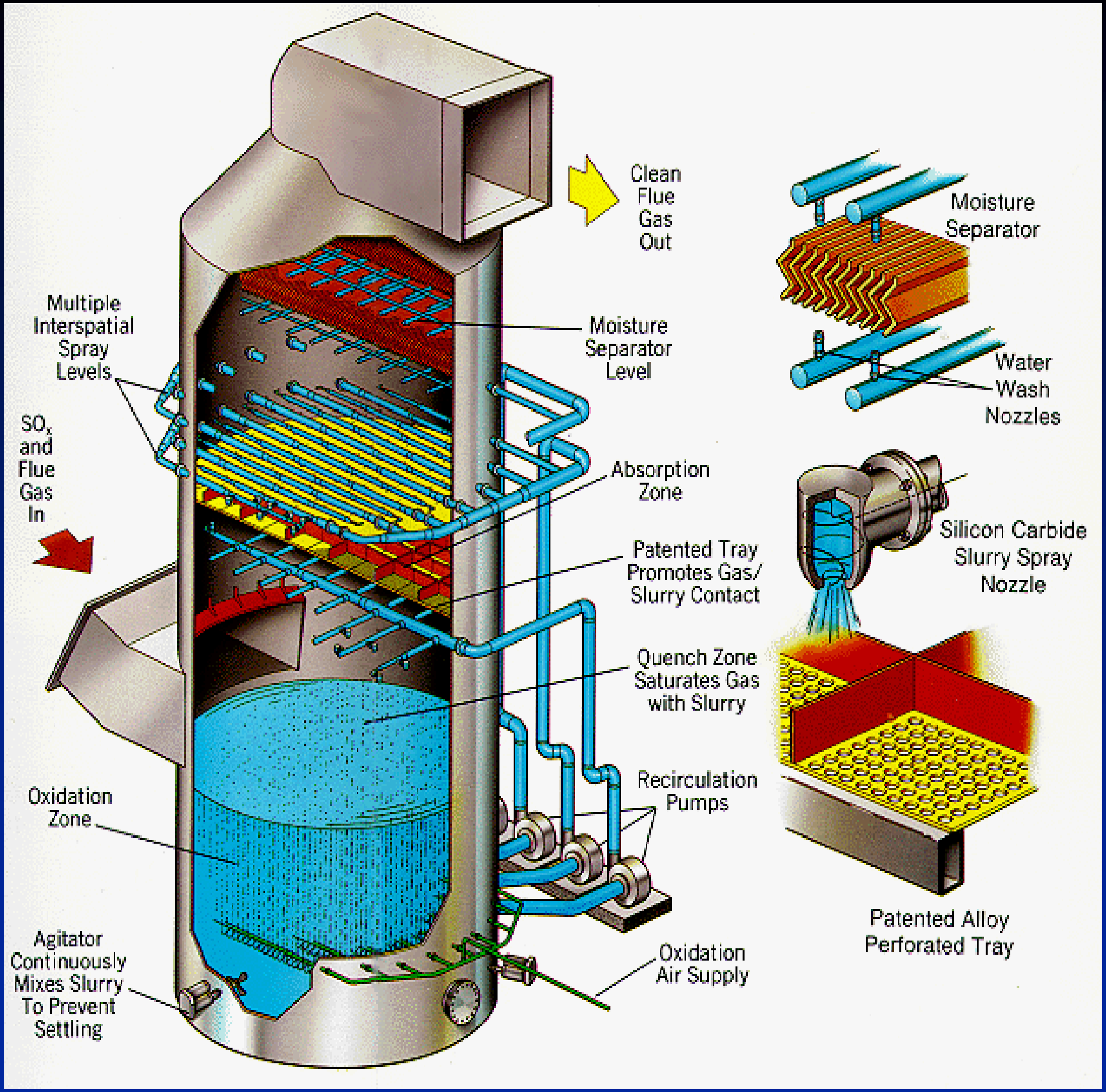
Let's Discuss FGD : Flue Gas Desulphurization

SO_2 Scrubbers

- Wet
- Spray Dry (Semi-Dry)
- Dry (DSI : Dry Sorbent Injection)

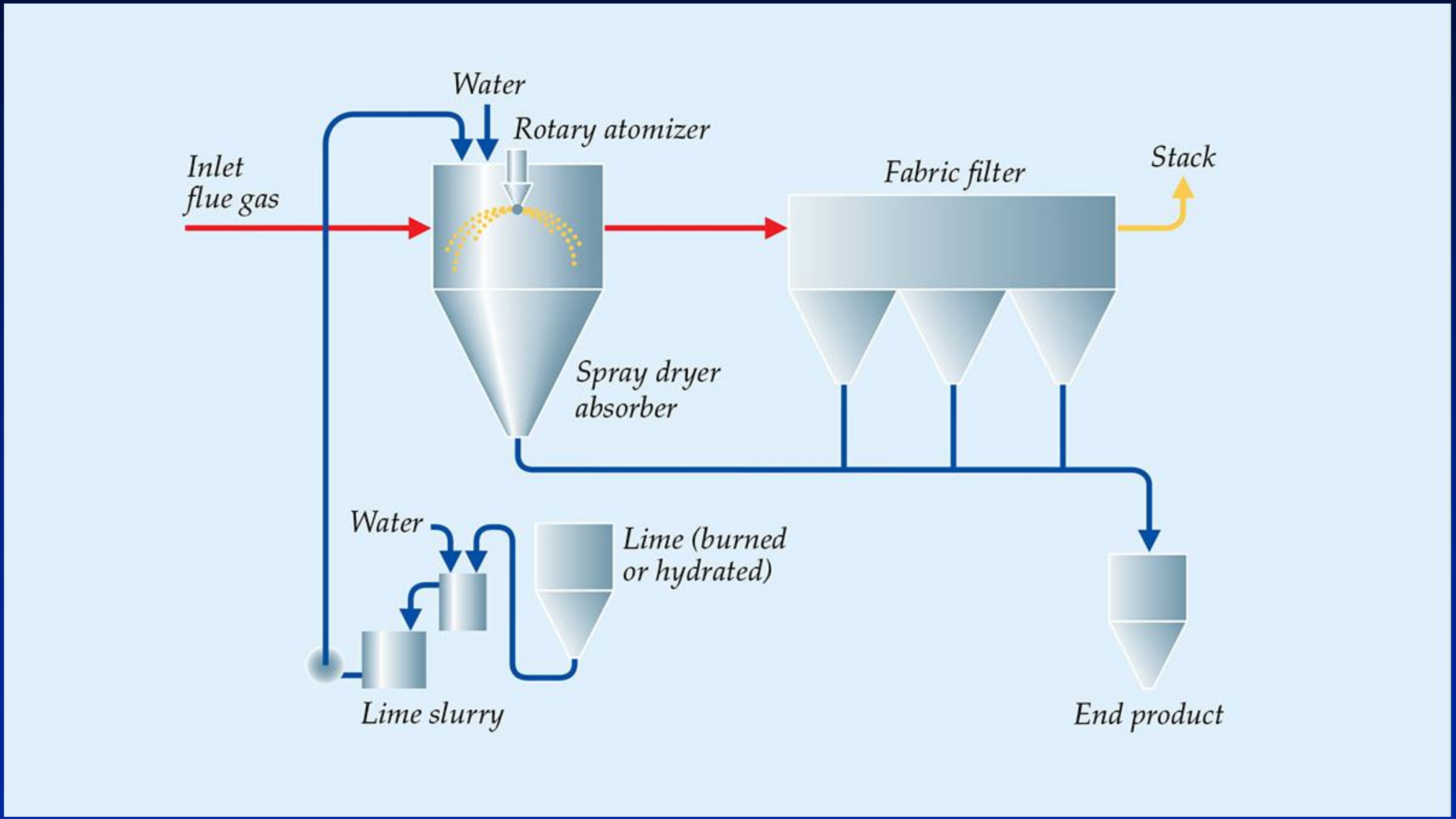
SOx Control

Wet FGD

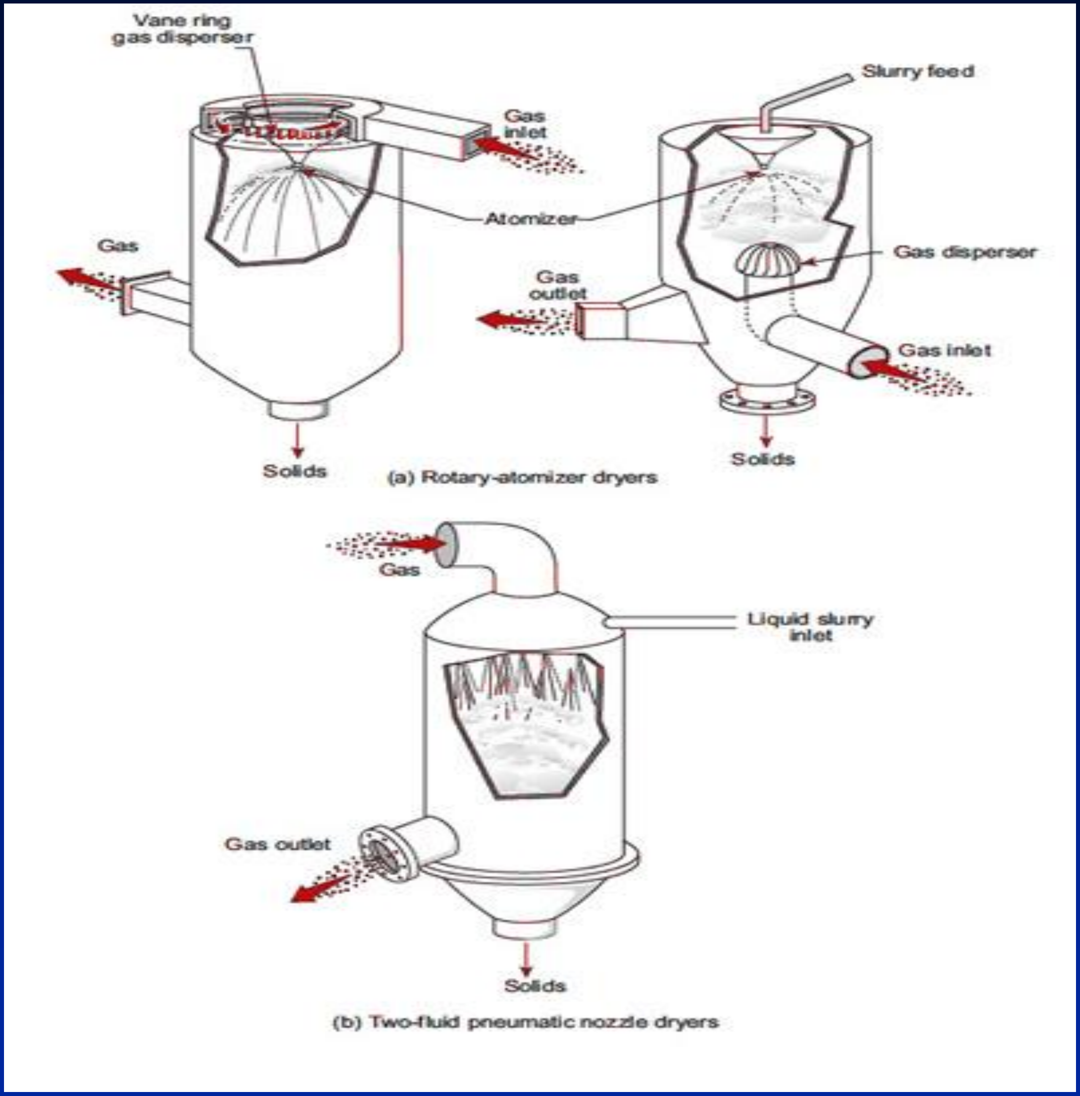


Five FGD Scrubber Modules on Utility Boiler

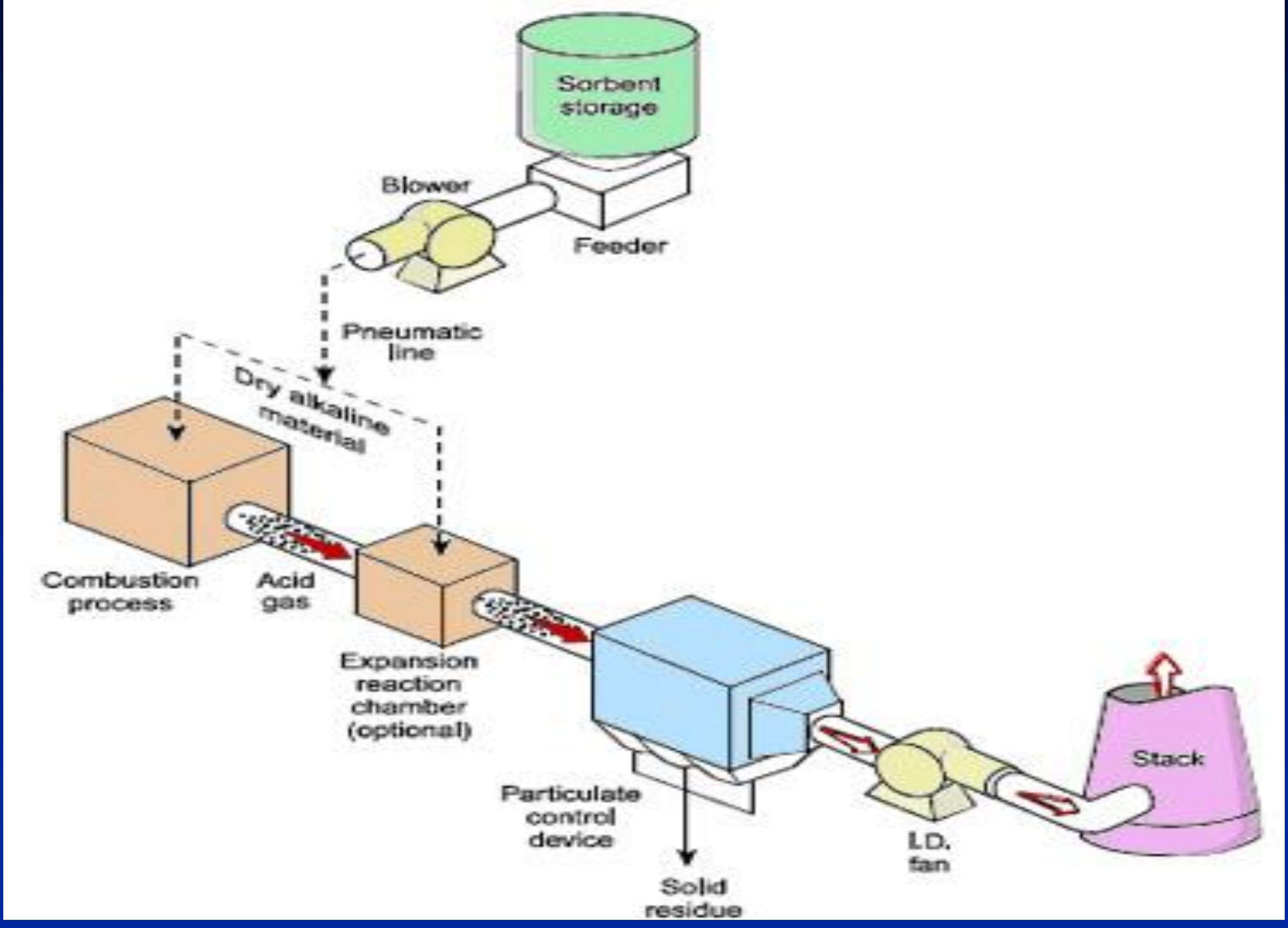
Spray Dryer Absorber



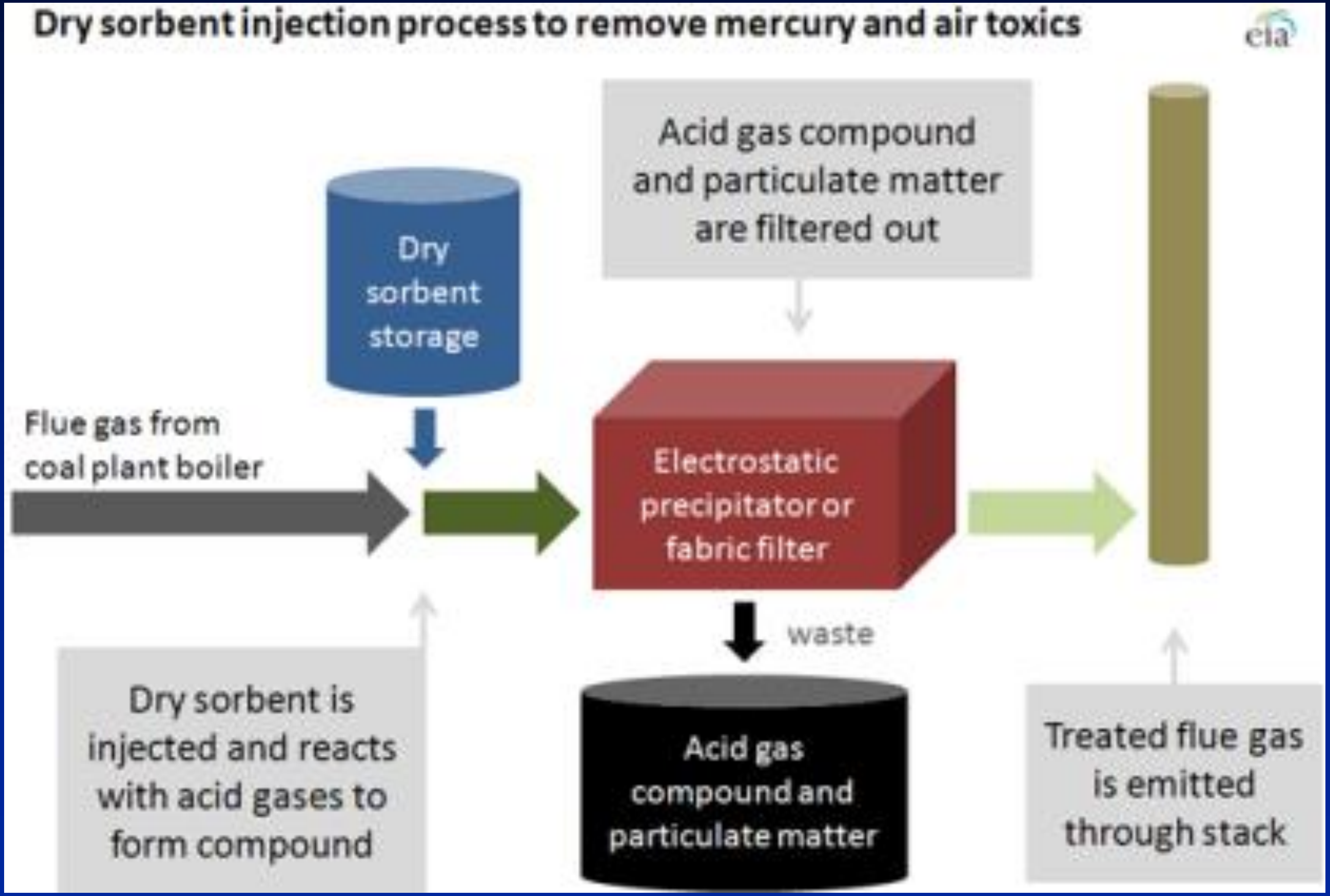
Spray Dryer Absorbers



Dry Sorbent Injection



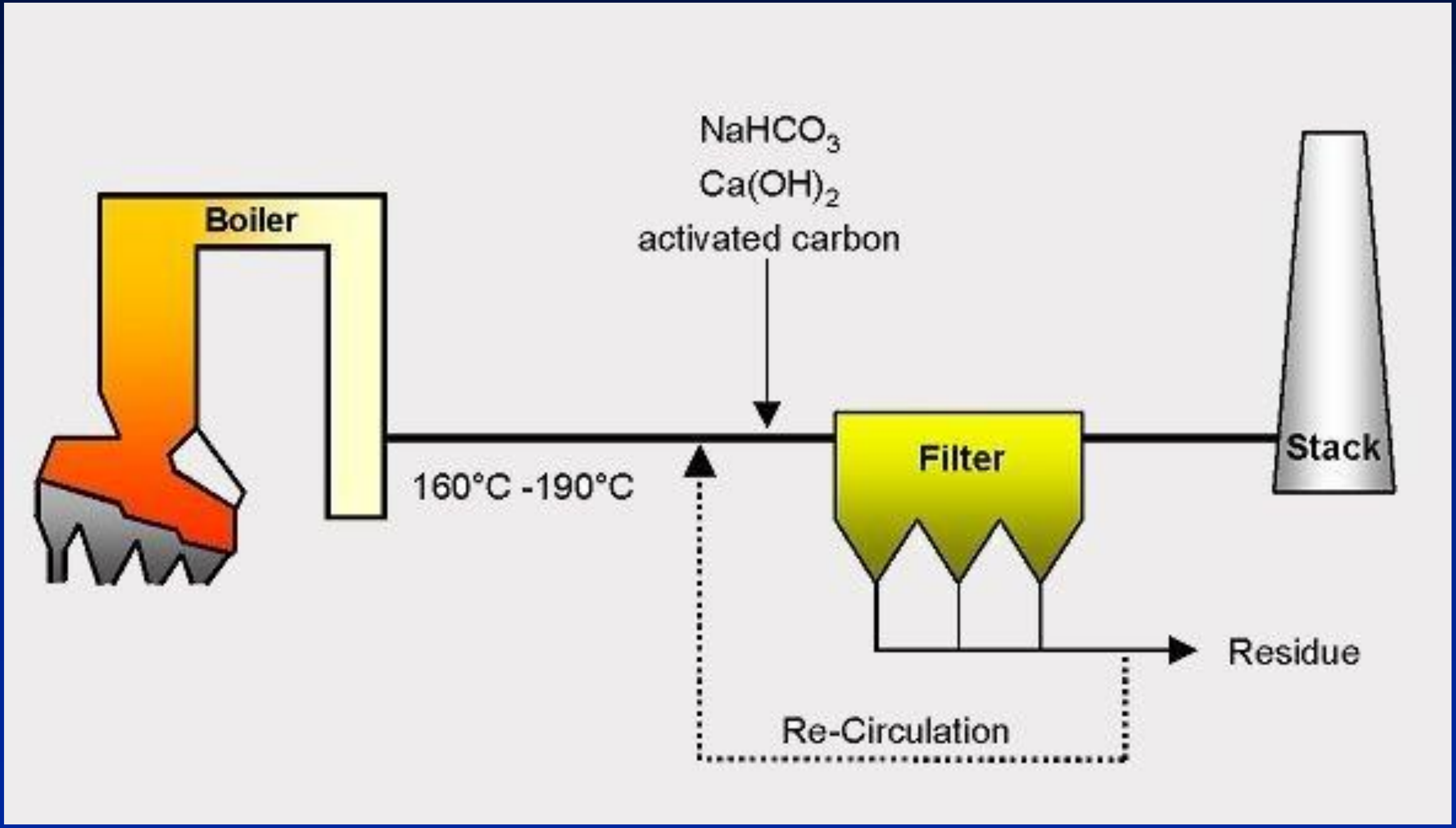
Dry Sorbent Injection



Pensacola's Gulf Power Scrubber

Dry Fork (Wyoming) Station

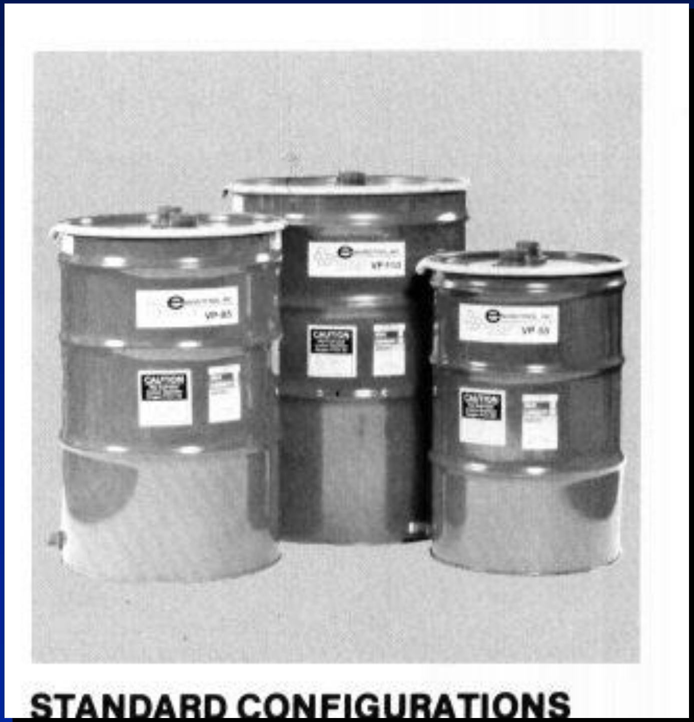
Mercury Control
Activated Carbon Injection

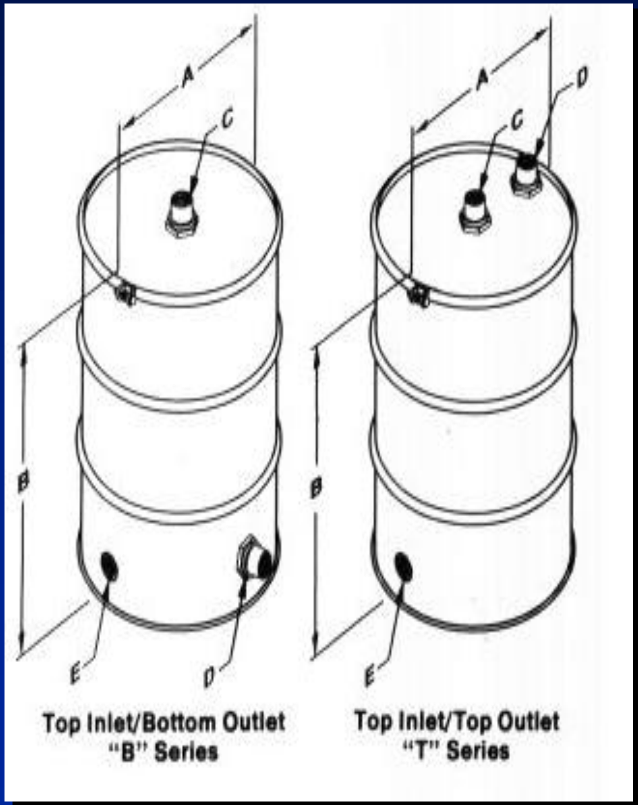


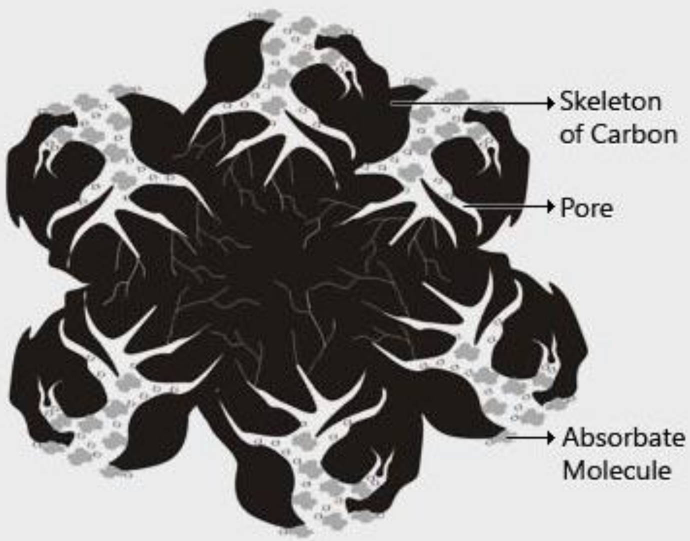

Let's Discuss
Carbon Adsorption
Systems

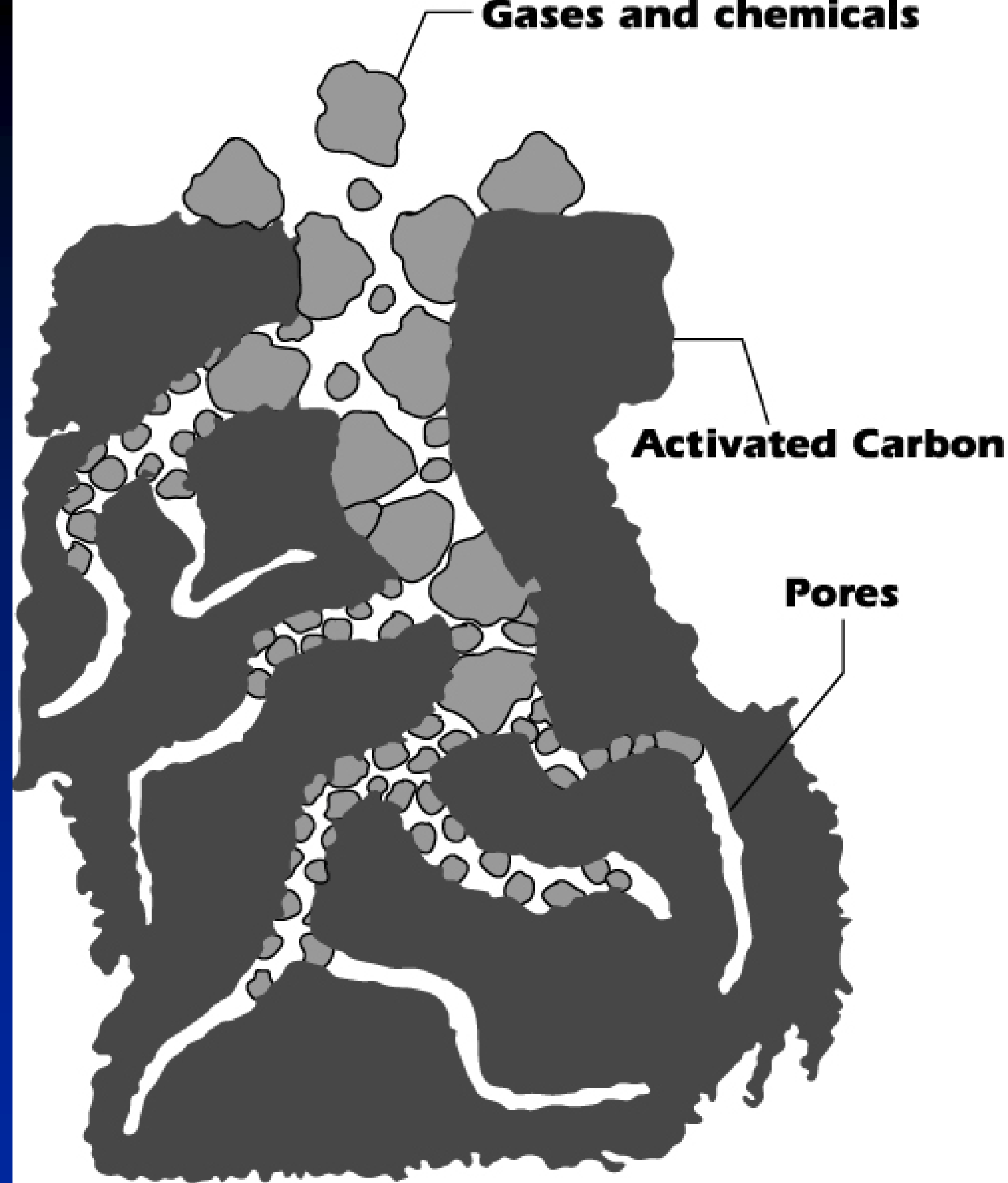
Carbon Adsorber

Carbon Adsorber – Fixed Bed Example









Activated Carbon adsorbs gases and chemicals

Carbon Adsorber

- General description
  - Gas molecules stick to the surface of a solid
  - Activated carbon often used as it
    - Has a strong attraction for organics
    - Has a large capacity for adsorption (many pores)
    - Relatively inexpensive

Carbon Adsorber

- Activated Carbon is typically made of charcoal
  - Wood
  - Coal
  - Nutshells
  - Coconut shells
- Other Common Types of Adsorbers
  - Silica gel
  - Activated alumina
  - Zeolites

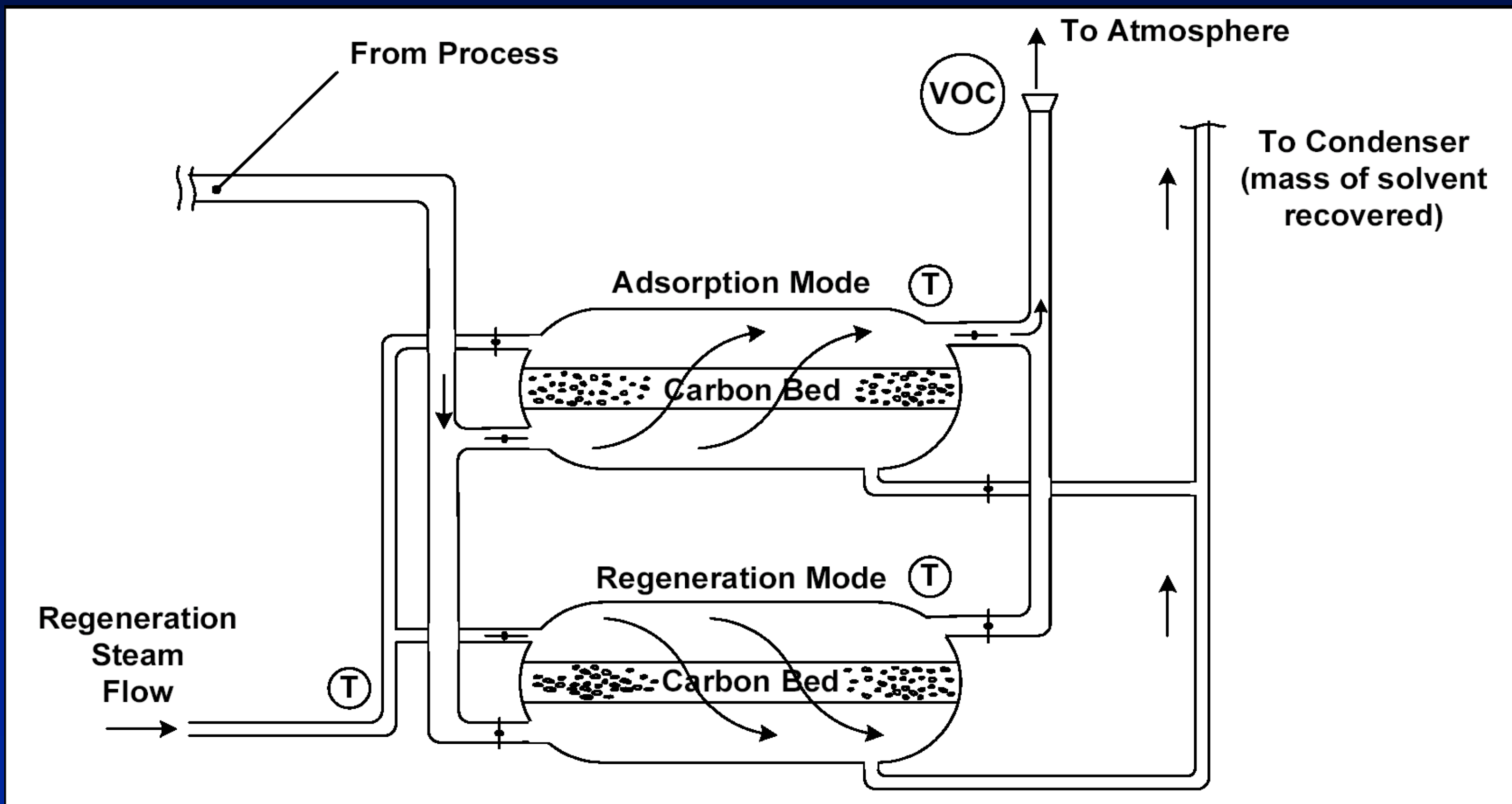
Carbon Adsorber

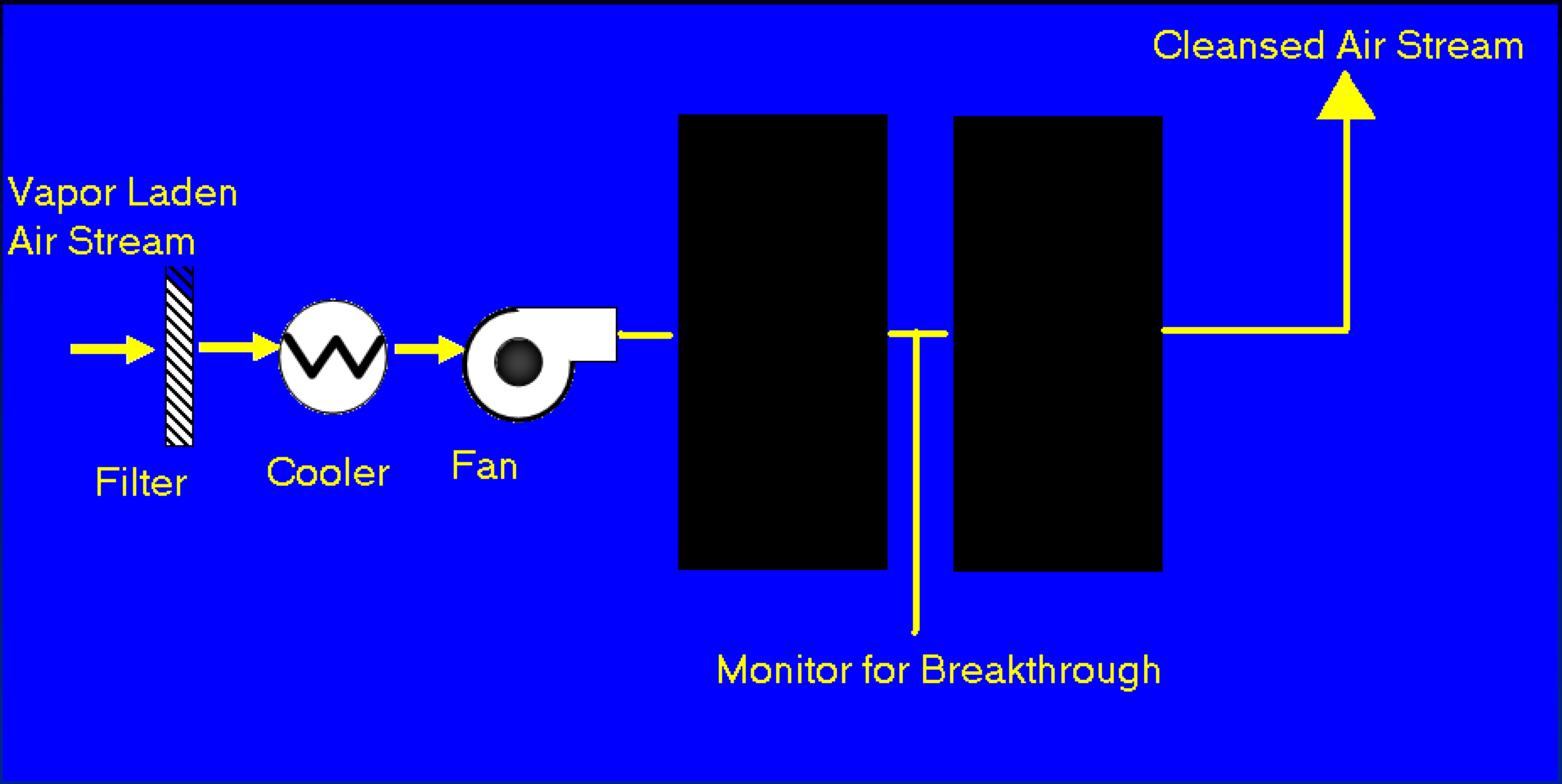
- 3 types – fixed bed (most common), moving bed, and fluidized bed
  - Typically appear in pairs – prevent carbon breakthrough
  - Used for control as well as recovery

Carbon Adsorber

- General description (continued)
  - Regeneration process
    - Steam
    - Hot gas
    - Vacuum
  - Work best if molecular weight of compound between 50 & 200 (depends on source of carbon raw material)

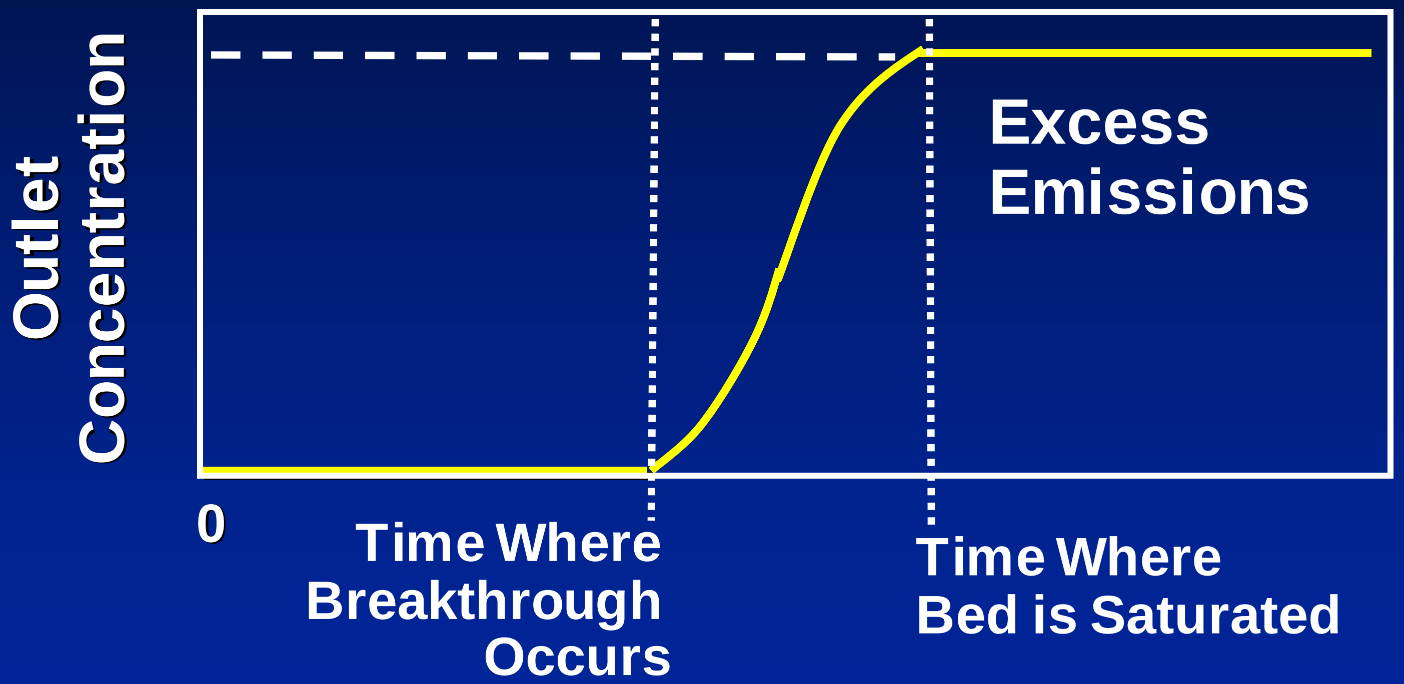
Carbon Adsorber – Fixed Bed Schematic





Carbon Adsorption System

Adsorber Breakthrough



Carbon Adsorber

- Factors affecting efficiency
  - Presence, polarity, and concentration of specific compounds
  - Flow rate & channeling
  - Temperature & fouling
  - Relative humidity

Carbon Adsorber

- Performance indicators
  - Outlet VOC concentration
  - Regeneration cycle timing or bed replacement frequency
  - Total regeneration stream flow or vacuum profile during regeneration cycle
  - Bed operating and regeneration temperature

Carbon Adsorber

- Performance indicators
  - Inlet gas temperature
  - Gas flow rate
  - Inlet VOC concentration
  - Pressure differential
  - Inlet gas moisture content
  - Leaks

Carbon Adsorbers at a Soil Remediation Site

Absorber/Condenser/Adsorber Unit at Marketing Terminal

Monitoring Approach – VOC

Indicator	Vacuum	Carbon bed I/M	LDAR
Approach	Pressure transducer	Daily insp. And annual sample	Monthly leak check w. portable analyzer
Indicator range	<2.5 min @ -27.5" Hg, shutdown	Failure to conduct, corrective action and reporting	> 10K ppm, corrective action and reporting

Monitoring Approach – VOC

Indicator	Vacuum	Carbon bed I/M	LDAR
Measuring location	Pump suction line	Visual, bed sample	Handheld monitor
QA/QC	Annual cal.	Training	Method 21
Frequency	Continuous during cycle	Daily and annual	Monthly

VOC Control via Incineration in Oxidizers

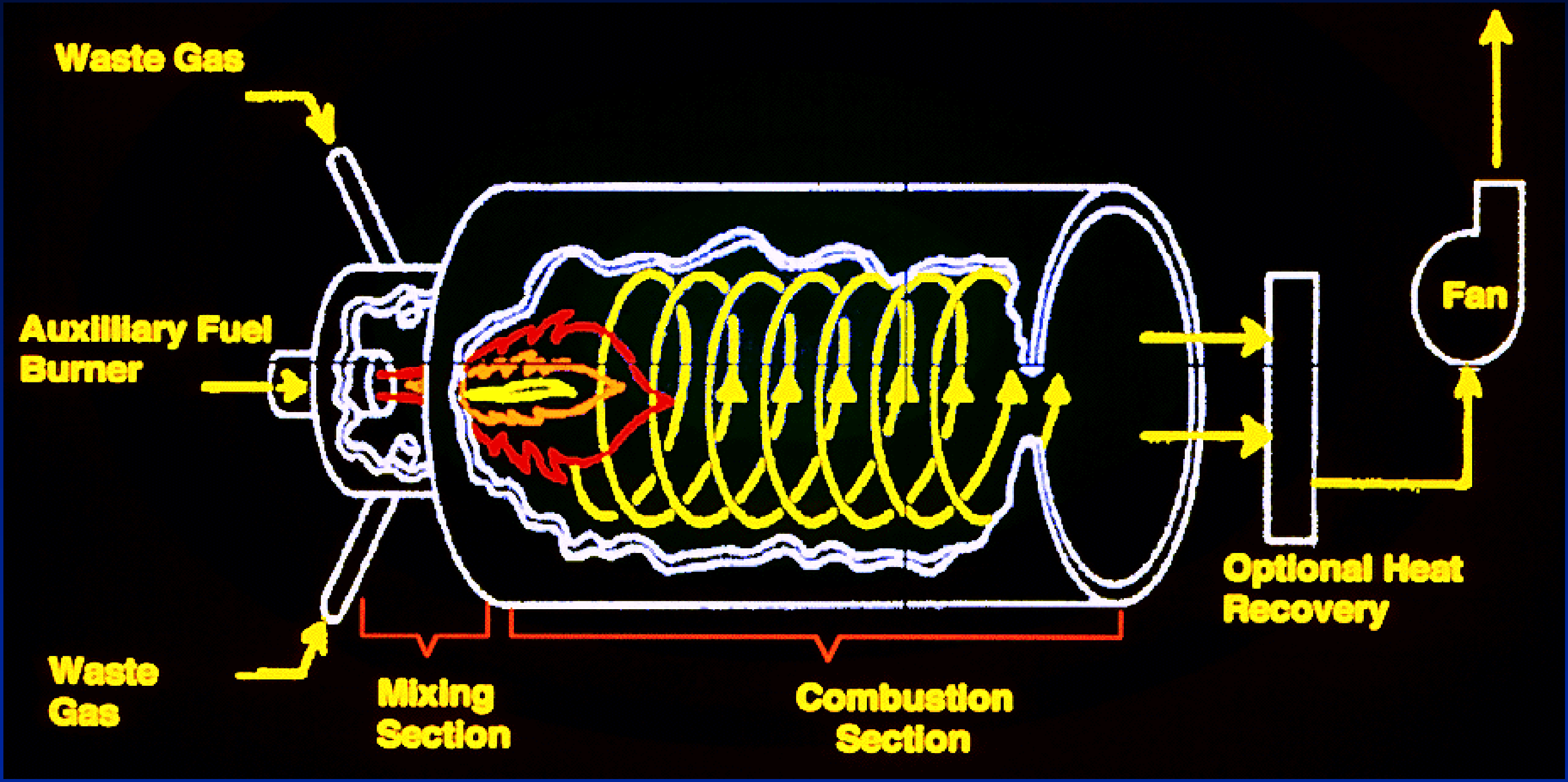
Combustion Considerations

Remember the 3 T's of Combustion

- Residence *T*ime
- *T*emperature
- *T*urbulence (mixing)
- Increase 3T's = more NOx
- Decrease 3T's = more CO and uncontrolled pollutant

Thermal Oxidizer

Thermal Oxidizer/Afterburner



Thermal Oxidizer

- General description
  - VOC gas (& organic HAP) gets oxidized to H_2O and CO_2
  - Higher operating temperatures (~ 1400°F to 1800°F)
  - Typically requires auxiliary fuel (natural gas or propane)

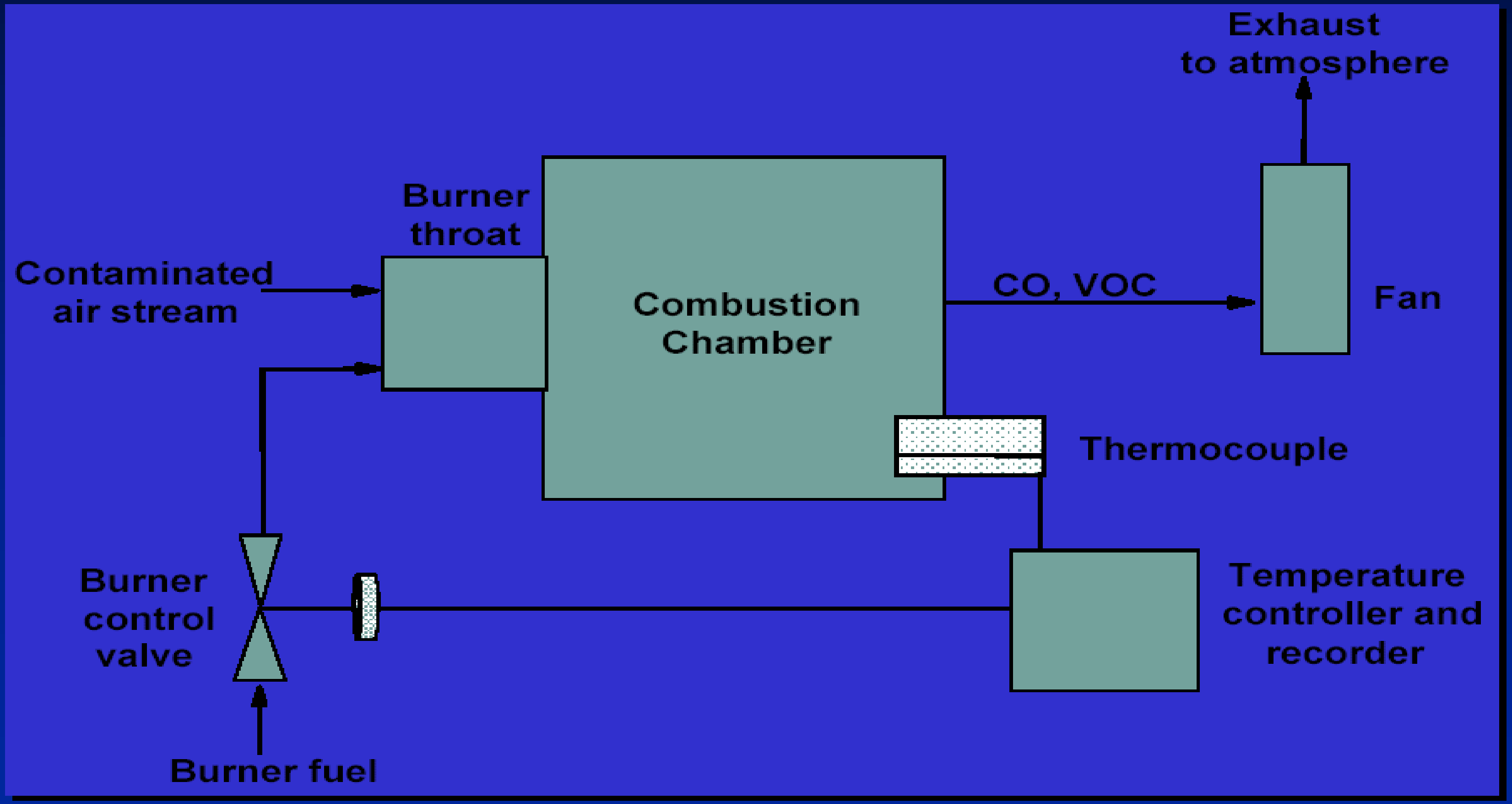
Thermal Oxidizer

- Good combustion requires
  - Adequate temperature
  - Turbulent mixing of waste gas with oxygen
  - Sufficient time for reactions to occur
  - Enough O_2 to completely combust waste gas

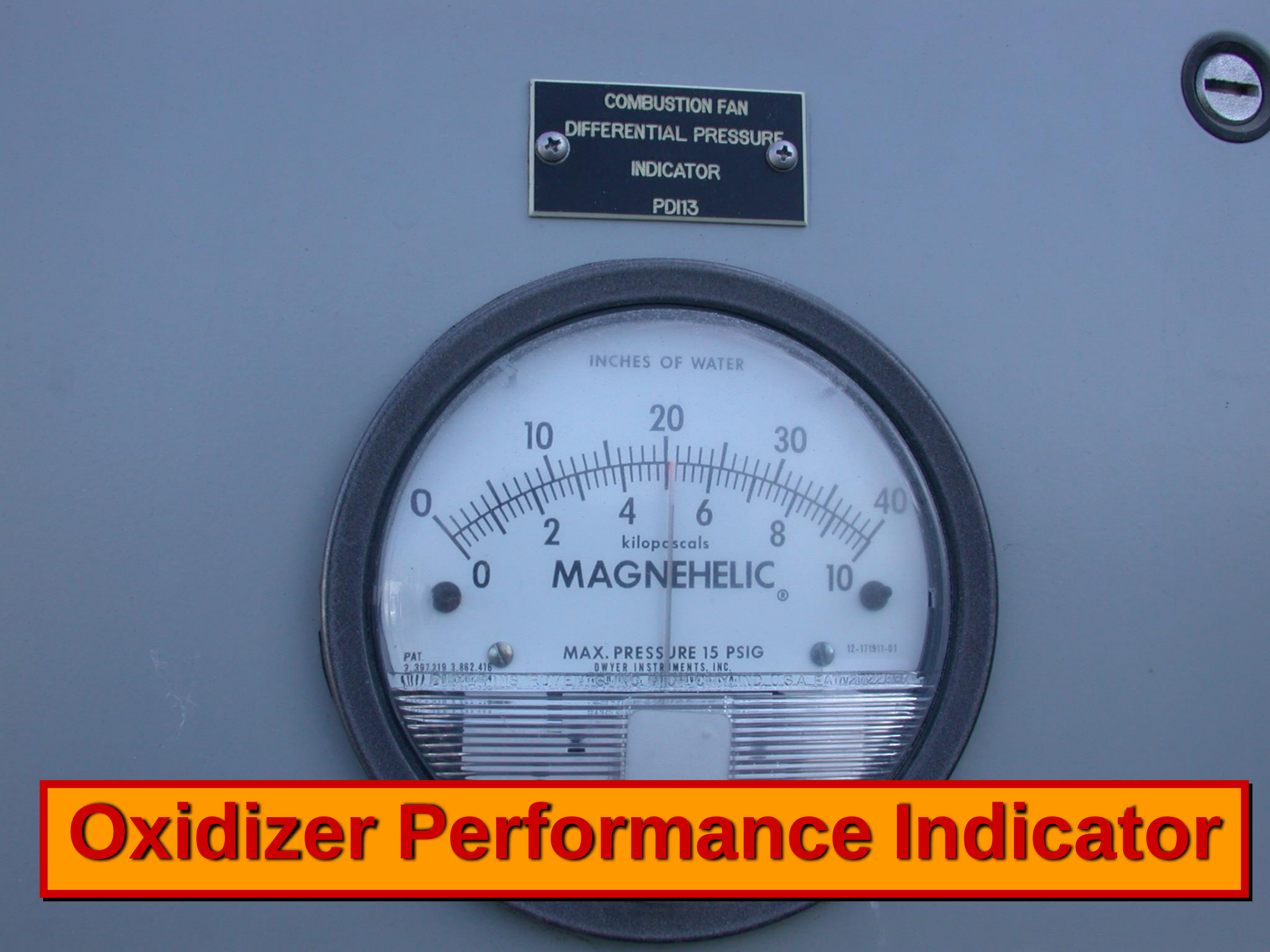
Thermal Oxidizer

- Only temperature and O_2 can be controlled after construction
  - Waste gas has to be heated to autoignition temperature
  - Common design relies on 0.2 to 2 seconds residence time, 2 to 3 length to diameter ratio, and gas velocity of 10 to 50 feet per second

Thermal Oxidizer - Schematic



- **Factors affecting efficiency**
  - **Waste gas flow rate**
  - **Waste gas composition and concentration**
  - **Waste gas temperature**
  - **Amount of excess air**

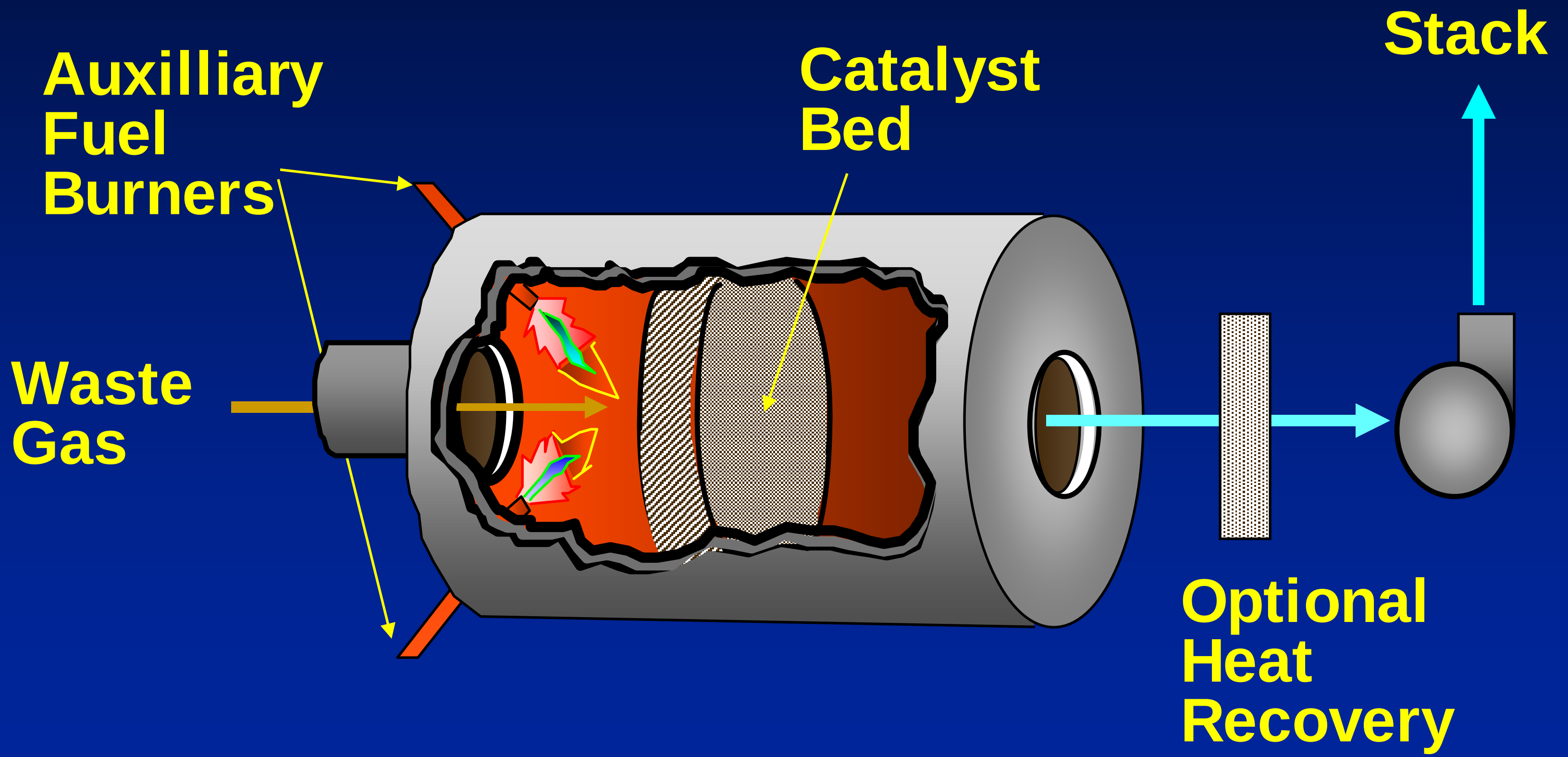


Oxidizer Performance Indicator

Thermal Oxidizer

- Performance indicators
  - Outlet VOC concentration
  - Outlet combustion temperature
  - Outlet CO concentration
  - Exhaust gas flow rate
  - Outlet O_2 concentration
  - Inspections

Catalytic Oxidizer/Incinerator



Catalytic Oxidizer/Incinerator

- General description
  - VOC gas (& organic HAP) gets oxidized to H_2O and CO_2
  - Catalyst causes reaction to occur faster and at lower temperatures
  - Saves auxiliary fuel

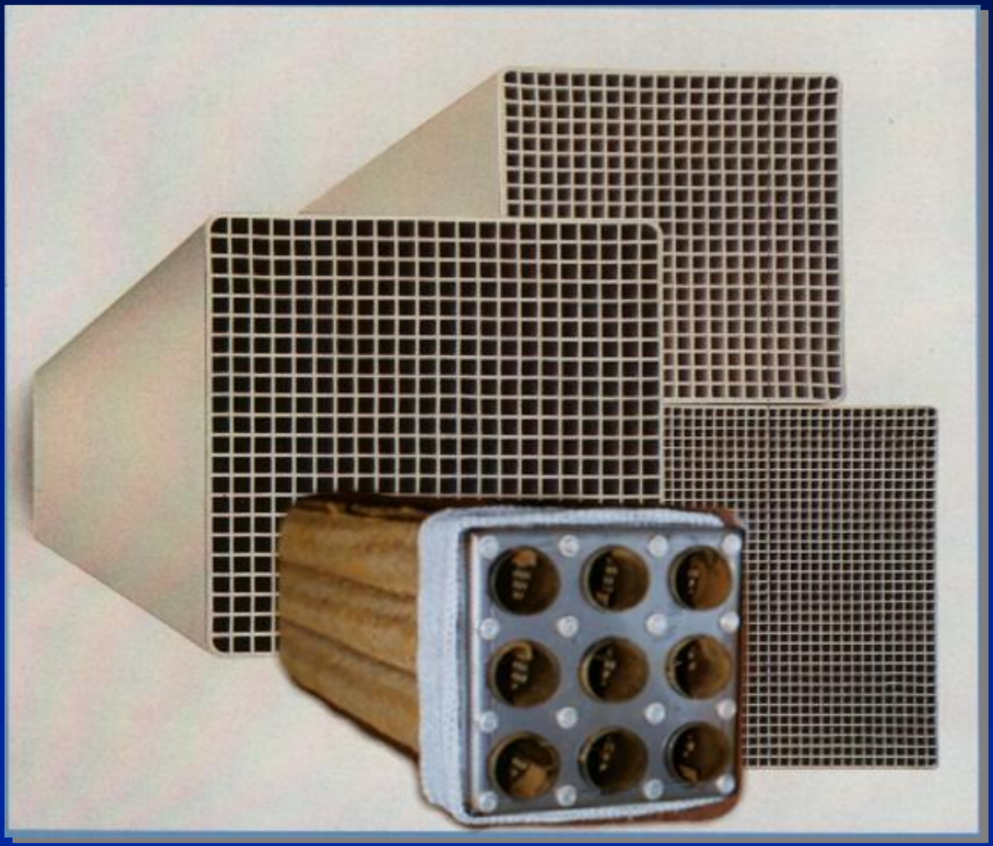
Catalytic Oxidizer/Incinerator

- General description (continued)
  - Catalysts allow lower operation temperatures (~ 600°F to 800°F)
  - Catalyst bed generally lasts from 2 to 5 years
    - Thermal aging, poisoning, and masking are concerns

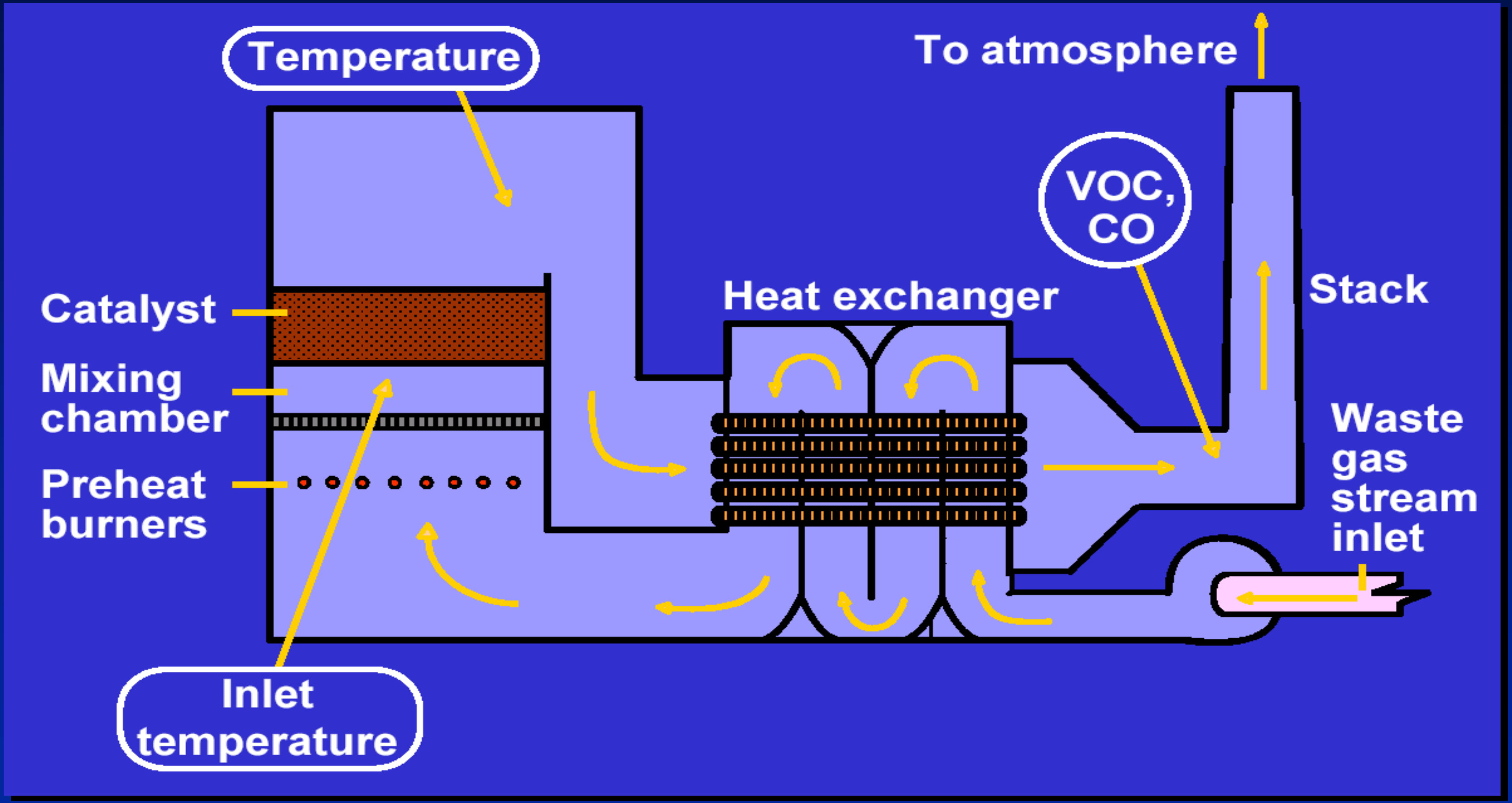
Catalytic Oxidizer/Incinerator

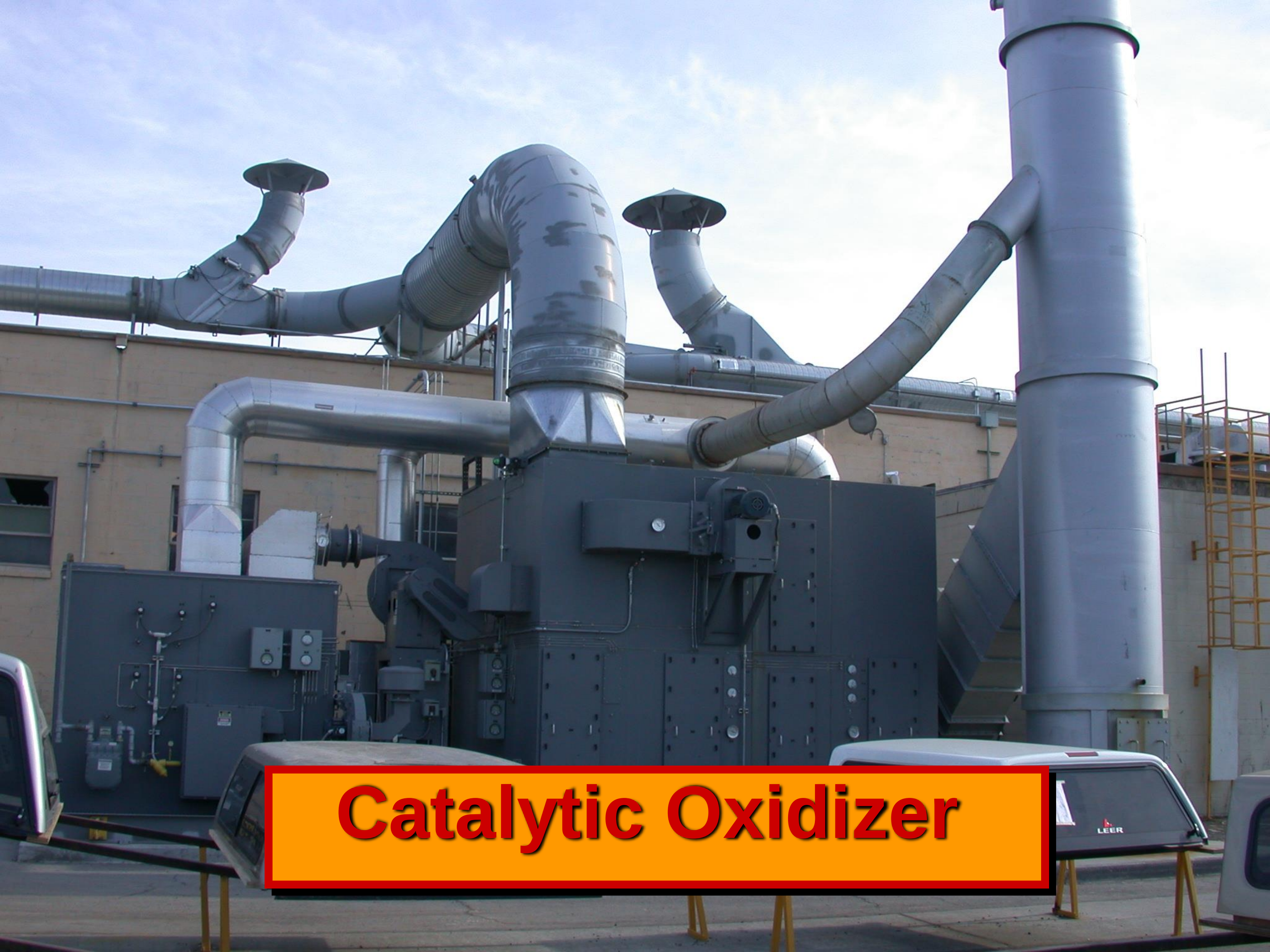
- General description (continued)
  - Excess air is added to assist combustion
    - Residence time and mixing are fixed during design
    - Only temperature and oxygen can be controlled after construction

Catalytic Oxidizer Incinerator Examples



Catalytic Oxidizer Incinerator Schematic





Catalytic Oxidizer

Catalytic Oxidizer/Incinerator

- Factors affecting efficiency
  - Pollutant concentration
  - Flow rate
  - Operating temperature
  - Excess air
  - Waste stream contaminants
    - Metals, sulfur, halogens, plastics

Catalytic Oxidizer/Incinerator

- Performance Indicators
  - Outlet VOC concentration
  - Catalyst bed inlet temperature
  - Catalyst activity
  - Outlet CO concentration
  - Temperature rise across catalyst bed
  - Exhaust gas flow rate

Catalytic Oxidizer/Incinerator

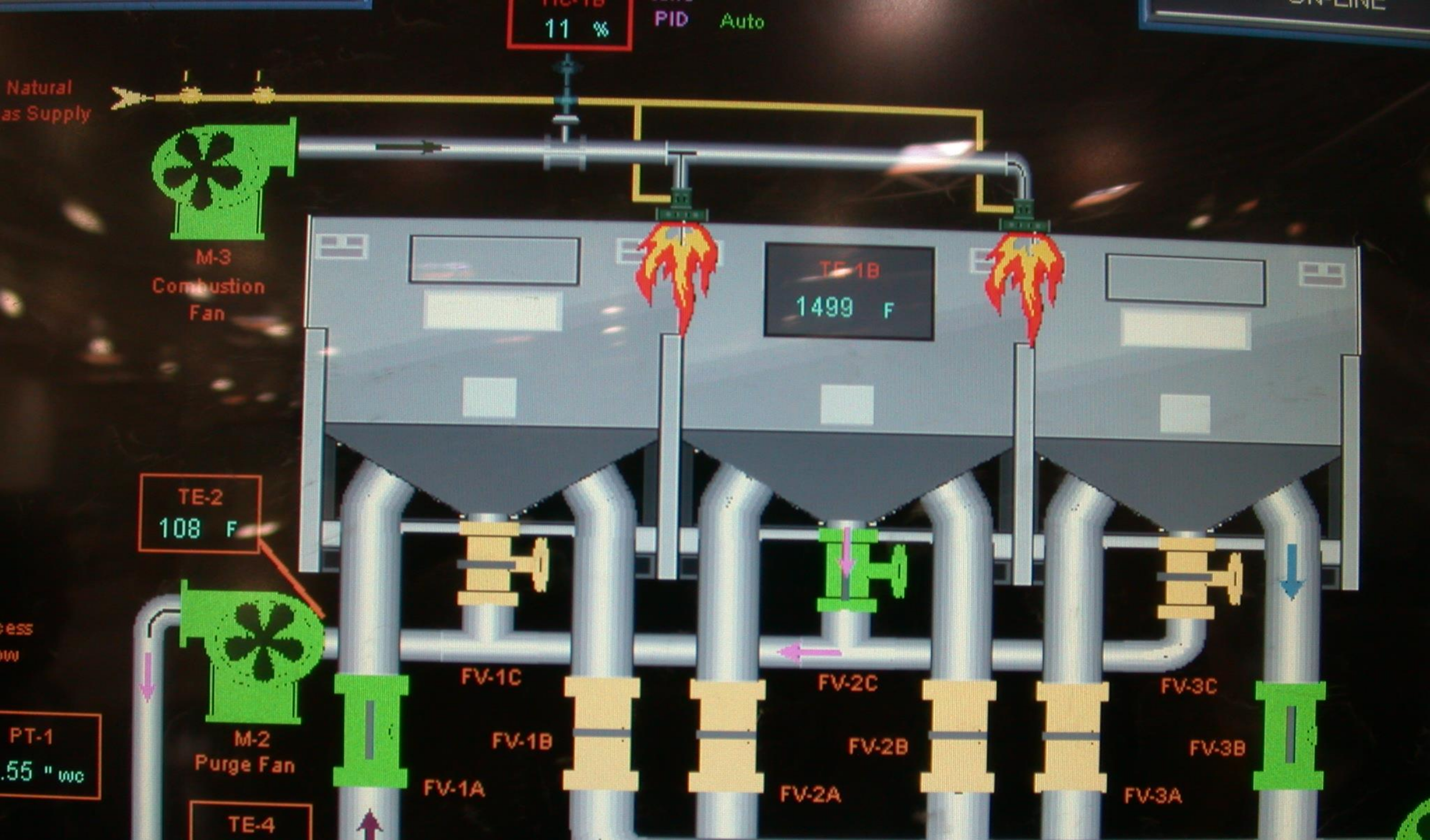
- Performance Indicators (continued)
  - Catalyst bed outlet temperature
  - Fan current
  - Outlet O_2 or CO_2 concentration
  - Pressure differential across catalyst bed

Catalytic Oxidizer – Monitoring Approach

- **Key Factors to Consider When Monitoring a Catalytic Oxidizer:**
  - **Catalyst bed operating temperature (inlet & outlet)**
  - **Catalyst activity (life) (core sampling & testing)**
  - **Periodic Inspection**
  - **Annual performance testing**

Catalytic vs. Thermal for VOC Control

Catalytic	Thermal
Lower Operating Temp. & Lower Fuel Usage	Higher Operating Temp. & Higher Fuel Usage
Higher Capital & Maintenance Costs	Lower Capital & Maintenance Costs
Catalyst Fouling & Poisoning	No Catalyst Involved Here



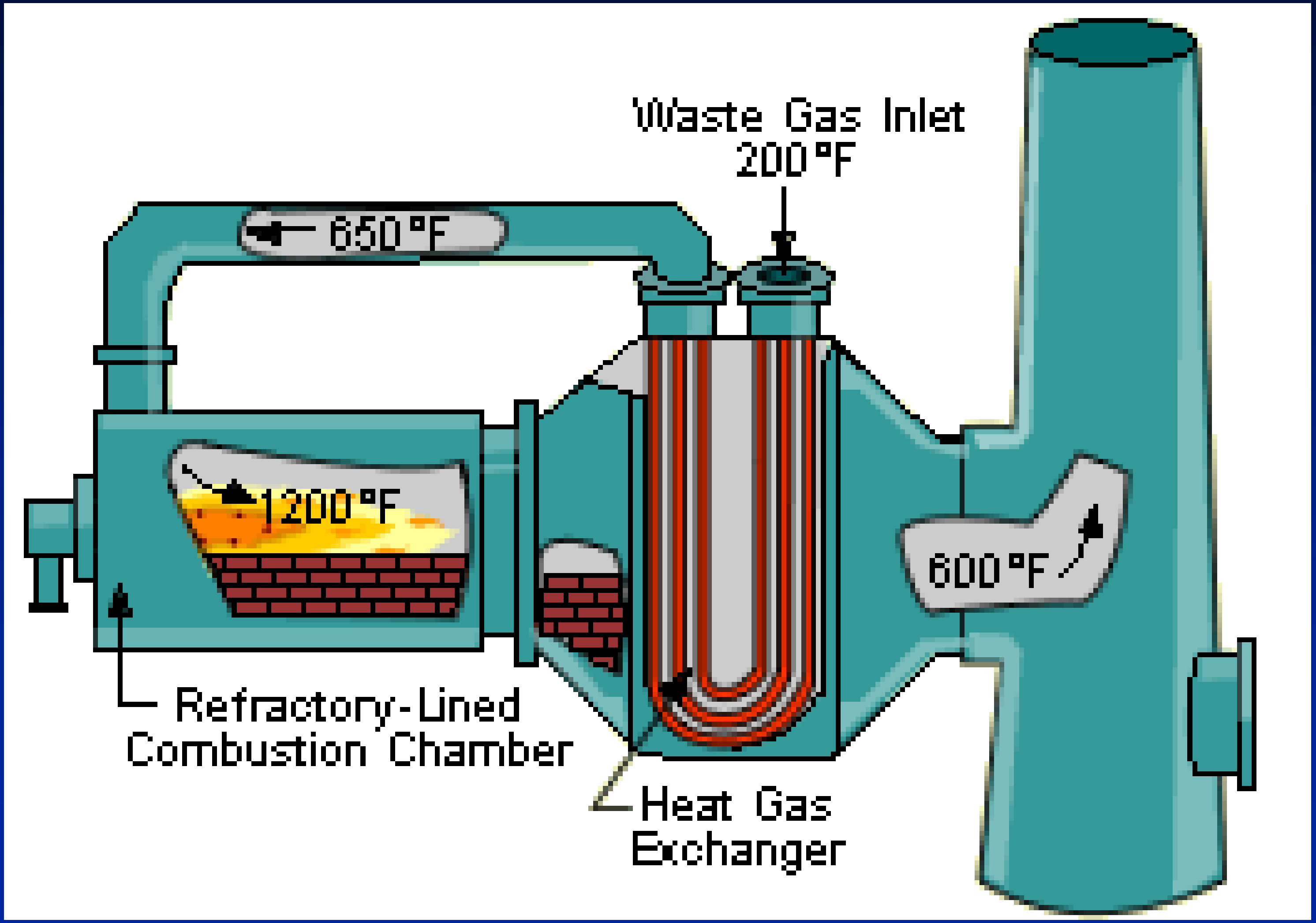
Heat Exchangers (Thermal and Catalytic Oxidizers)

Thermal & Catalytic Oxidizer Heat Exchangers

There are two basic types of heat exchangers used for thermal or catalytic oxidizers

- Metal Heat Exchangers or "recuperative heat exchangers"
- Ceramic Bed Heat Exchangers or "regenerative heat exchangers"

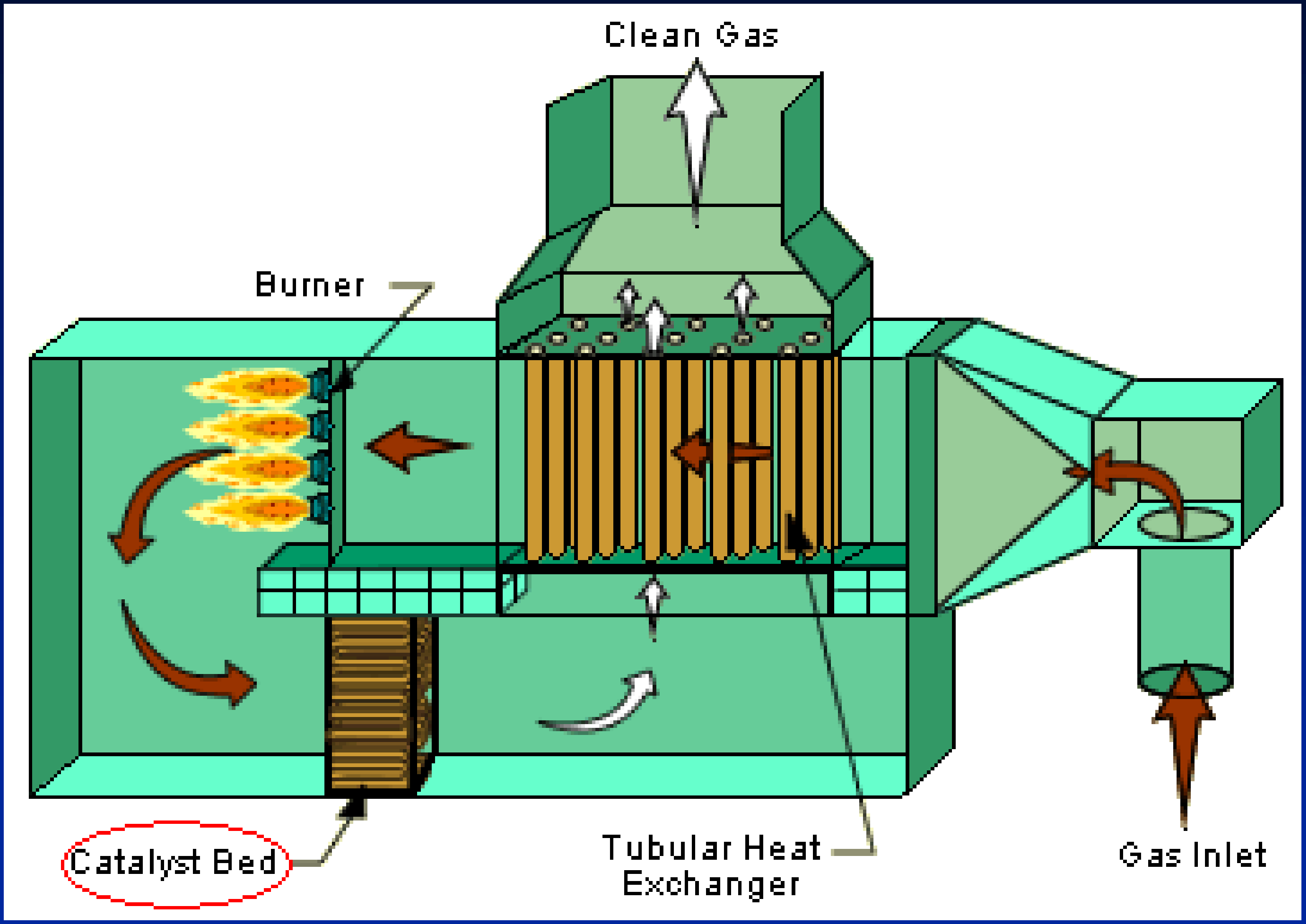
Recuperative TO



TO with Recuperative Heat Exchangers

- Thermal efficiency range of 30% to 70%
- Shell & tube or plate-type
- Usually constructed of alloy steel
- Welded systems have very low leakage rates when new
- Susceptible to cross-leakage as heat exchanger ages
- Not typically used with acid gases
- Susceptible to thermal shock on startup and shutdown

Catalytic Recuperative

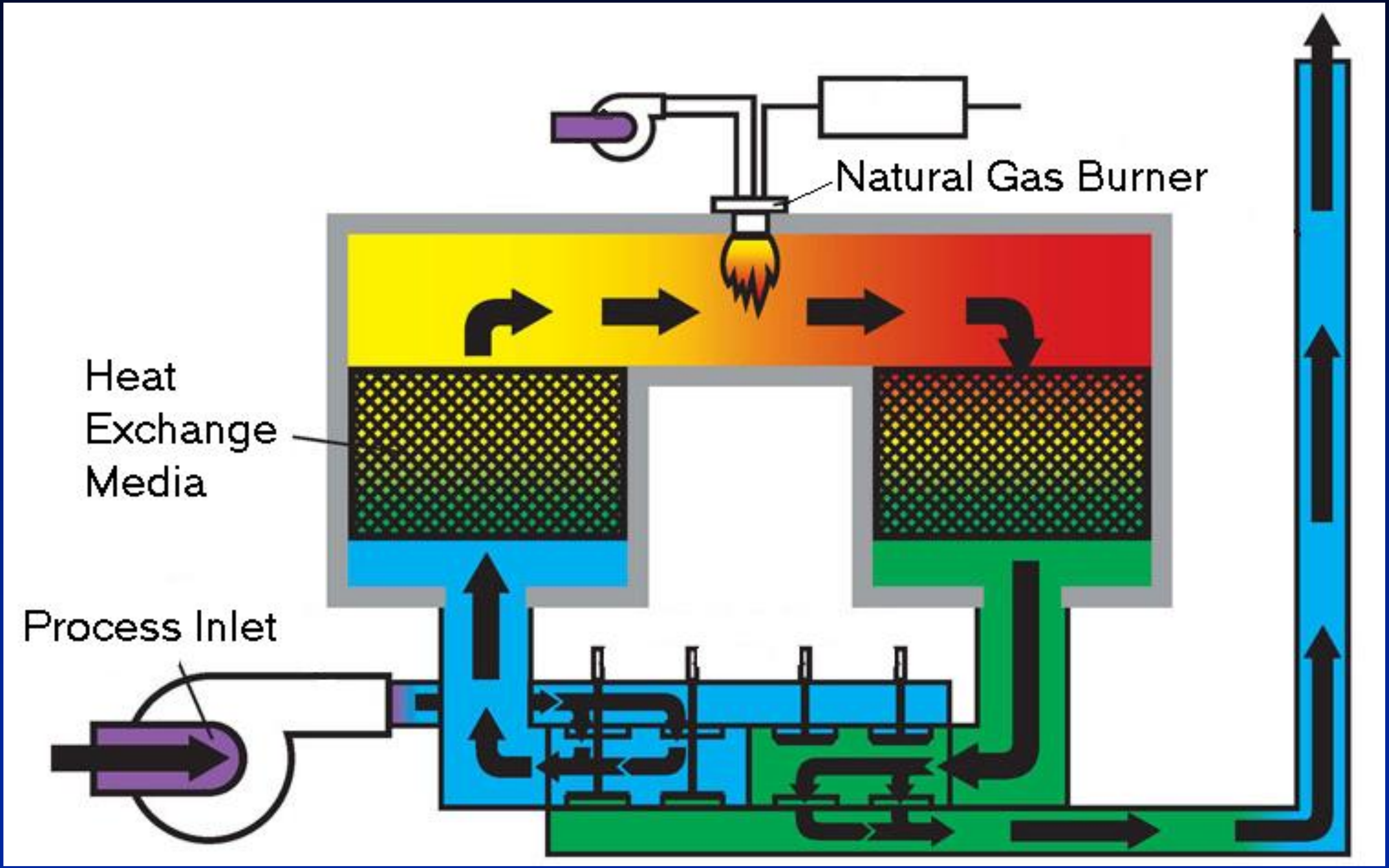


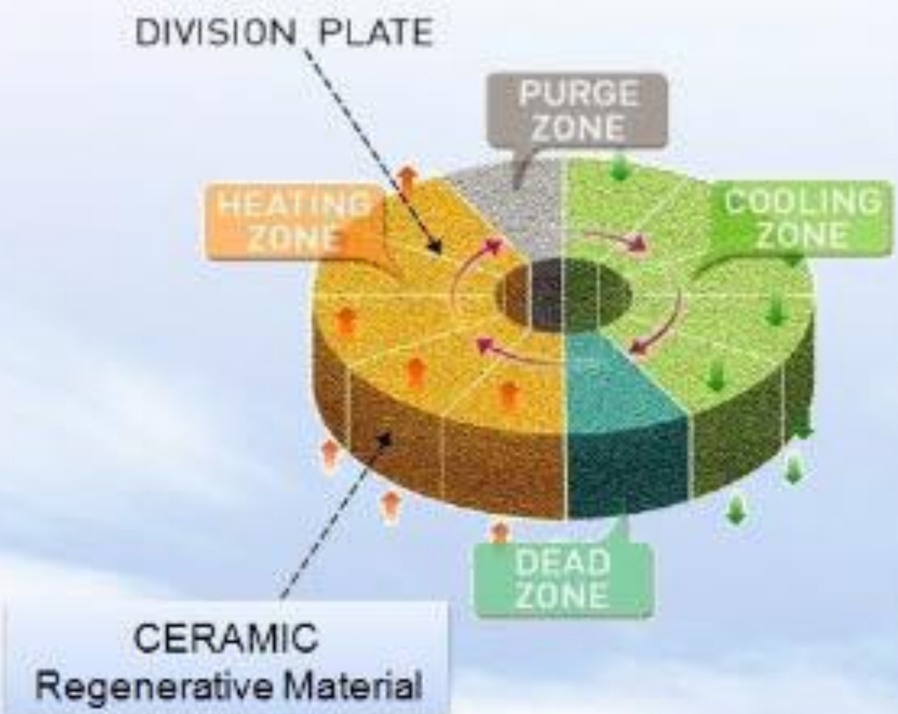
Recuperative TO – Monitoring Approach

- **Key Factors to Consider When Monitoring a Recuperative TO:**
  - **Annual inspection and/or testing of heat exchanger to assess leakage per manufacturer's recommendations.**

Regenerative Thermal Oxidizers

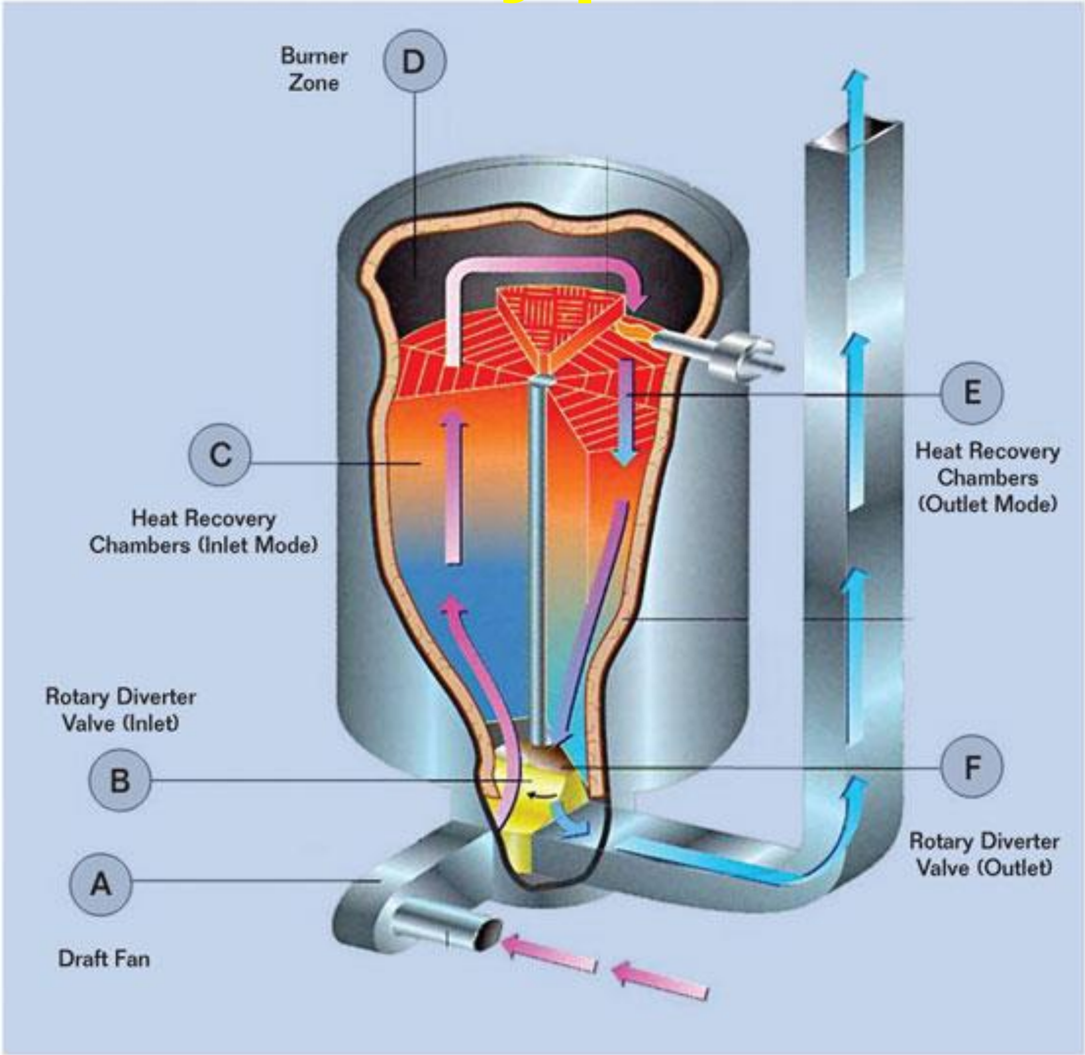
Regenerative TO





ONE CAN TYPE RTO

Can Type RTO

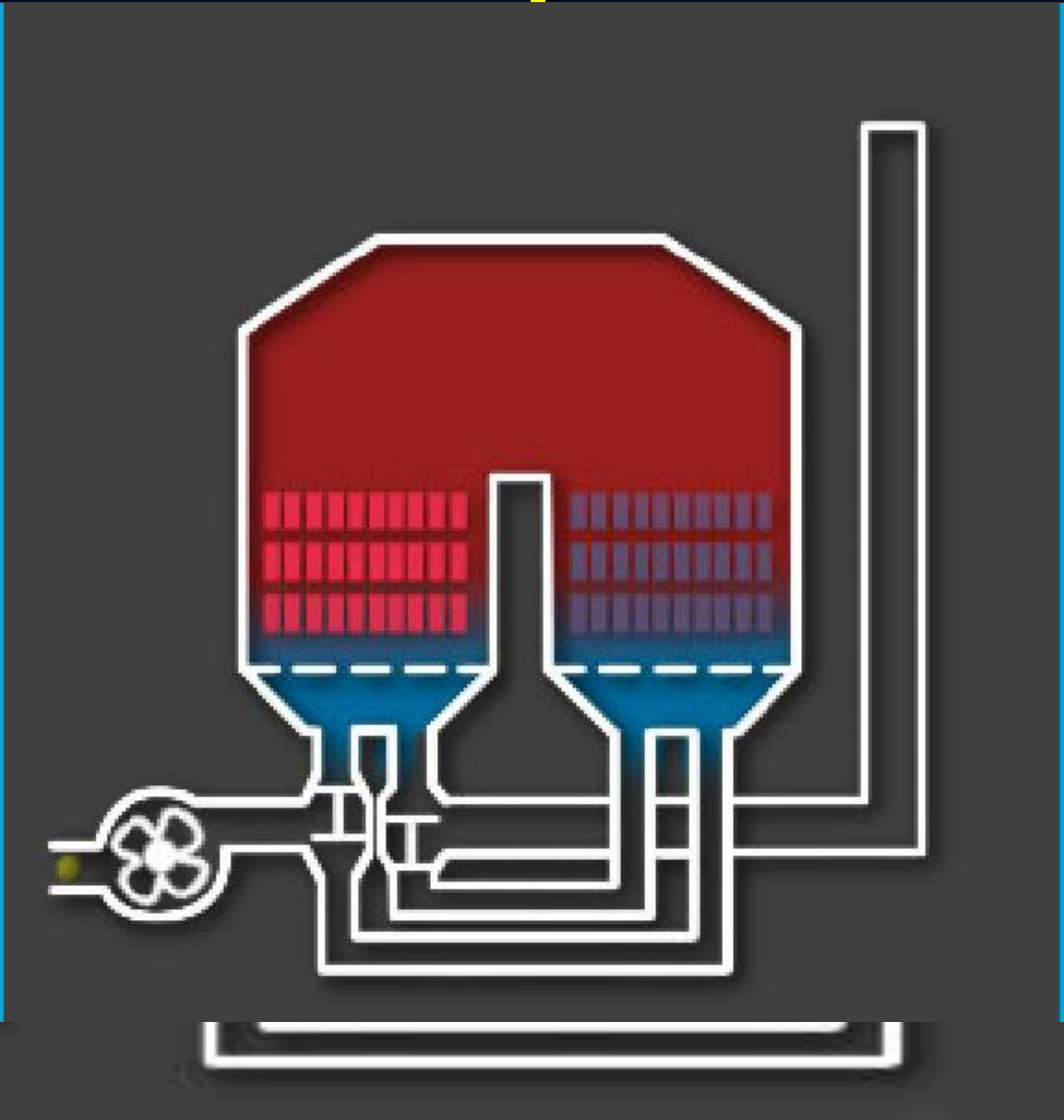


In the regenerative thermal oxidizer, the single rotary valve indexes across an open air path and methodically seals it off by reaching the next set position. A continuous air purge captures any scavenging dirty air in the switch and returns it for treatment in the oxidizer.

Regenerative Thermal Oxidizer (RTO)

- Thermal efficiency range of 80% to 95%
- Can be random packing or structured
- Extremely tolerant of very high temperatures
- Highly resistant to thermal shock
- Can resist corrosion by many acid gases
- May be susceptible to fouling or plugging
- Subject to cross-leakage because of geometry
- May be used with catalysts (RCOs)

RTO Operation



Regenerative Thermal Oxidizer Monitoring Approach

- **Key Factors to Consider When Monitoring a Regenerative TO:**
  - **Assessment of proper closure of valves: Annual inspection/testing**
  - **Annual documentation of valve timing control system parameters**

Heat Exchange Problems

- Any cracks or leaks in a recuperative HX will bleed emissions into the clean side
- Uncoordinated valves in a regenerative HX will transfer emissions into the clean air.
- A regenerative HX usually burps some emissions into the clean air each time the valves switch the flow.

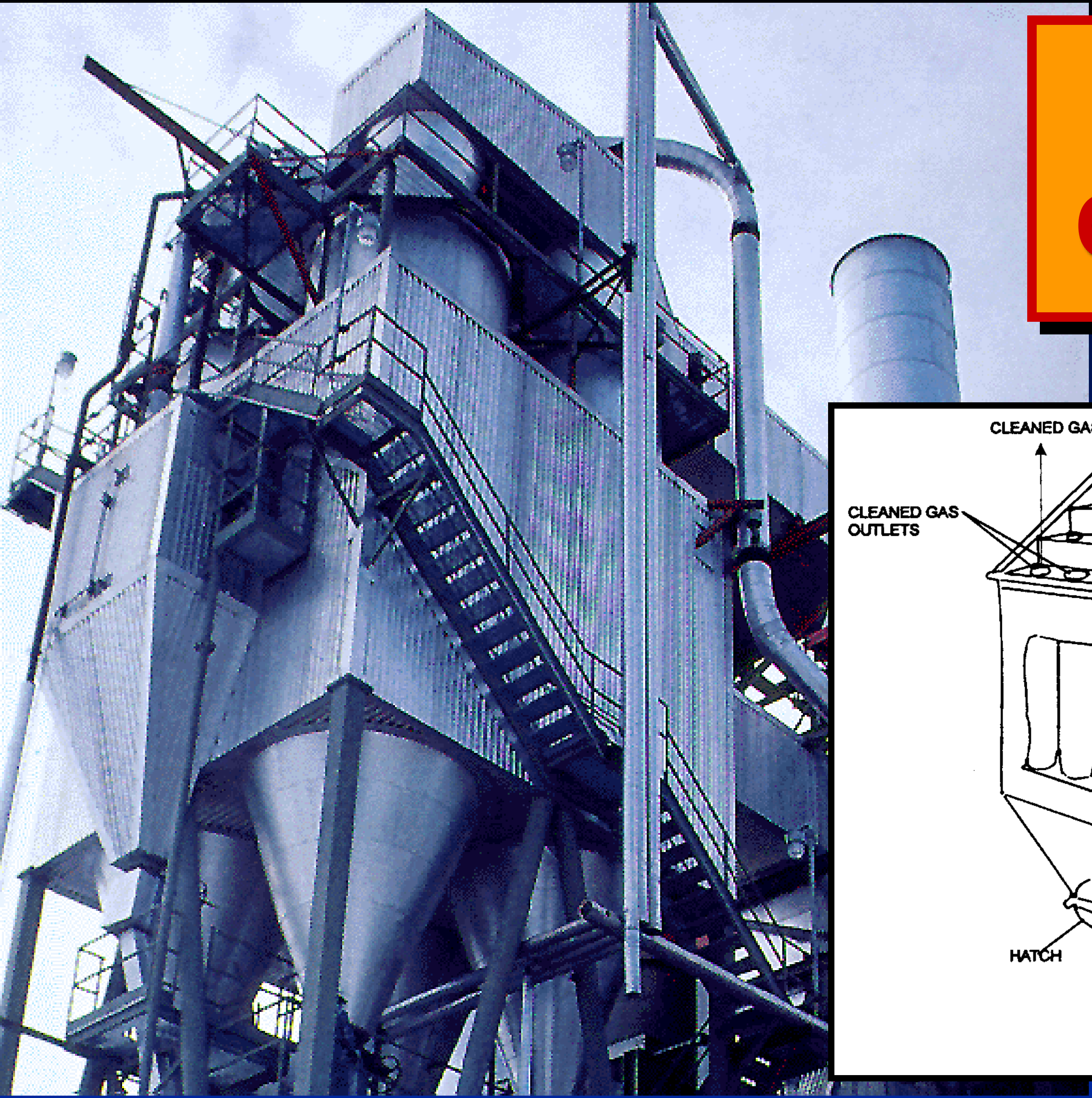
Compliance Issues?

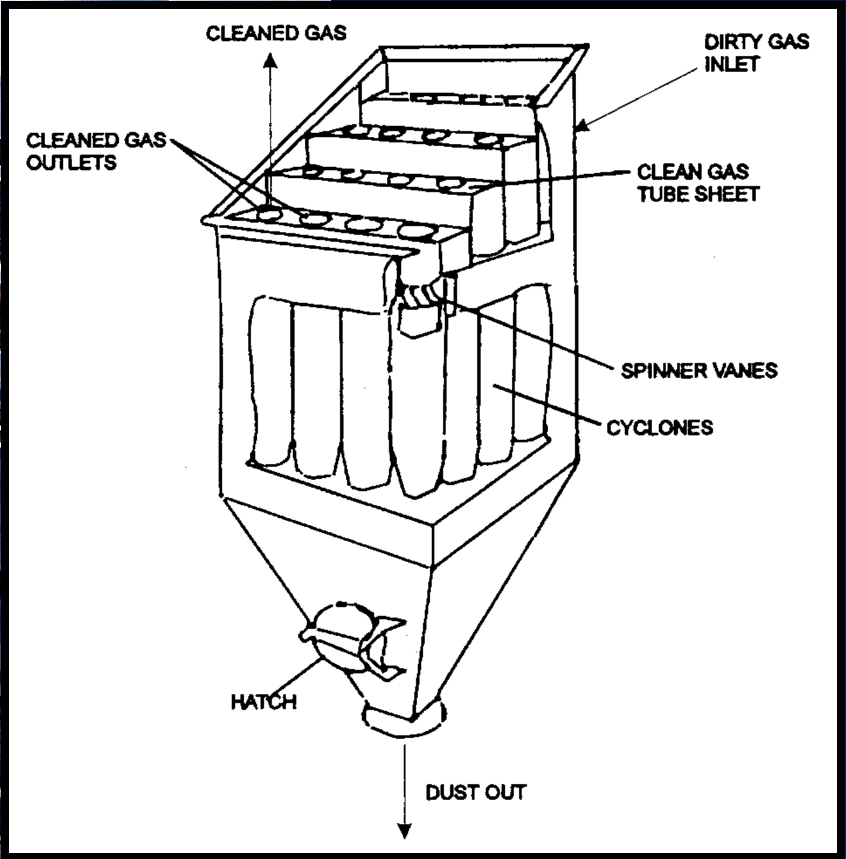
Let's Discuss PM Control

- Cyclones
- Baghouses
- ESPs
- Scrubbers
- Particulate Filters

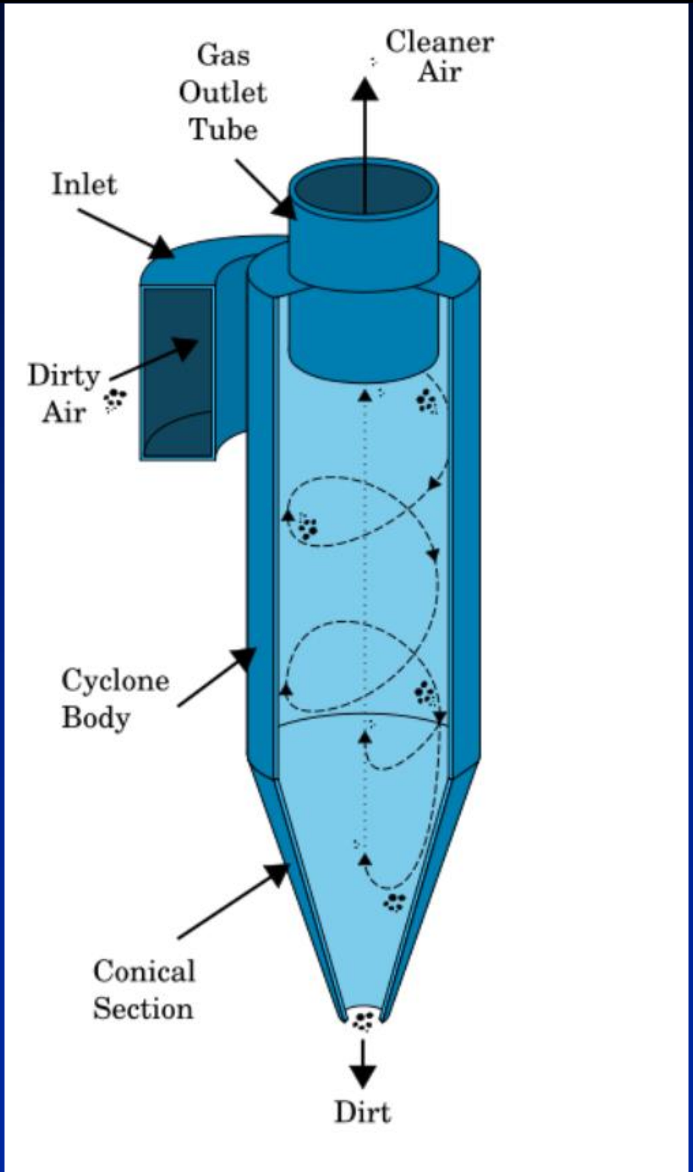
Cyclones

Multi-Cyclone





PM Control Techniques - Cyclone



How a Cyclone Works

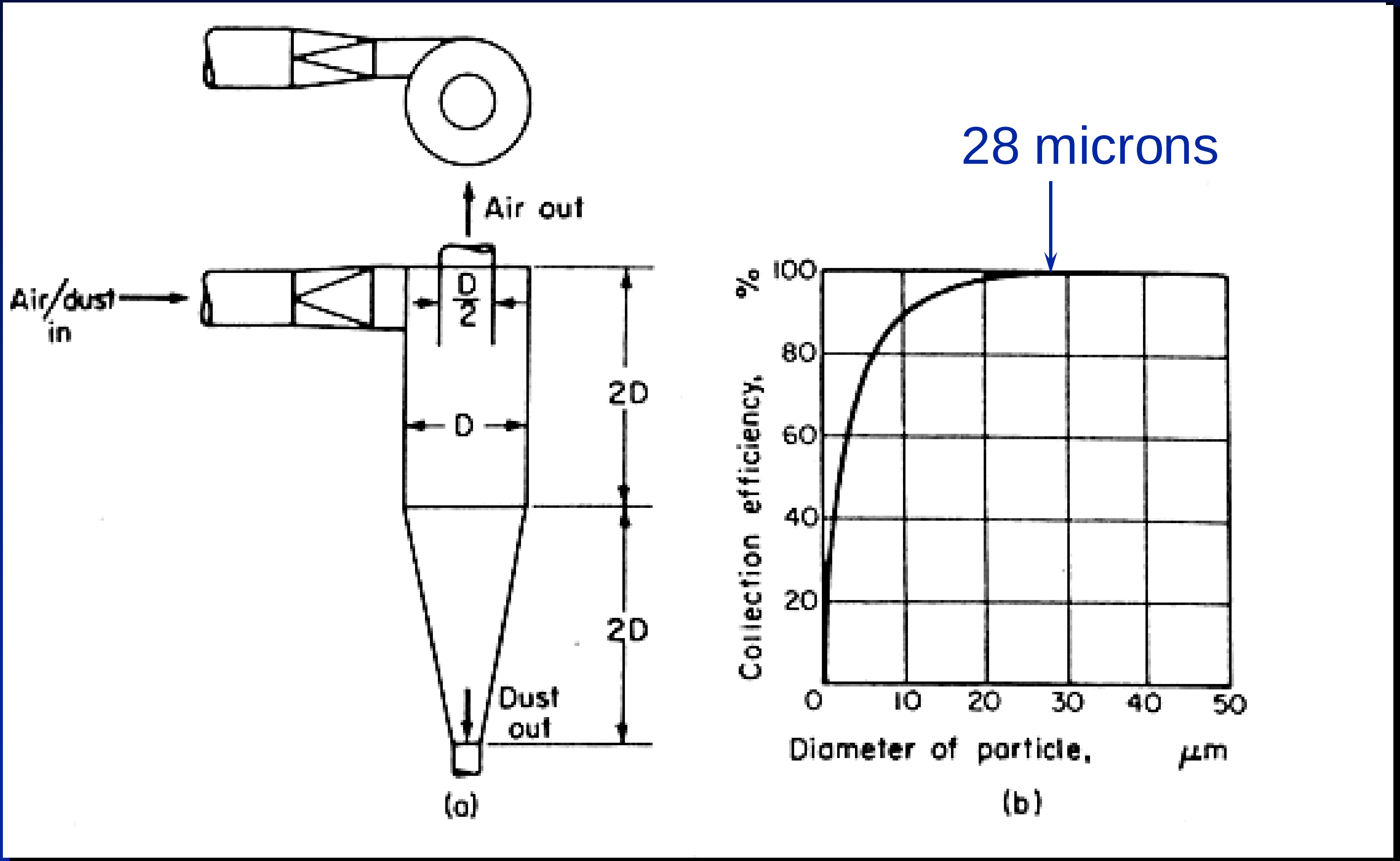
PM Control Techniques - Cyclone

- General description
  - Particles hit wall sides and fall out
  - Often used as precleaners
    - Especially effective for particles larger than 20 microns
  - Inexpensive to build and operate
  - Can be combined in series or parallel

Cyclone - Classification

1D-2D vs.
1D-3D

Cyclone – Control Efficency



Cyclone – Control Efficency

- Conventional Cyclones
  - 30-90% for PM_{10}
  - 0-40% for $PM_{2.5}$
- High Efficiency Single Cyclones
  - 60-95% for PM_{10}
  - 20-70% for $PM_{2.5}$
- Multi-Cyclones
  - 80-95% for PM_5

Cyclone – Failure Modes

- Failure Modes
  - Inlet and outlet plugging
  - Air leakage
    - Component erosion
    - Acid gas corrosion

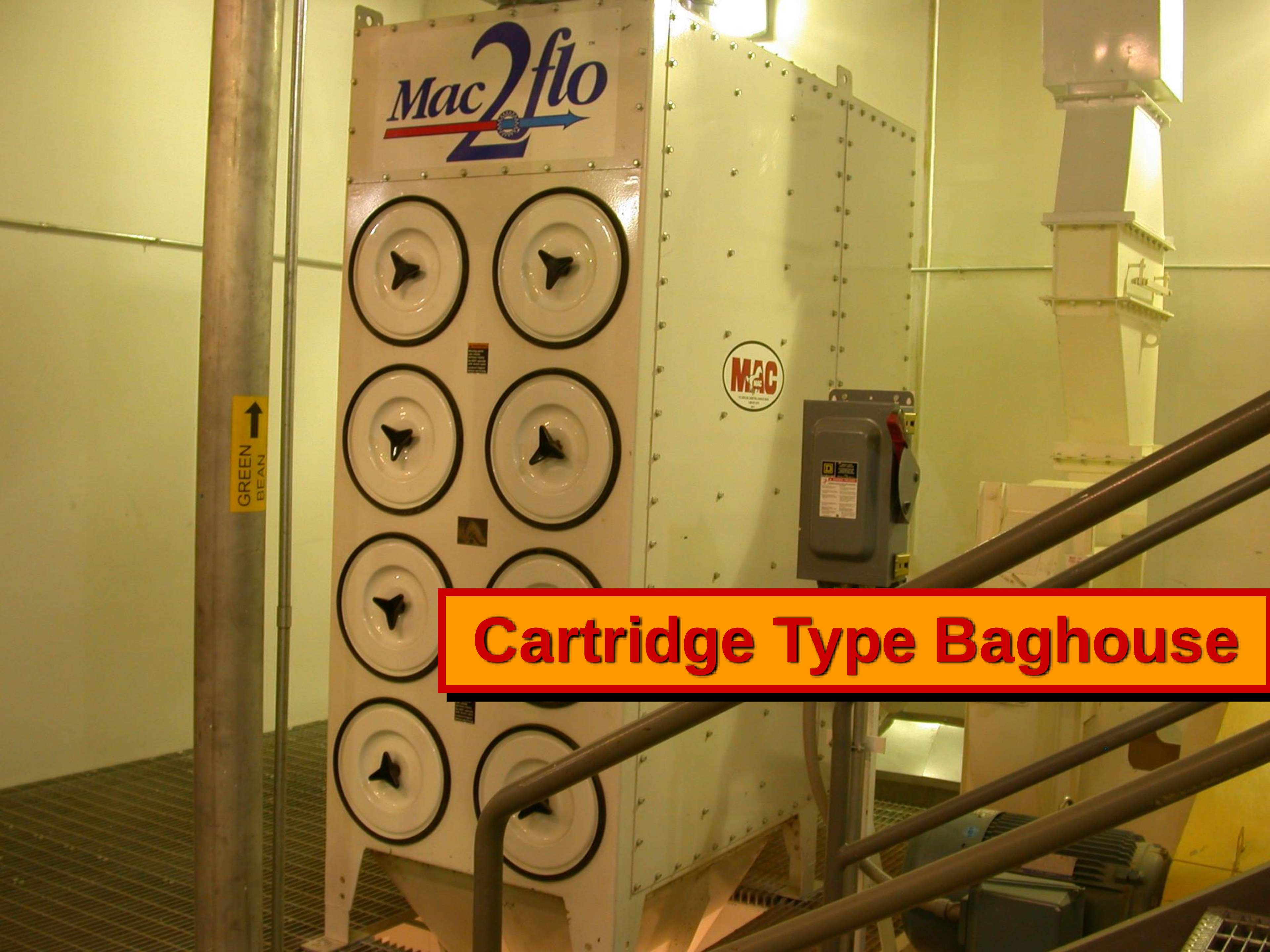
PM Control Techniques - Cyclone

- Performance indicators
  - Opacity (VEE)
  - Pressure differential

PM Control Techniques - Baghouses

Fabric Bag Baghouses

Cartridge Type Baghouse



PM Control Techniques – Baghouse

- General description
  - Generic name - dust collectors
  - Particles trapped on filter media, then removed
  - Either interior or exterior filtration systems
  - Forced Draft or Induced Draft fan
  - Require a cleaning mechanism

PM Control Techniques – Baghouse

Forced Draft vs. Induced Draft		
Fan Type	Pros	Cons
Forced	• Smaller motor • Less expensive • Easy to identify leaks	• Fan Blade Erosion
Induced	• Fan on clean side • Particulate Contained	• Larger motor • More expensive • Harder to indentify leaks

PM Control Techniques – Baghouse

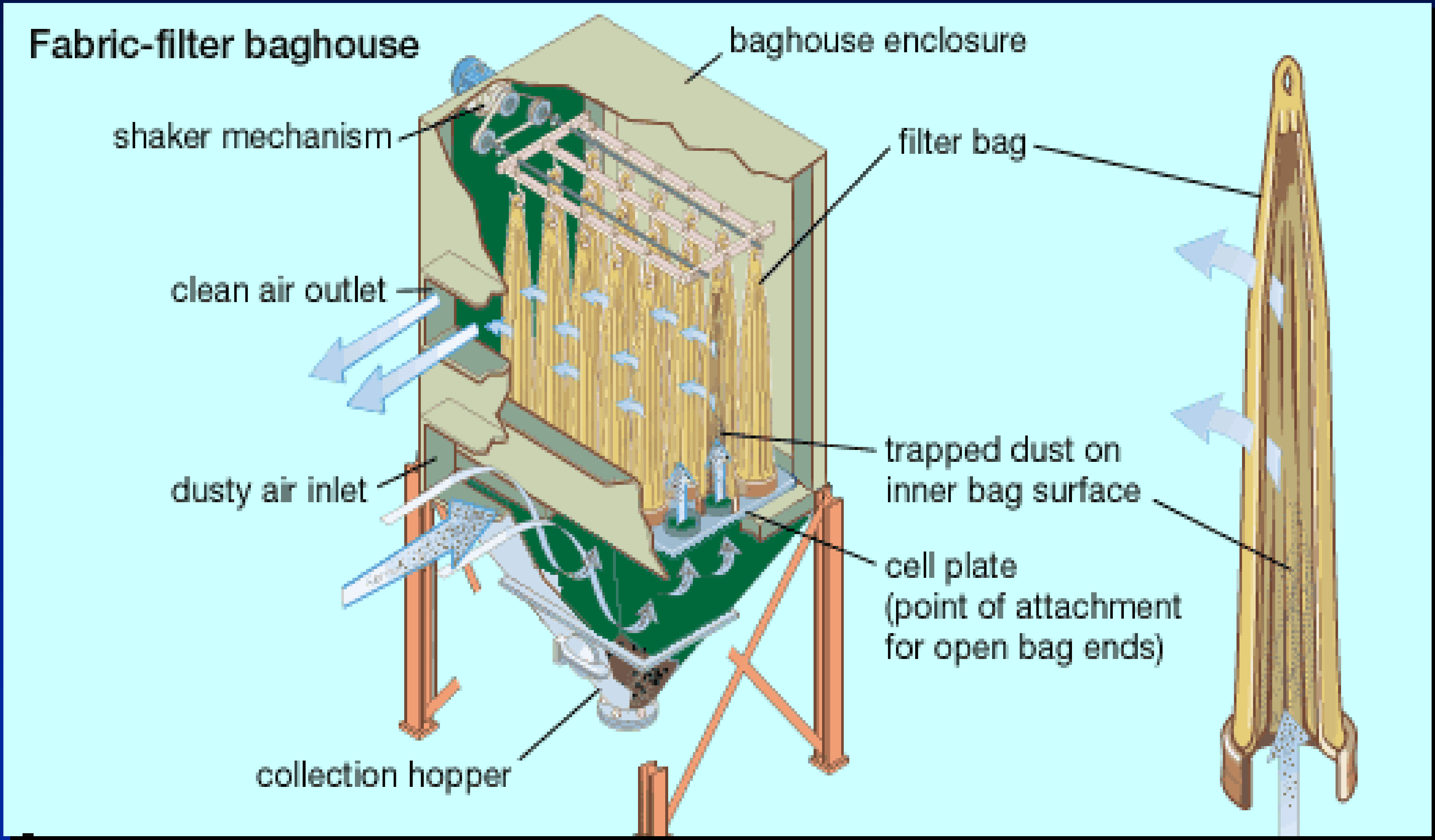
- Cleaning Mechanisms

  4 Types

  - Mechanical Shaker (off-line)
  - Reverse air (low pressure, long time, off line)
  - Pulse jet (60 to 120 psi air, on line)
  - Sonic horn (150 to 550 Hz @ 120 to 140 dB, on line) – rarely used alone

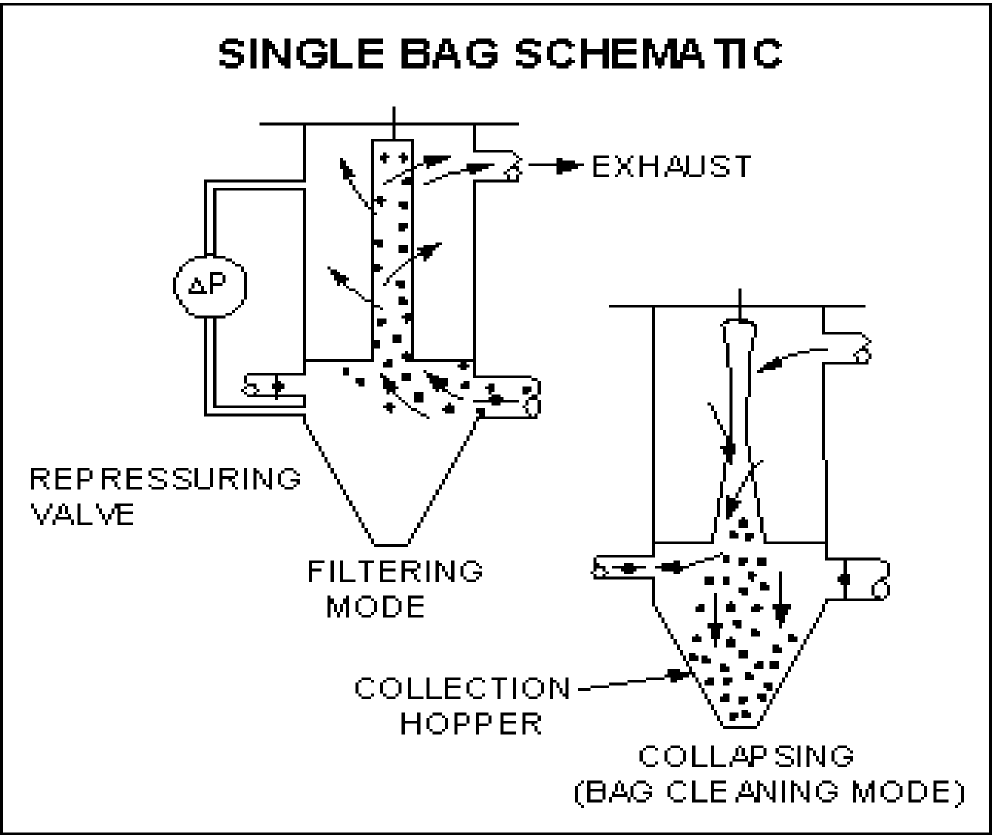
Baghouse Cleaning Methods

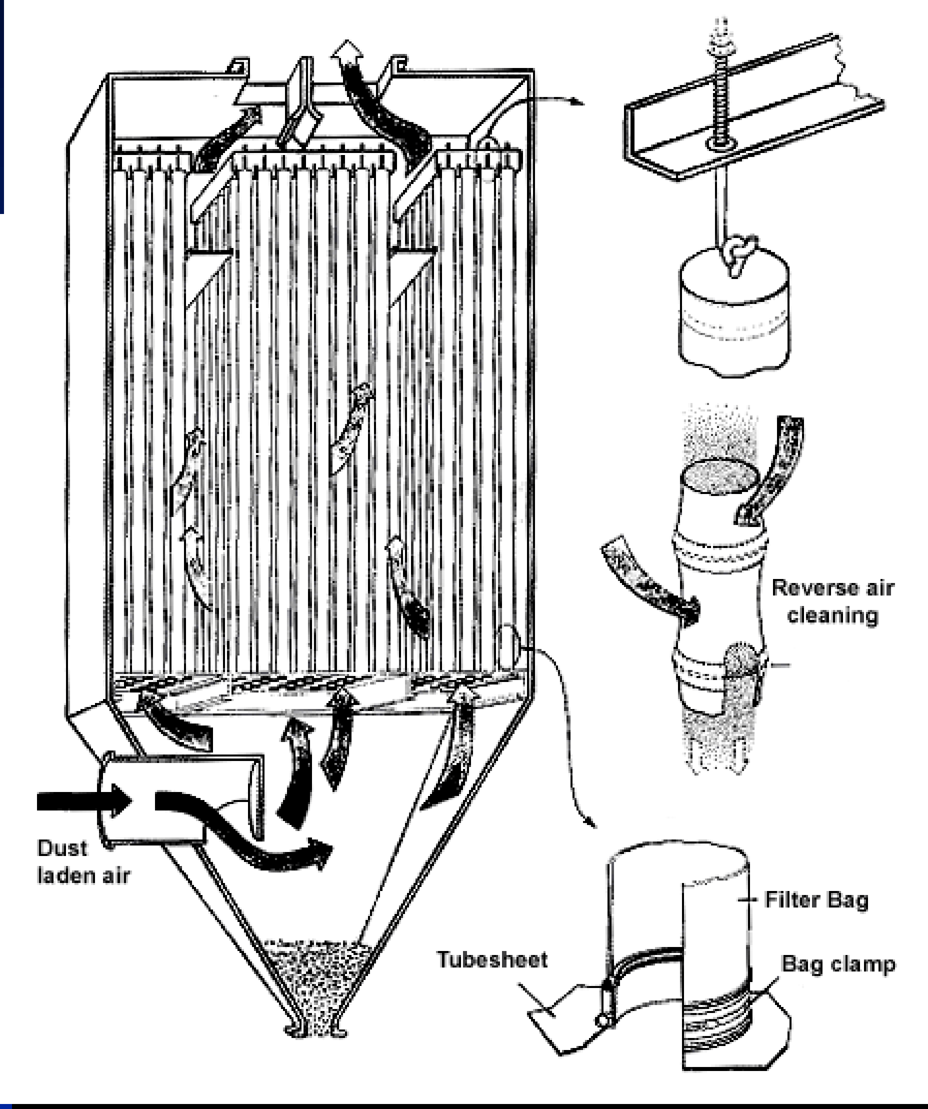
Mechanical Shaker



Baghouse Cleaning Methods

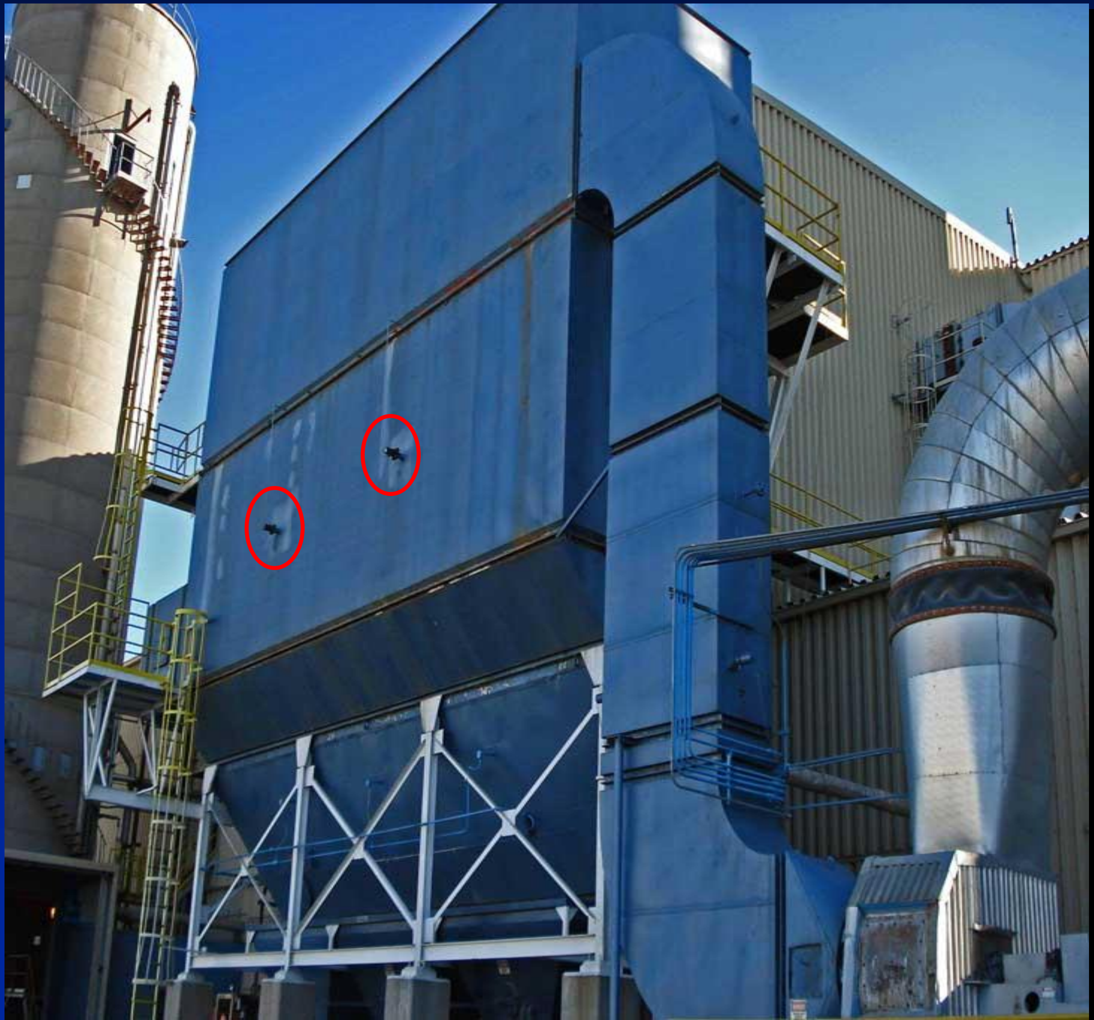
Reverse Air

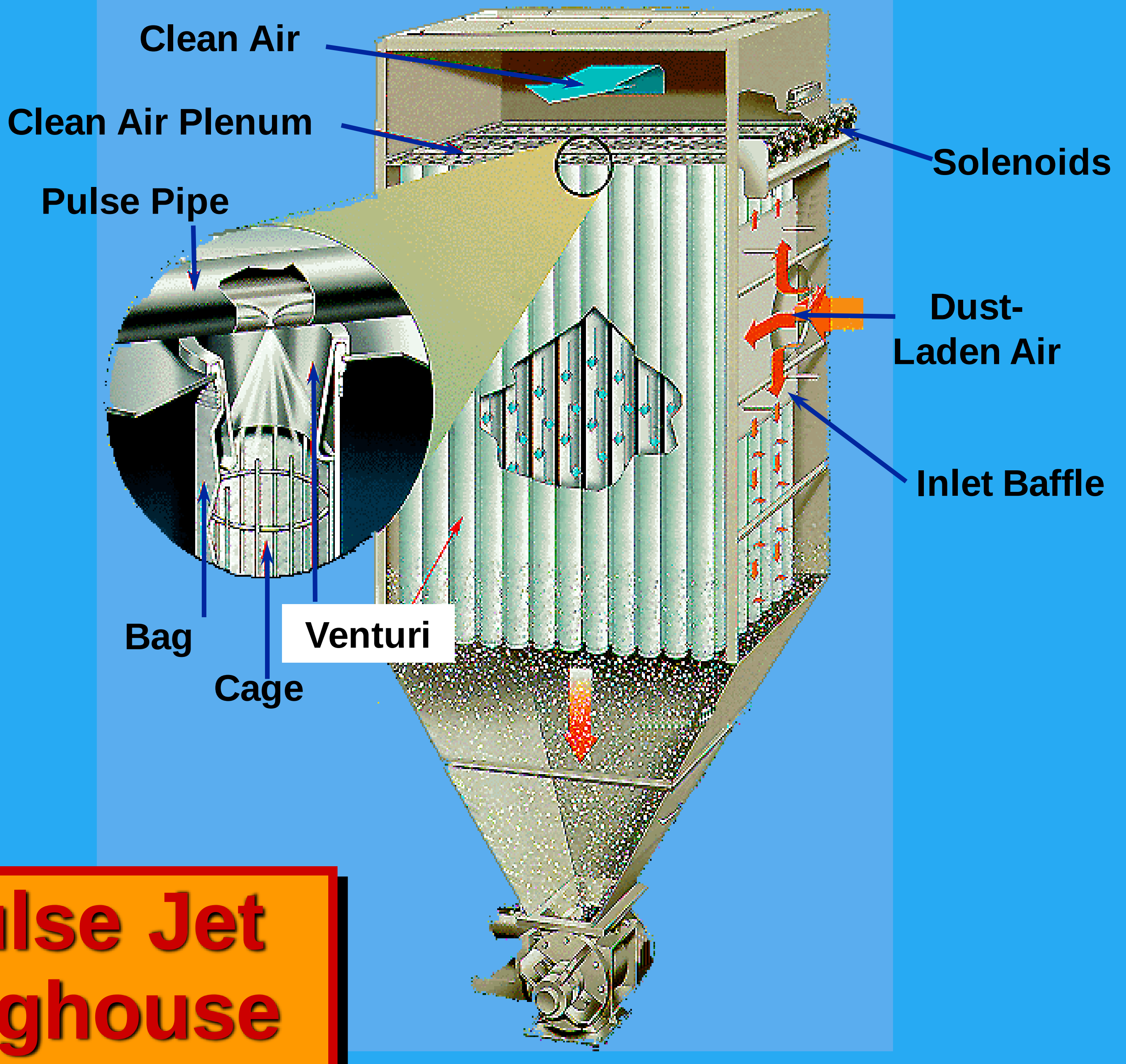




Baghouse Cleaning Methods

Sonic Horns





Pulse Jet Baghouse

Inside a Pulse Jet Baghouse

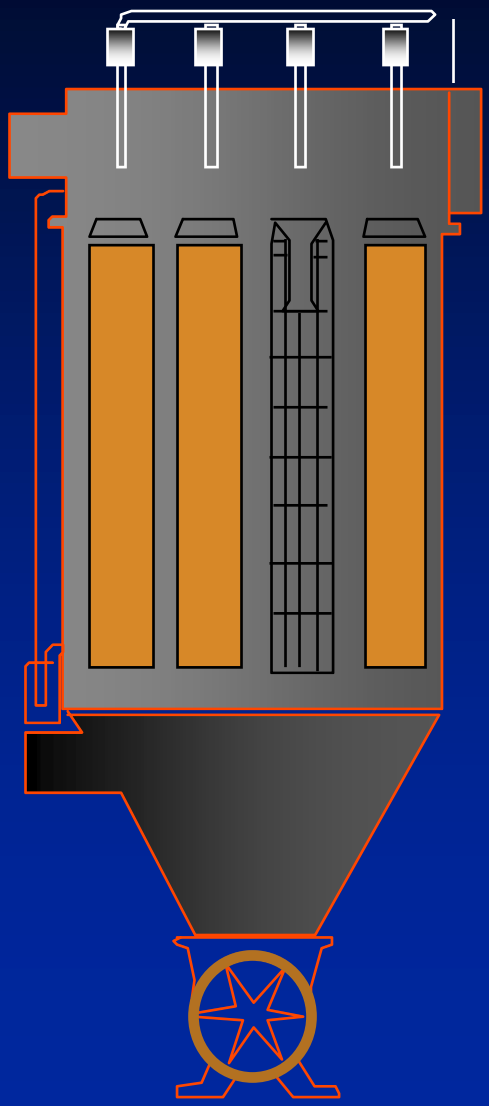

Pulse Jet
Bag

Control Efficiency - Baghouse

- Conventional Baghouses
  - 95% - 99.9% for PM_{10}
  - 95% - 99% for $PM_{2.5}$
- High Efficiency Particle Air (HEPA)
  - 99.97% for $PM_{0.3}$
- Ultra Low Penetration Air (ULPA)
  - 99.9995% for $PM_{0.12}$

Baghouse Design Considerations

- Pressure Drop
- Air-To-Cloth Ratio
- Collection Efficiency
- Fabric Type
- Cleaning
- Temperature Control
- Space and Cost



Causes of Failure - Baghouse

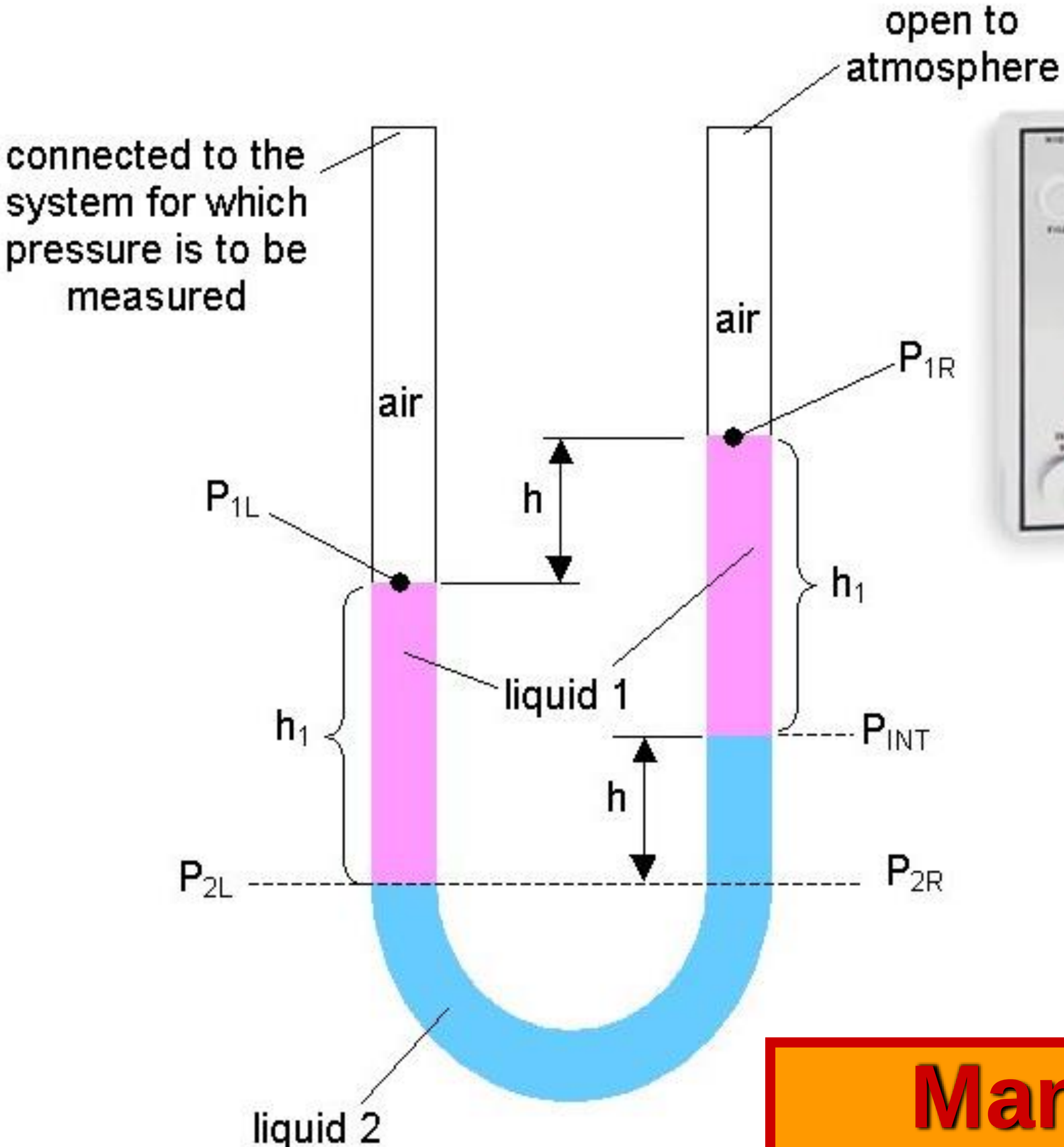
- Bag
  - Abrasion
  - High temperature
  - Chemical attack
  - Concretion of particulate
- Plenum
  - Abrasion
  - Chemical attack
  - Corrosion
- Outer Wall
  - Abrasion
  - Chemical attack
  - Corrosion
  - Physical Damage

Baghouse – Performance Indicators

- Performance indicators
  - Outlet opacity (VEE)
  - Pressure differential
  - Outlet PM concentration (COMS)
  - Bag leak detectors
  - Exhaust gas flow rate
  - Cleaning mechanism operation
  - Inspections and maintenance

Monitoring Equipment

- Magnehelic or Manometer (ΔP)
- Continuous Opacity Monitoring Systems (COMS)
- Tribo Electric Sensors

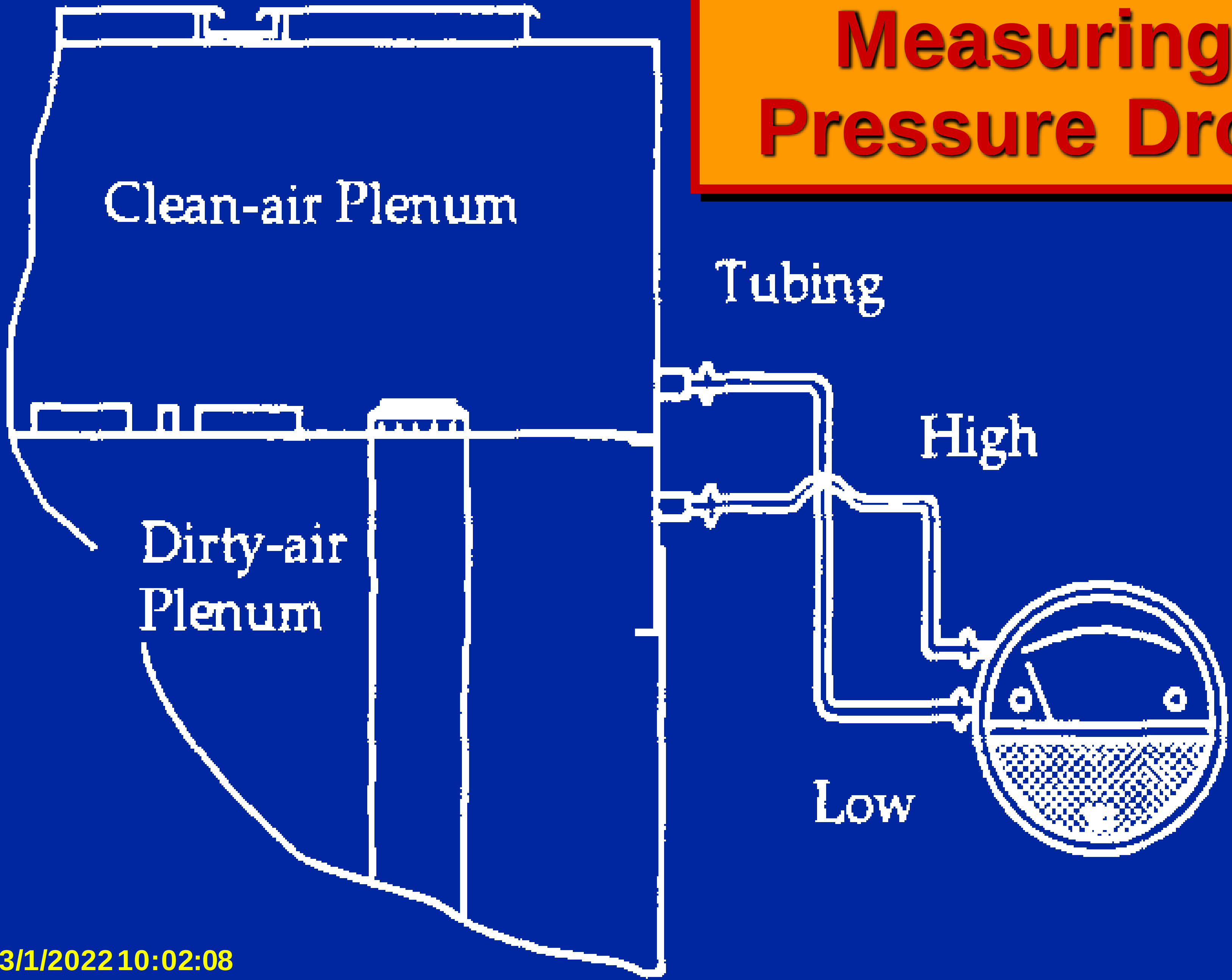

open to atmosphere
connected to the system for which pressure is to be measured
air
air
P_{1R}
P_{1L}
h
h_1
liquid 1
P_{INT}
h_1
h
P_{2L}
P_{2R}
liquid 2


Dwyer
MARK II
INCHES OF WATER COLUMN
3
2
1
0
.10
.20
.30
.50
-.05


47.7

Manometer

Measuring Pressure Drop



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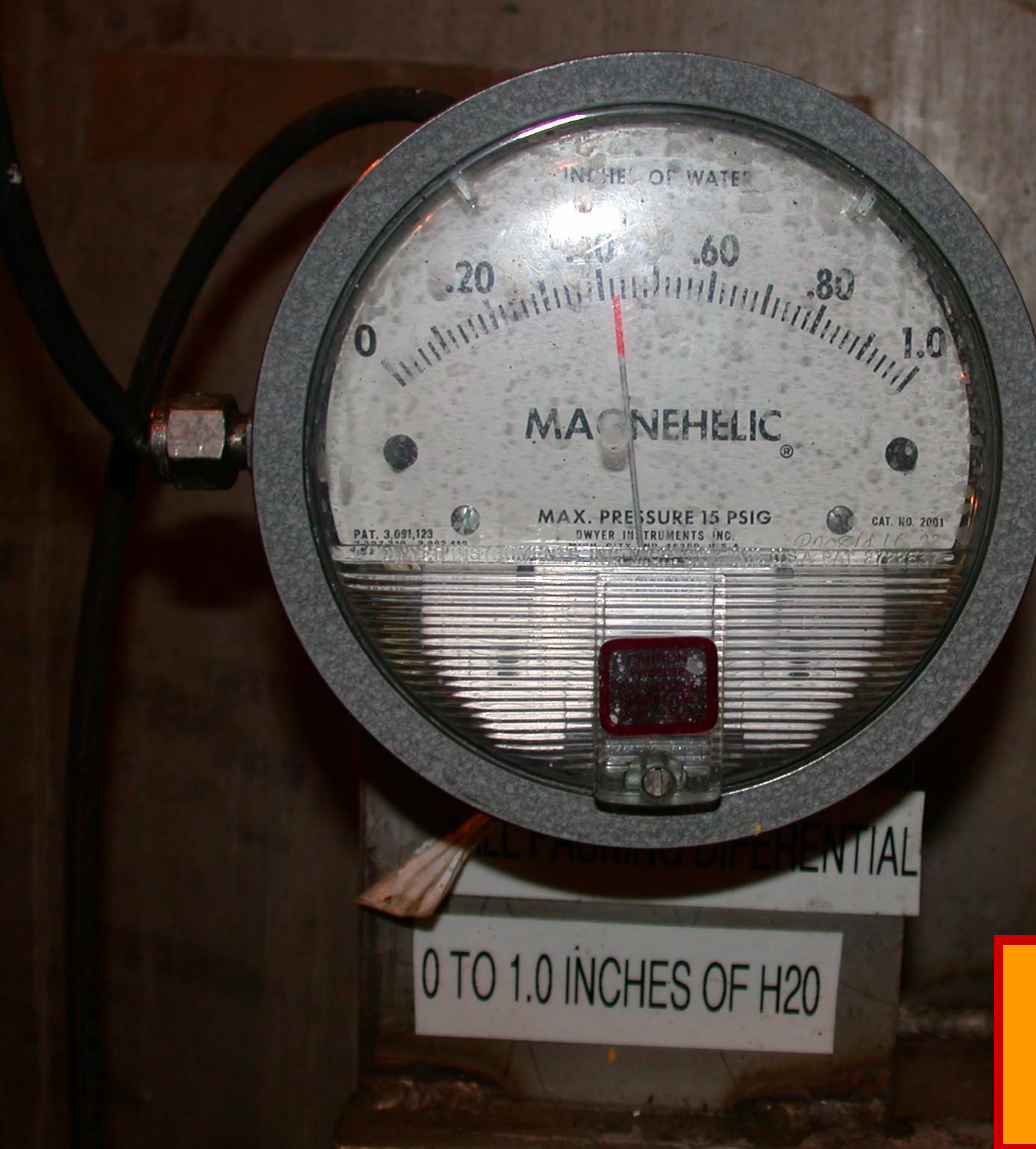


Magnehelic Gauge

Baghouse Pressure Drop

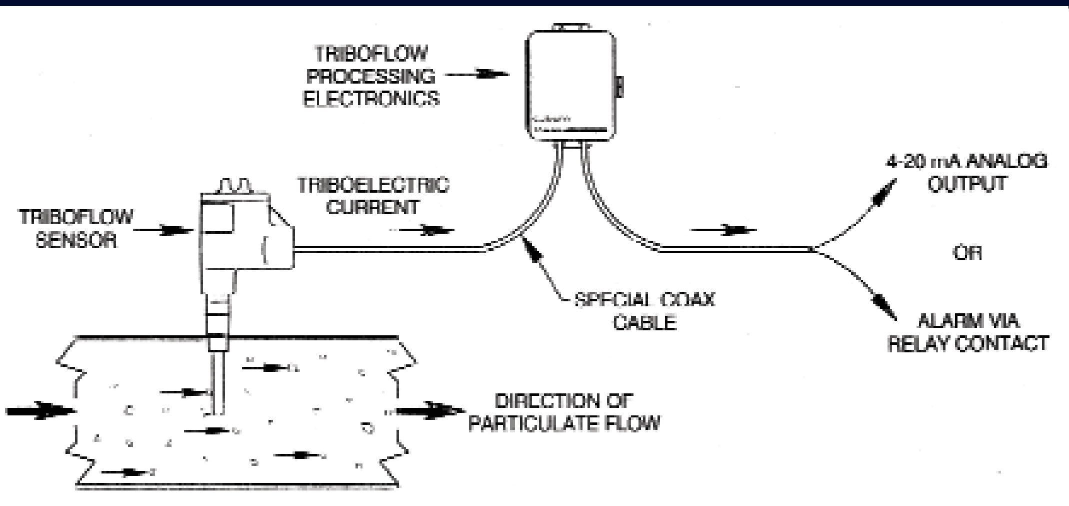
- ΔP shows air flow – it's in operation
- ΔP may fluctuate 10% as a function of the bag cleaning cycle.
- Continued rise in ΔP will result from bags that become permanently plugged (blinded).
- High ΔP will lead to premature bag failure.
- Daily/weekly record of ΔP can be a useful monitoring tool

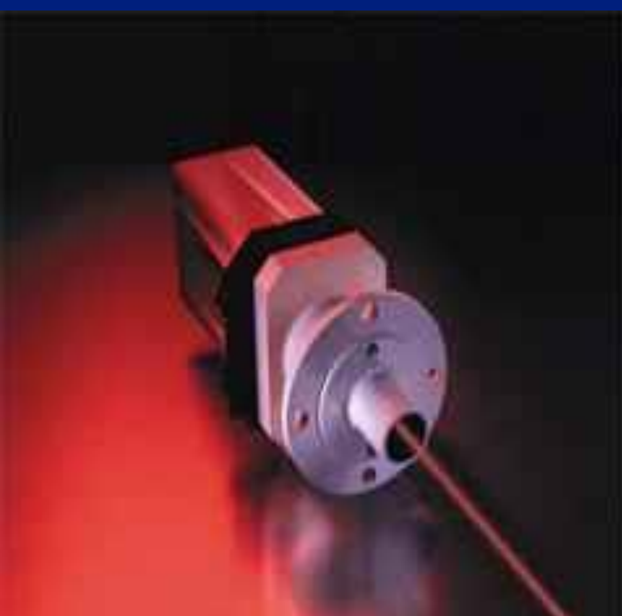
PM COMS

Opacity

- Not very sensitive – shows a gross failure.
- Baseline (new) bag house opacity is probably << 1%
- Emissions must increase about 10x to be visible.
- Opacity useful where particulate emissions limit is high.

Triboelectric Sensors





Baghouse Monitoring

- Normal baghouse emissions are very low.
  - Opacity sensors (COM) aren't very good below 1-2%, so they don't detect initial problems.
  - Opacity will show a major particulate emissions increase.
  - COM or Method 9 may be OK for loose emission limits.

Tribo Electric Sensors

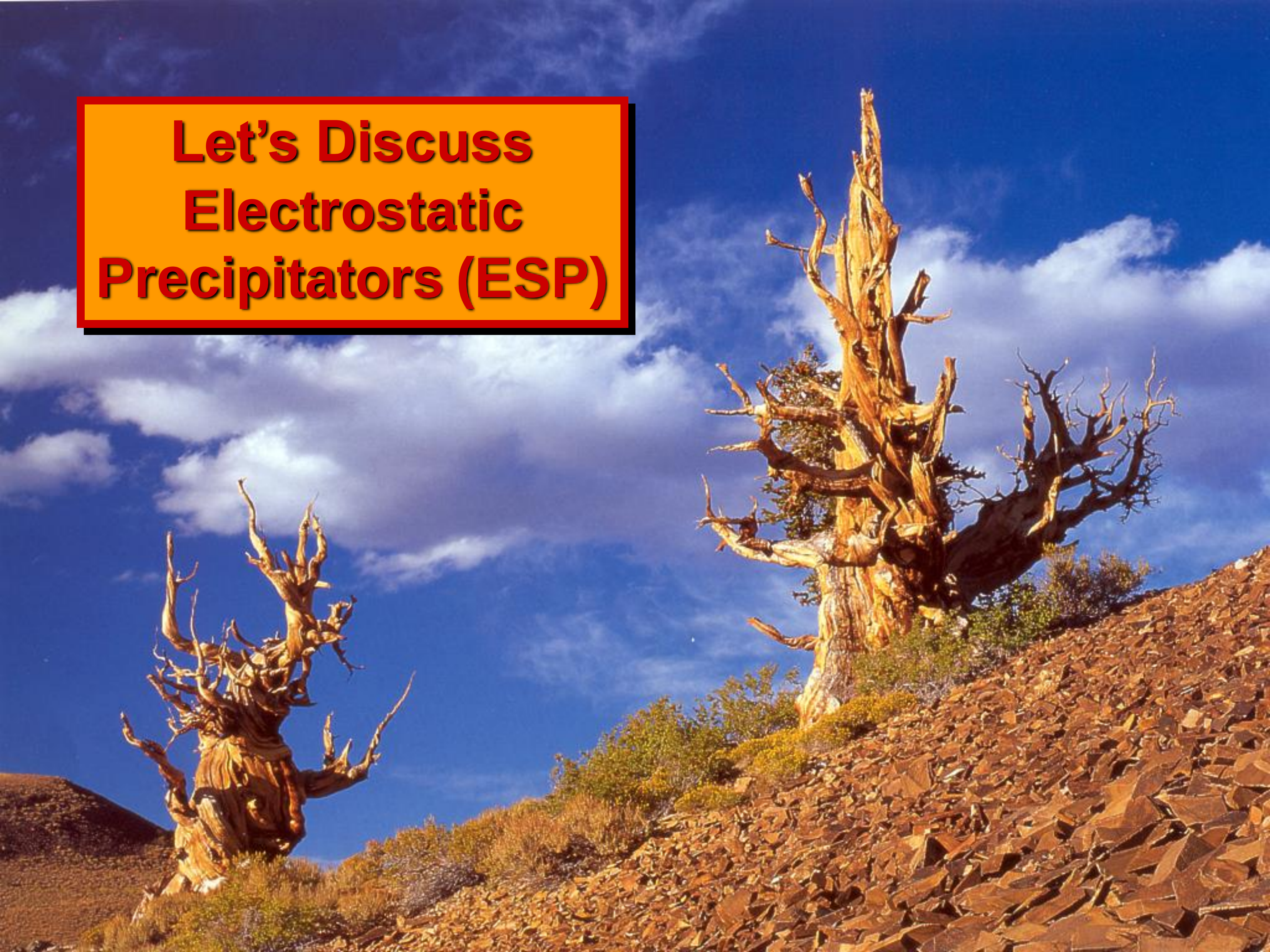
- Tribo electric sensors (TES) work well at very low particle concentrations (very sensitive).
- TES detects micro amp current from particles hitting a metal probe.
- TES is simple and inexpensive.
- TES is an effective monitor when a small to moderate increase in emissions is of concern.

BH Monitoring Summary

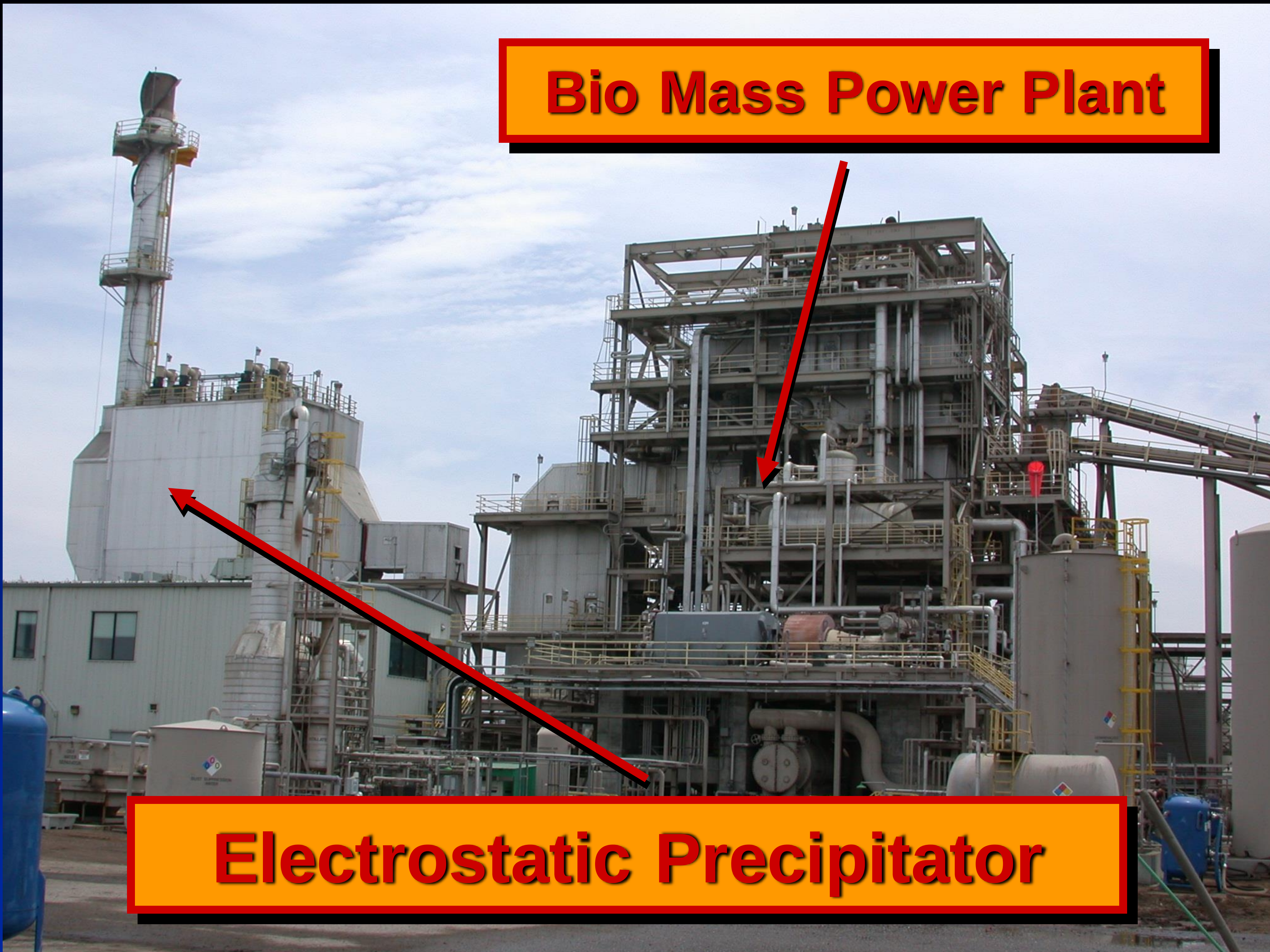
- Use TES for sensitive indication of changes in particulate emissions
- Opacity will indicate large increases in particulate emissions.
- An increasing pressure drop is indicative of long term problems

Baghouse : Secondary Containment

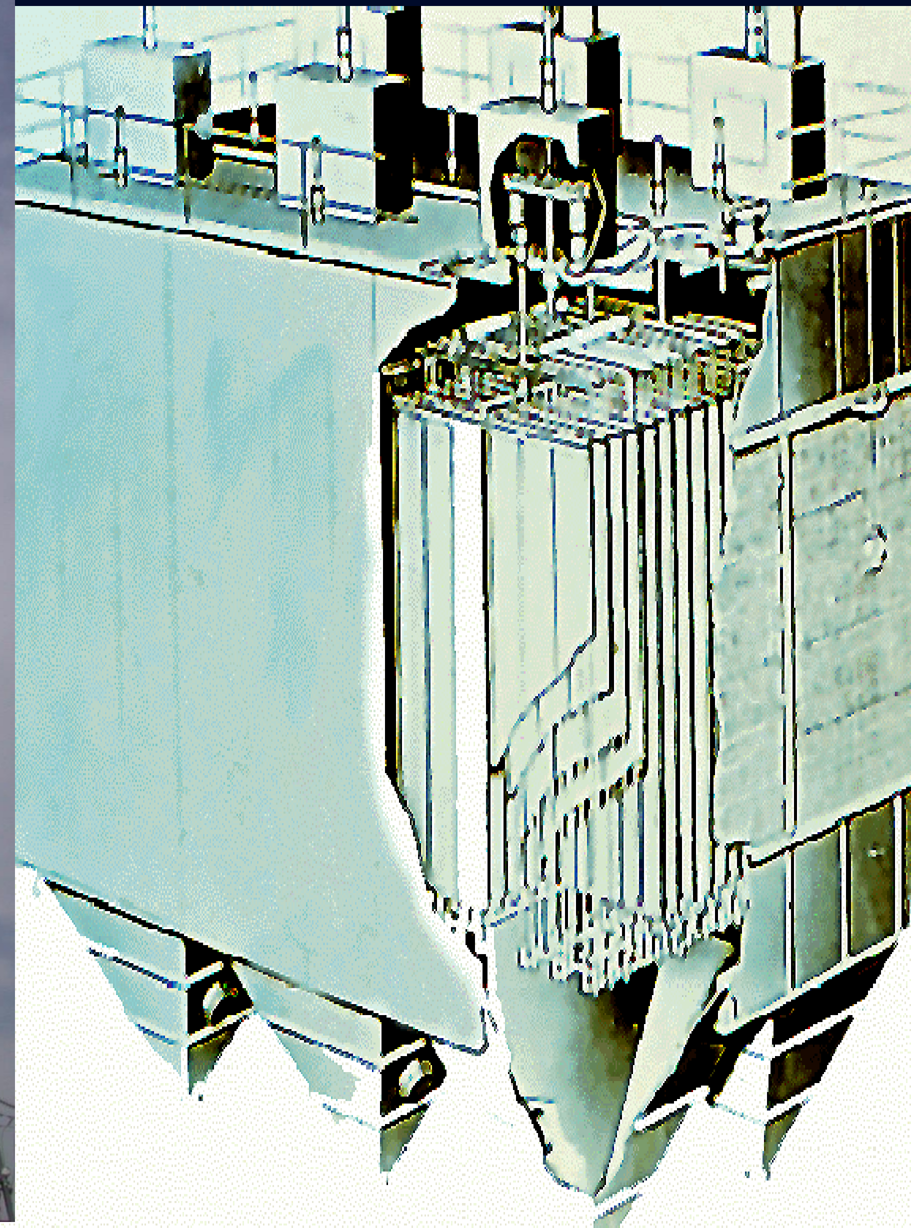
Let's Discuss Electrostatic Precipitators (ESP)



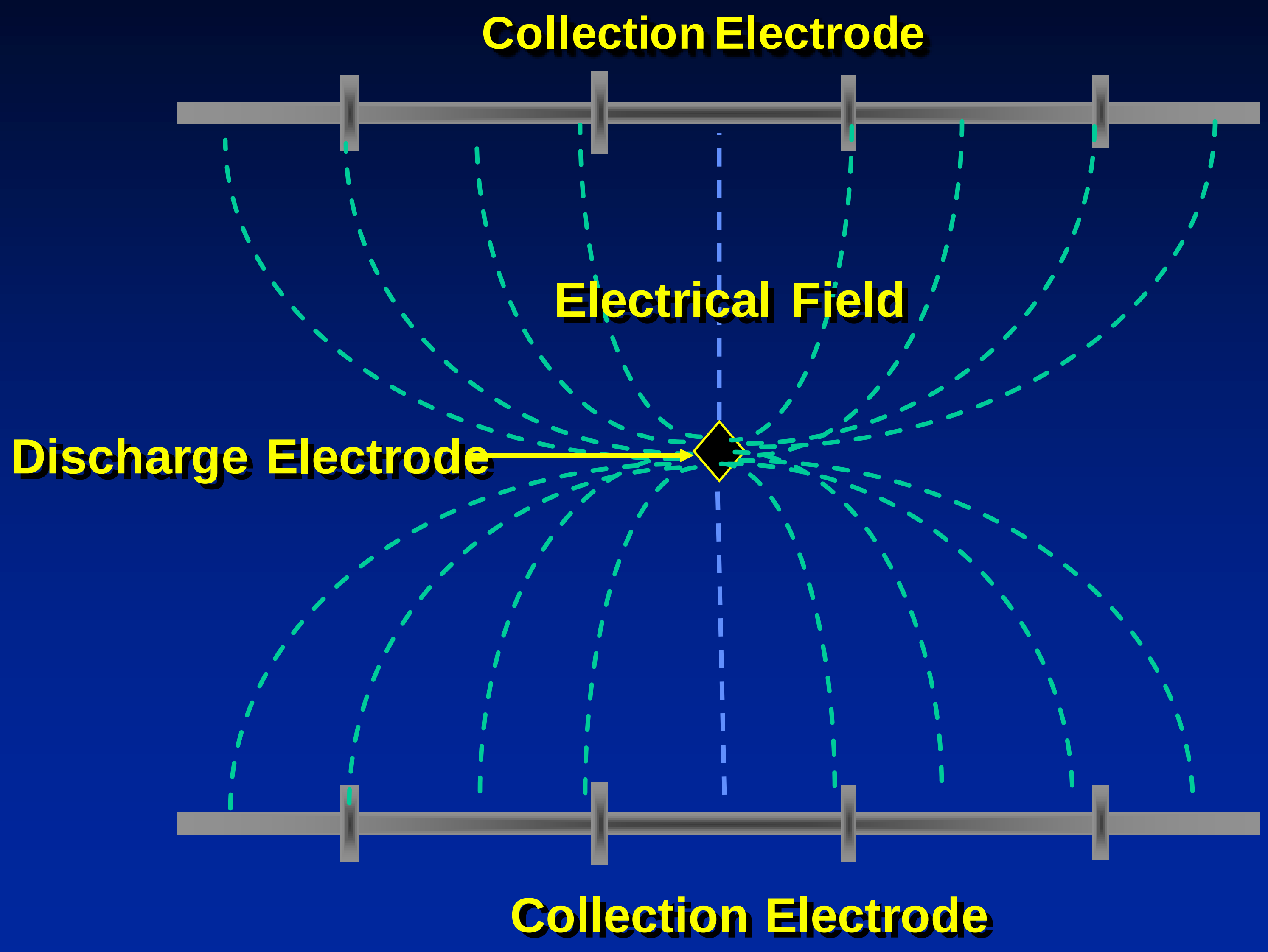
Prometheus Tree – 4,844 years old


Bio Mass Power Plant
Electrostatic Precipitator

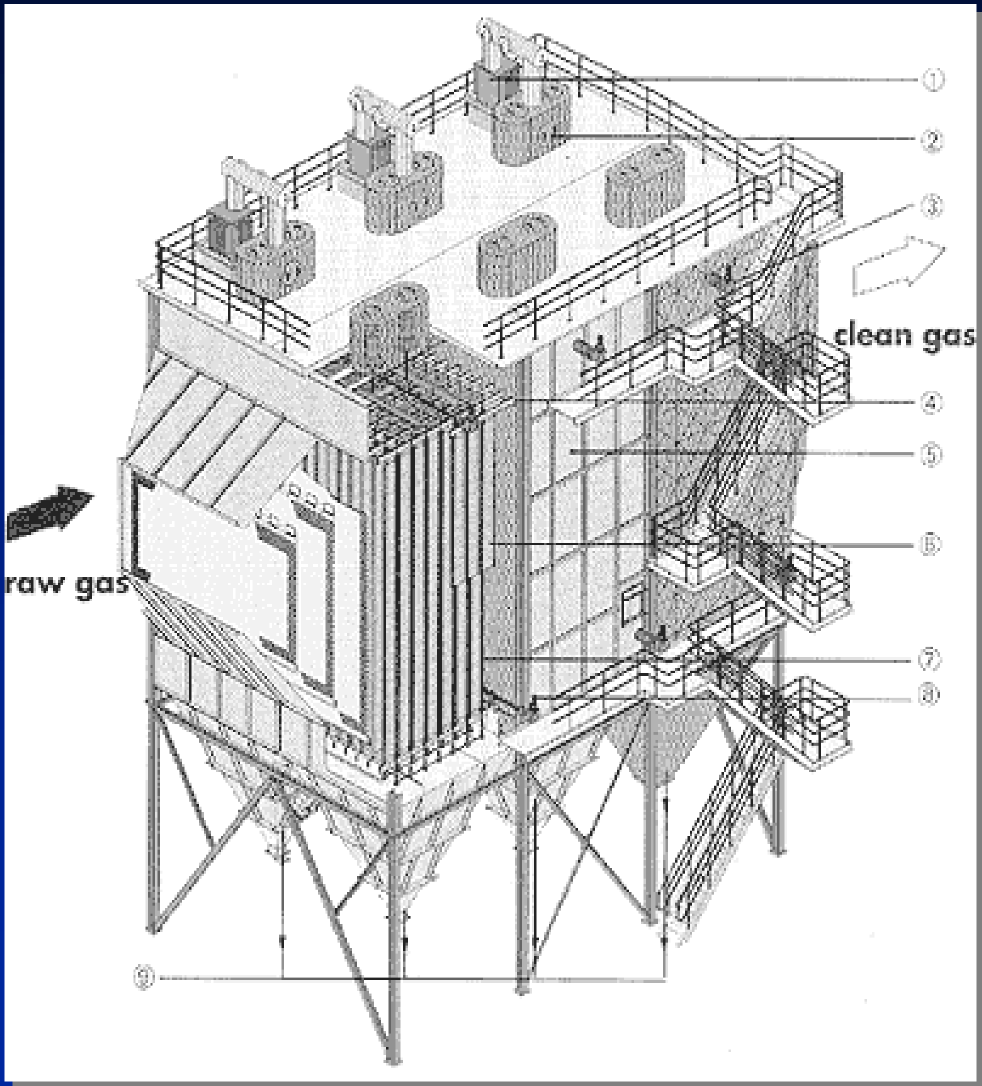
Electrostatic Precipitator

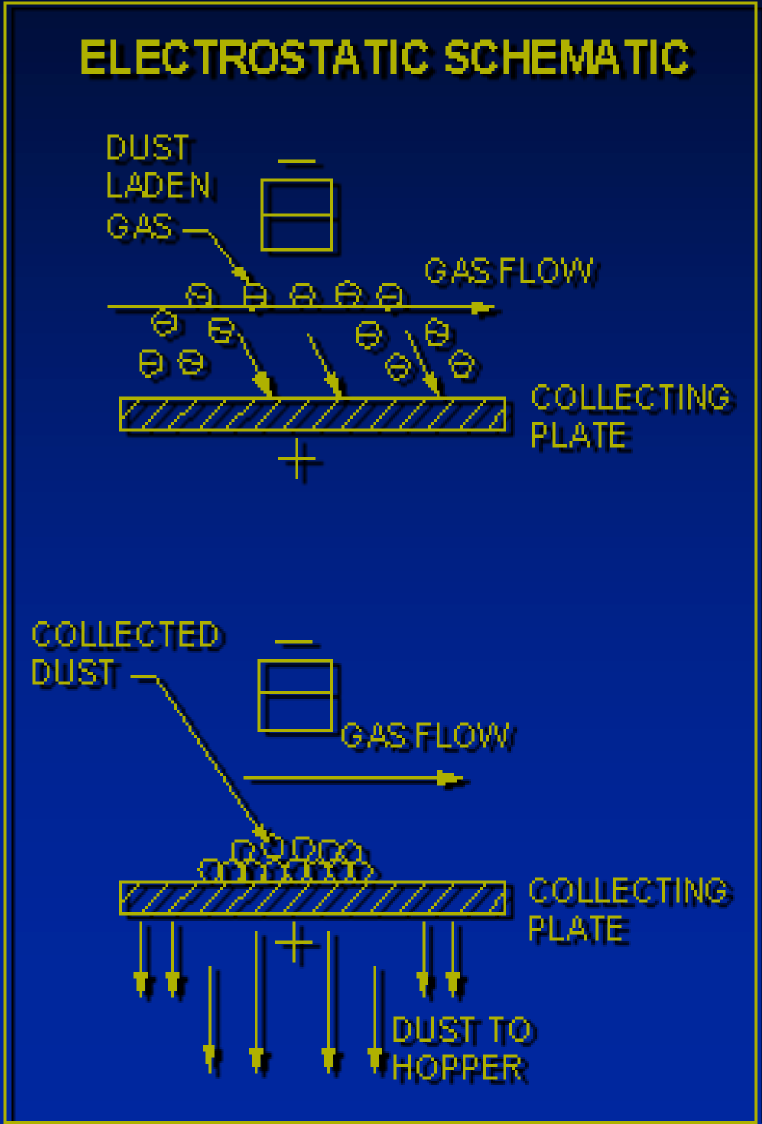


Electrical Field Generation

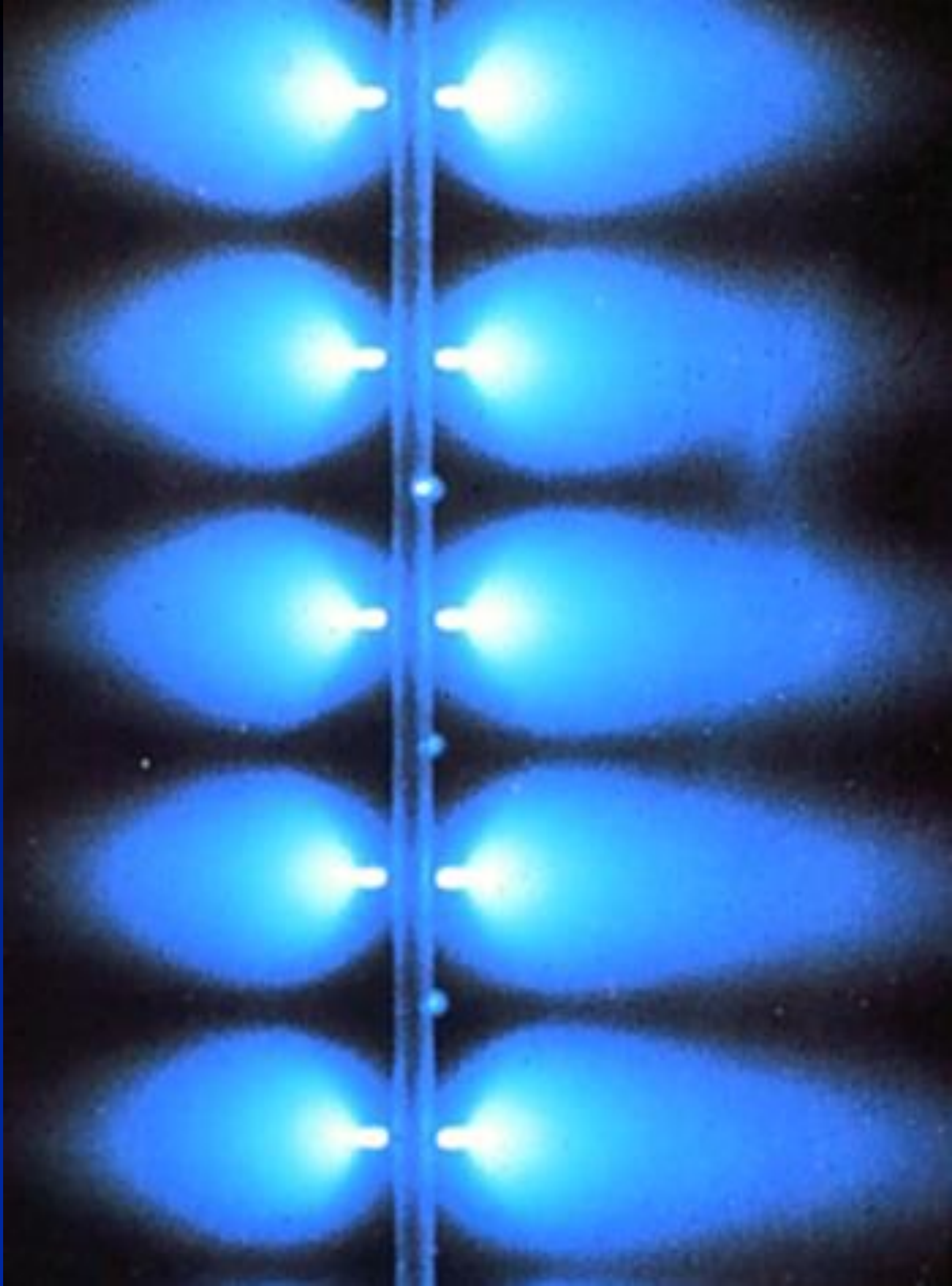


Electrostatic Precipitator





Corona
(voltage negative)



Avalanche Multiplication

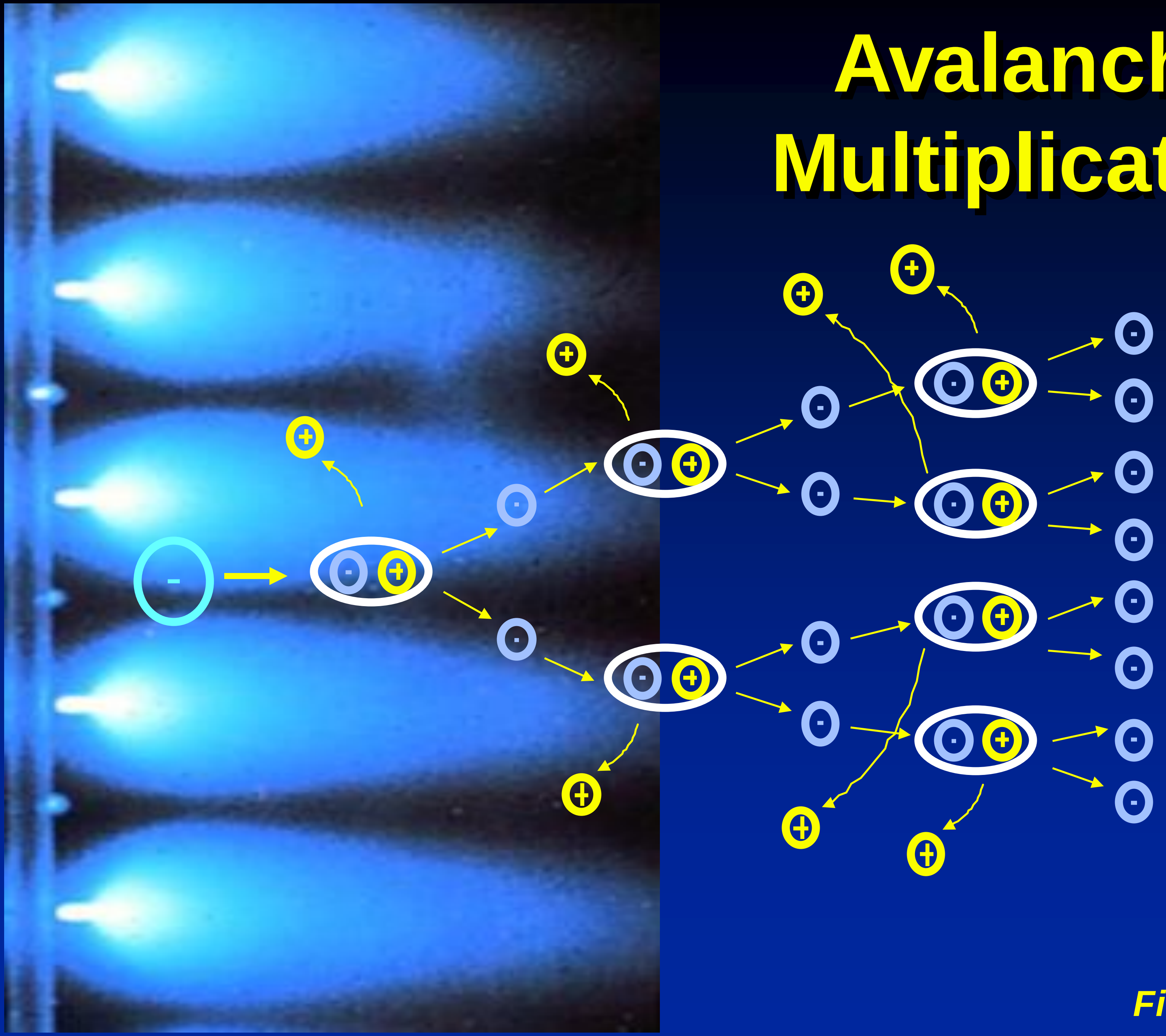
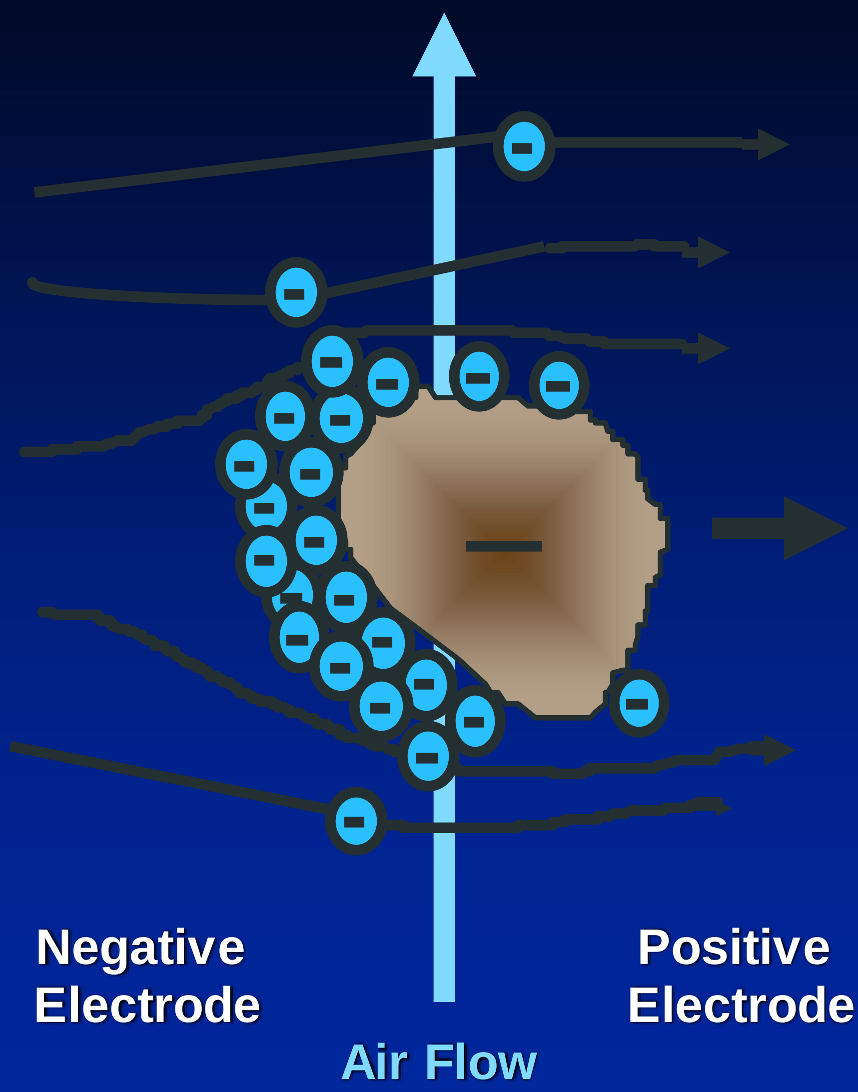
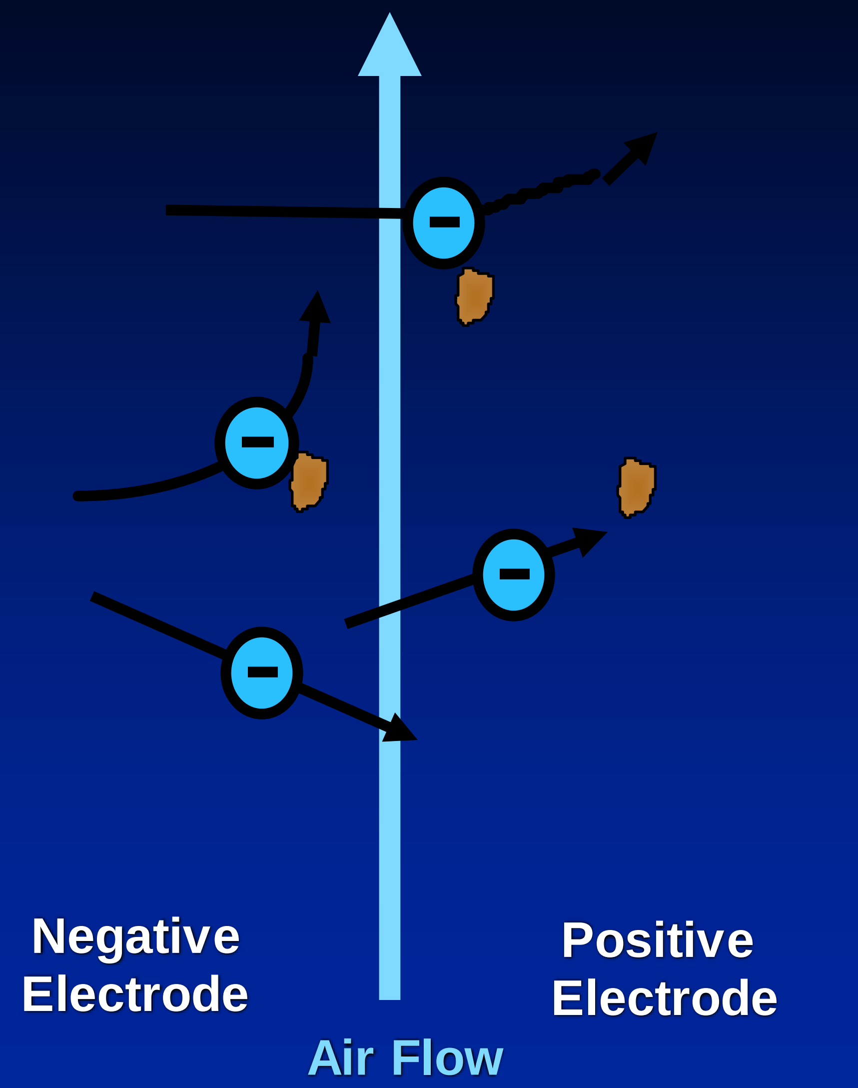


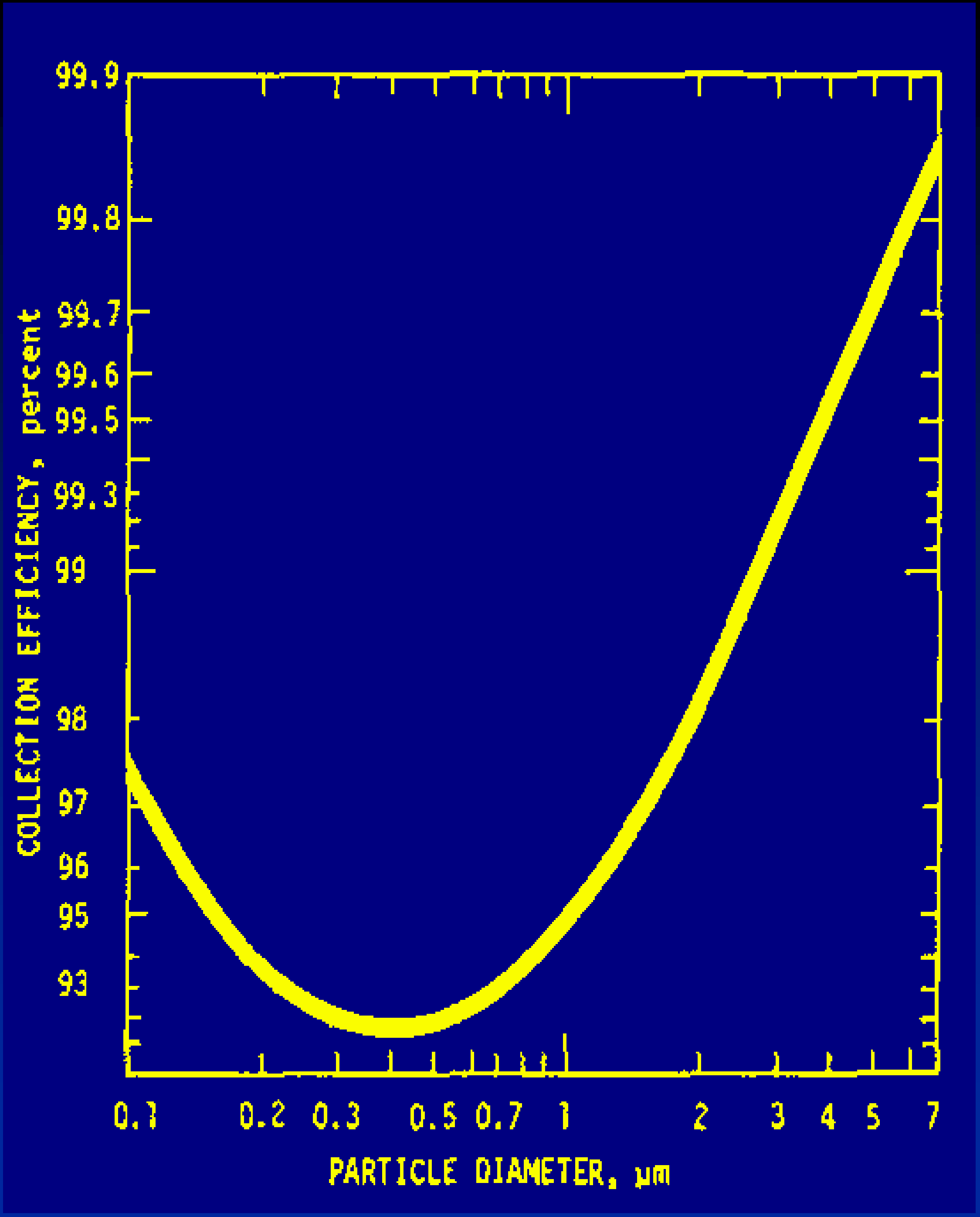
Figure 301.3

Field Charging



Diffusion Charging





Particle Size & Collection Efficiency

Figure 305.5

Electrostatic Precipitator

- General Description
  - Two types
    - Dry type use mechanical action to clean plates
    - Wet type use water to prequench and to rinse plates

Electrostatic Precipitator

- General Description
  - High voltages are required
    - 20,000 – 100,000 VDC
  - Multiple sections (fields) may be used
  - They usually can meet emission target with one field out of service or operating at reduced power

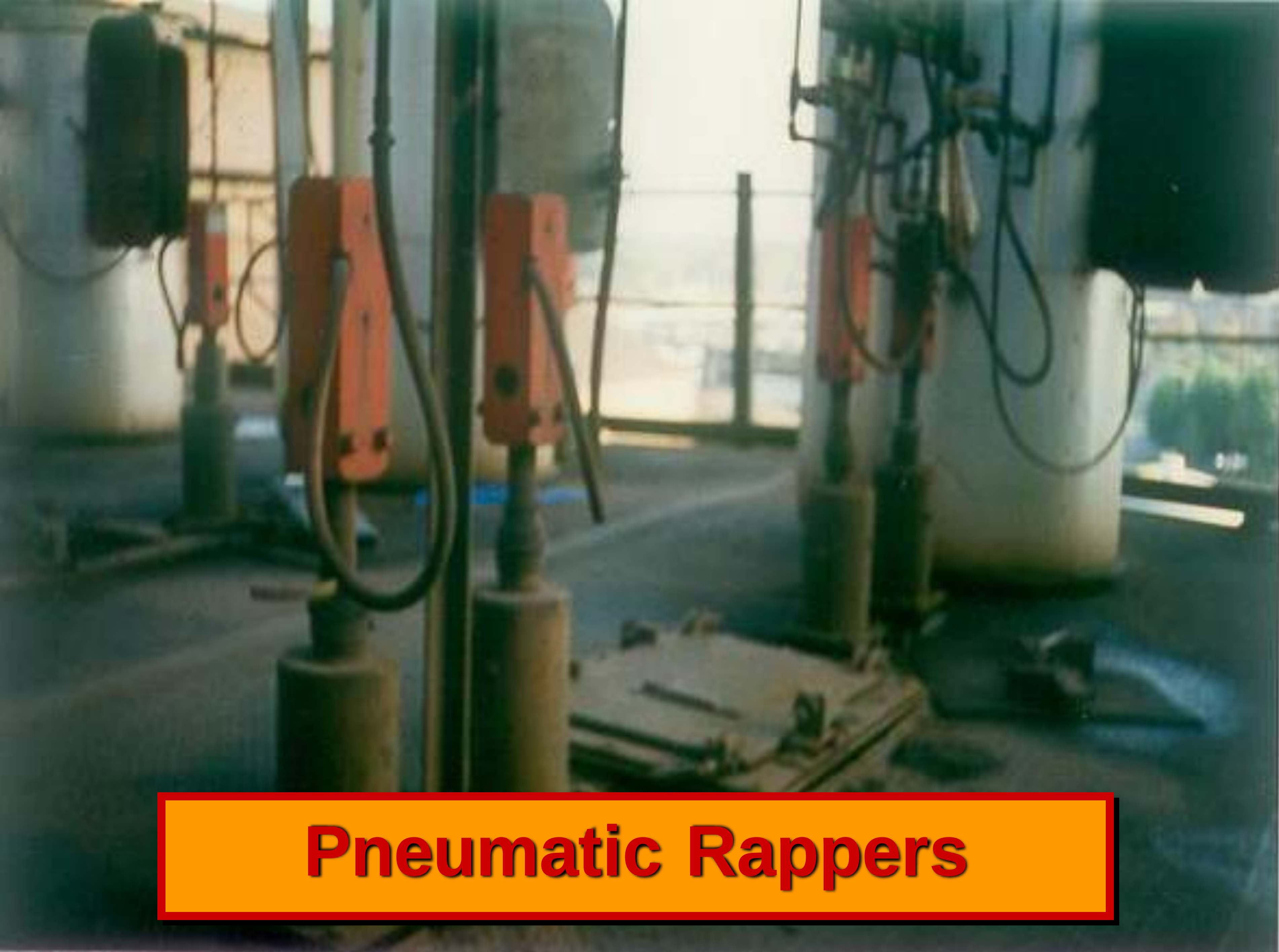
Electrostatic Precipitator

- General Description
  - High airflow rates
    - 200,000 – 1,000,000 scfm
  - High temperatures
    - Up to 1,300 °F
  - Pollutant Loading
    - 1 – 50 grains/scfm

Electrostatic Precipitator

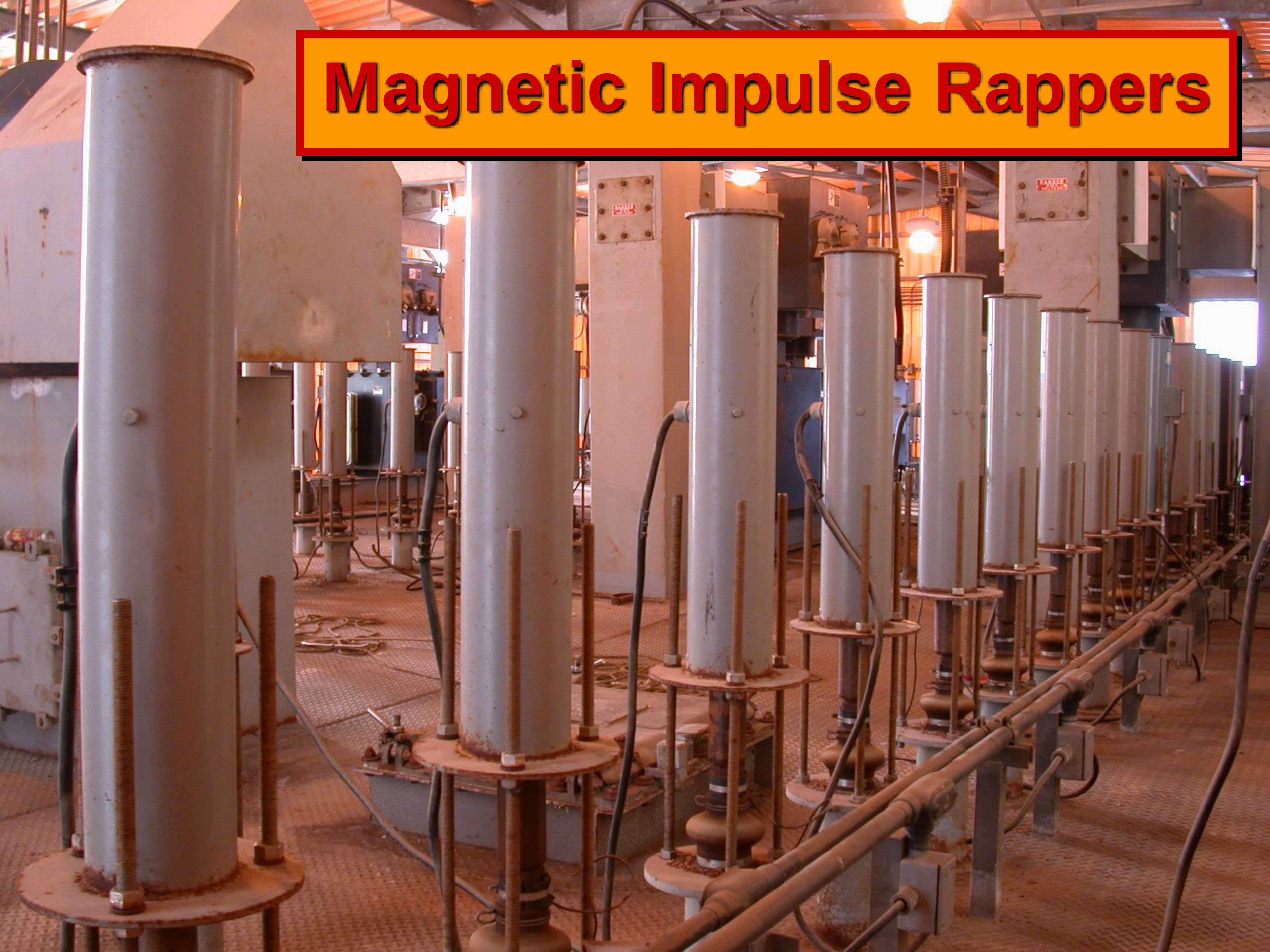
- A high voltage field creates a corona (current)
  - Particles are charged by electrons in the corona
  - The DC field draws charged particles to the plate
- Dust layers on the plates are cleared by mechanical rapping. Dust falls into the hoppers.
- Several fields in the direction of flow
  - Voltage/current to each is separately controlled
  - The first field collects most of the dust (75%)
  - Not much dust left in the last field

Mechanical Tumbling Hammer Rappers



Pneumatic Rappers

Magnetic Impulse Rappers



Electromagnetic Rapper

Control Efficiency - ESPs

- Older Existing ESPs
  - 90% - 99.9% for PM_{10}
- Typical New ESPs
  - 99% - 99.9% for PM_{10}

ESPs: Design Factors Affecting Performance

- Specific Collection Area
- Aspect Ratio
- Collection Plate Spacing
- Sectionalization
- Power Requirements/Spark Rate

Electrostatic Precipitator

- Factors affecting efficiency
  - Gas temperature, humidity, flow rate
  - Particle resistivity
  - Fly ash/Fuel composition
  - Plate length
  - Surface area

Electrostatic Precipitator

- Factors affecting efficiency
  - ESP is sensitive to gas flow rate
  - Flow monitoring may be appropriate
  - An ESP won't work well if the velocity distribution is not uniform.
- ESP internal factors
  - Dust layer thickness & electrical resistance.
  - Changes in geometry (damage)
  - Air leaks, condensation

Electrostatic Precipitator

Baseline operating and emission data is needed to establish:

- Emissions level and control capability at max gas flow.
  - Does it work as intended?
  - Typical secondary current and voltage levels
- Operating margin - number of fields and power required to meet emission requirements.
- Normal operating temperature.

Electrostatic Precipitator

- Performance indicators
  - Outlet opacity (VEE)
  - Pressure differential
  - Outlet PM concentration (COMS)
  - Secondary corona power (current & voltage)
  - Spark rate
  - Primary power (current & voltage)

ESP: Performance Indicators

Electrostatic Precipitator

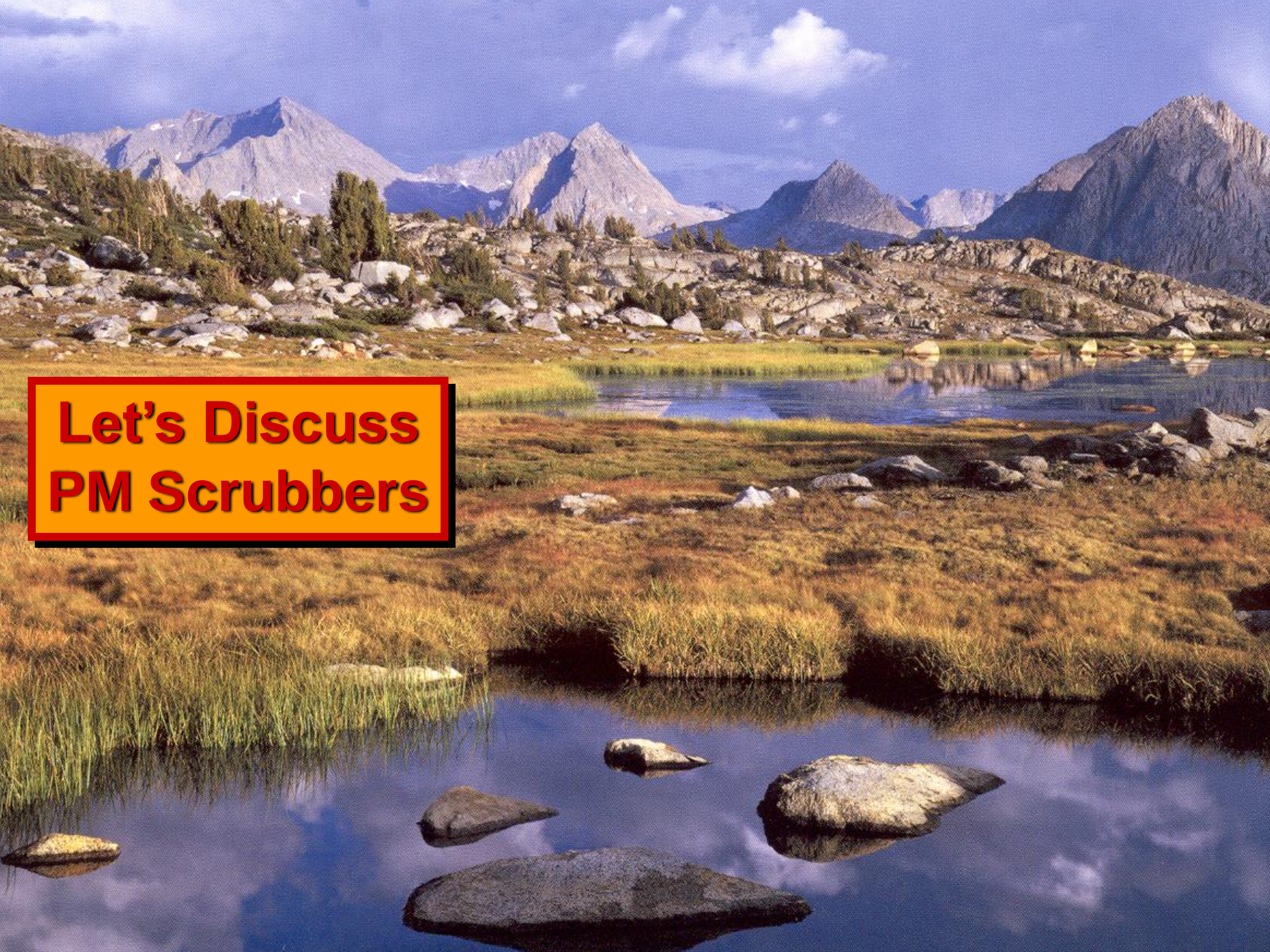
- Performance indicators (cont.)
  - Inlet gas temperature
  - Gas flow rate
  - Rapper operation
  - Fields in operation
  - Inlet water flow rate (wet type)
  - Flush water solids content (wet type)

Summary of ESP Monitoring

- Obtain convincing baseline emissions data
  - Linked to flow rate, power levels and type of fuel
- Key monitoring parameters
  - Opacity
  - Electrical power levels (Secondary I & V)
- Secondary parameters
  - Temperature
  - Fuel composition
  - Inspection & routine maintenance


ESP:
Soot
Blowing
&
Opacity

ESP : Secondary Containment

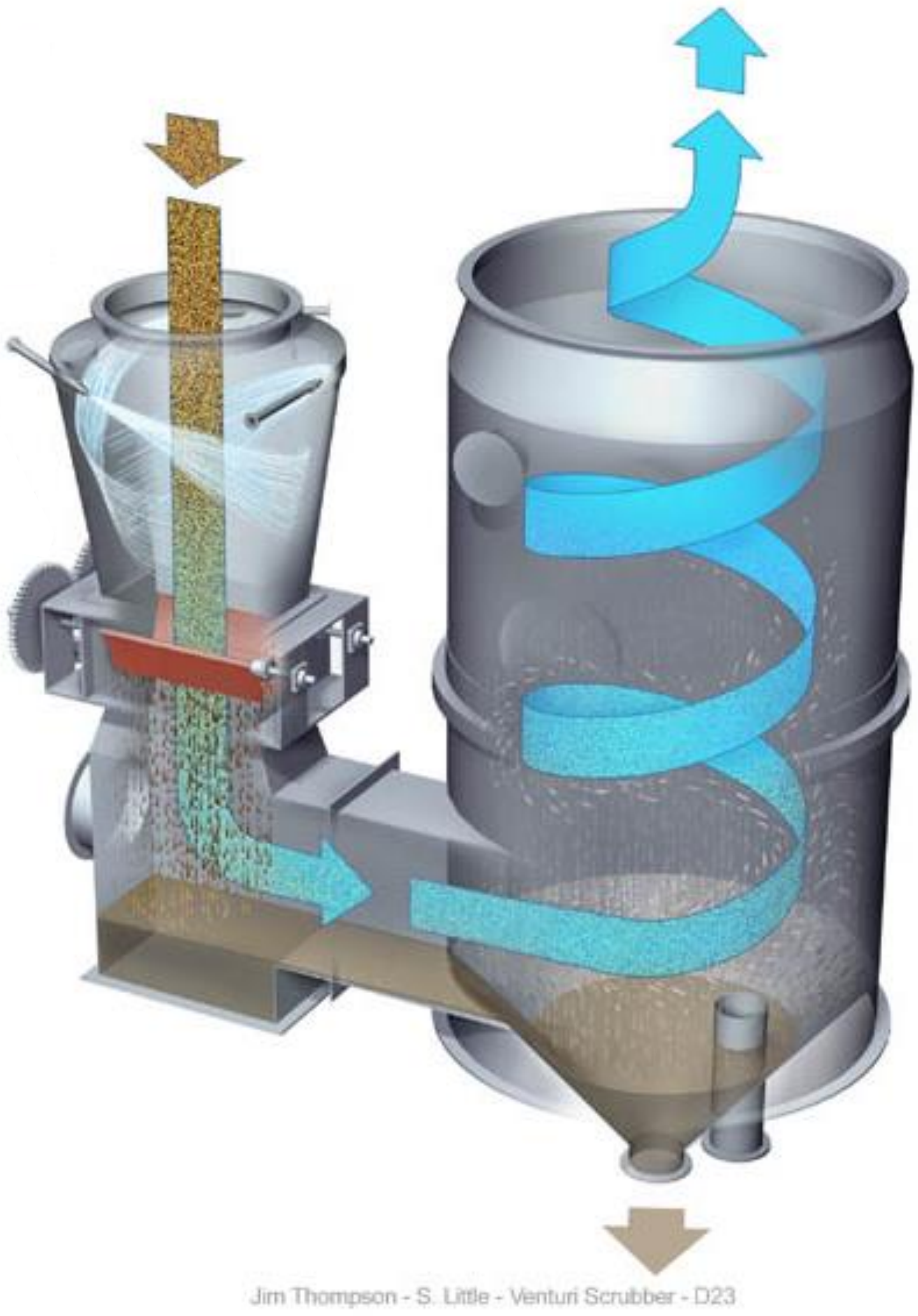

Let’s Discuss
PM Scrubbers

Control Techniques – Wet Scrubber

- General description
  - Particles (and gases) get trapped in liquids
    - Inertial impaction and diffusion
  - Liquids must contact pollutants and dirty liquids must be removed from exhaust gas
  - Four types
    - Spray; venturi or orifice; spray rotors; and moving bed or packed towers

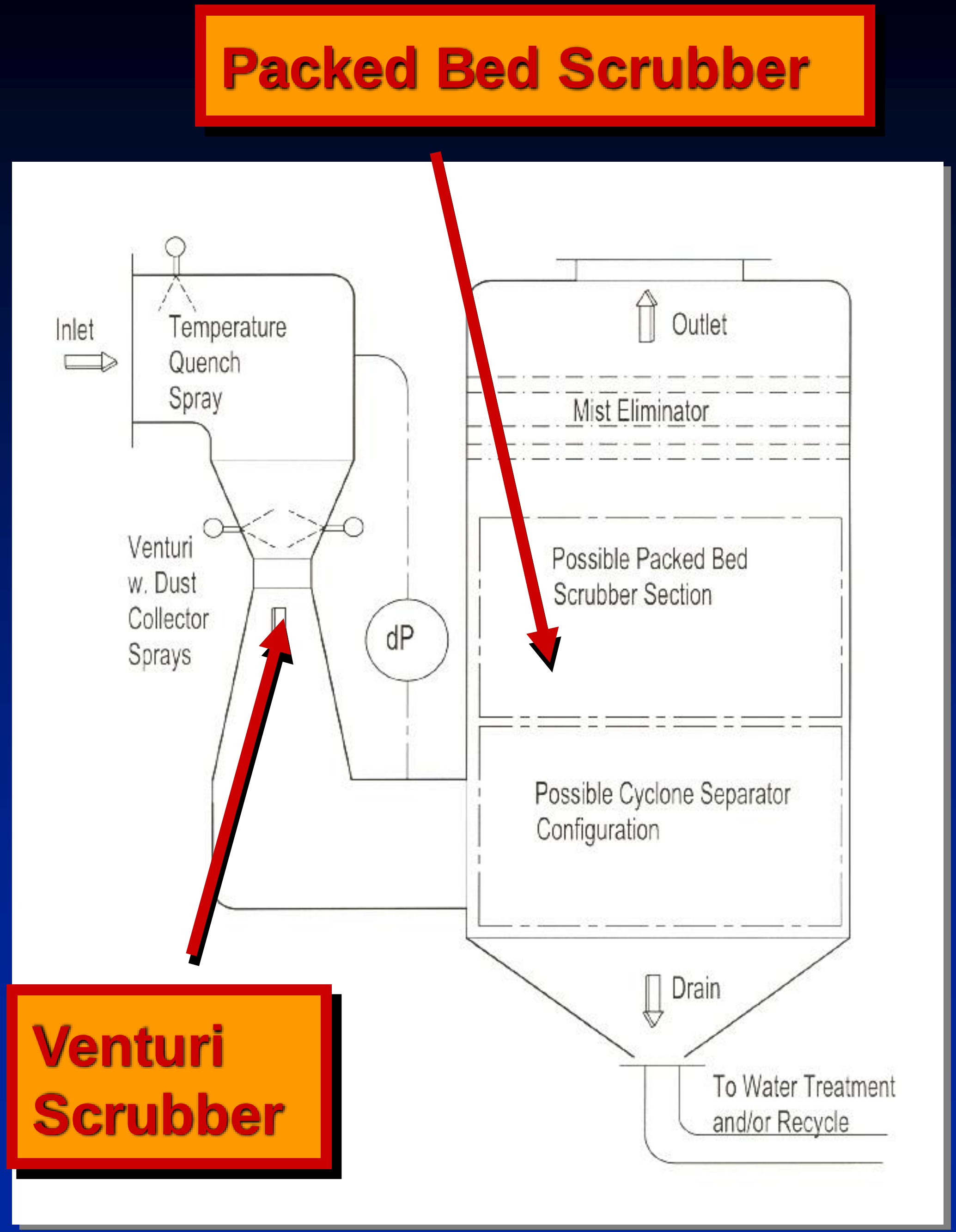

Venturi
Scrubber

Venturi Scrubber



Wet Scrubber Operation

- **Particles collected by impaction**
- **Gasses collected by diffusion & absorption**



Venturi Scrubbers

- Control Efficiency
  - 70 - 99% for PM_{10}
- Moderate airflow rates
  - 500 – 100,000 scfm
- Moderate temperatures
  - Up to 750 °F
- Pollutant Loading
  - 0.1 – 50 grains/scfm

Scrubber Control Efficiency

- Factors affecting efficiency
  - Gas and liquid flow rate
  - Condensation of aerosols
  - Poor liquid distribution
  - High dissolved solids content in liquid
  - Nozzle erosion or pluggage
  - Re-entrainment
  - Scaling

Scrubber Monitoring

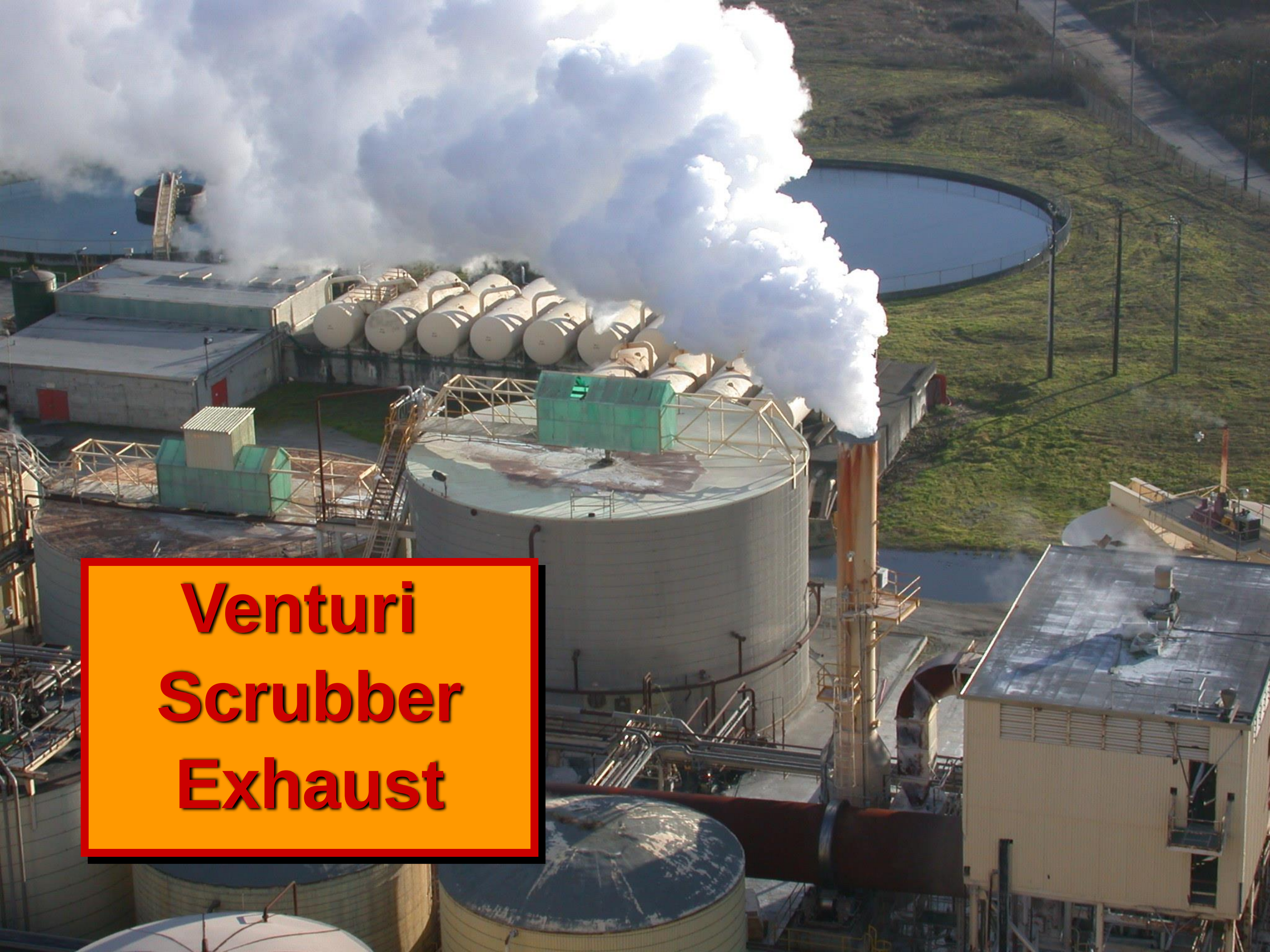
- Venturi pressure drop (ΔP)
  - The higher the ΔP the smaller the collected particles
  - Some venturis have adjustable vanes
- Water flow rate (gallons/min)
  - Flow below a critical level will degrade performance.
- Water cleanliness – evaporated residue & mist carryover.

Scrubber Performance

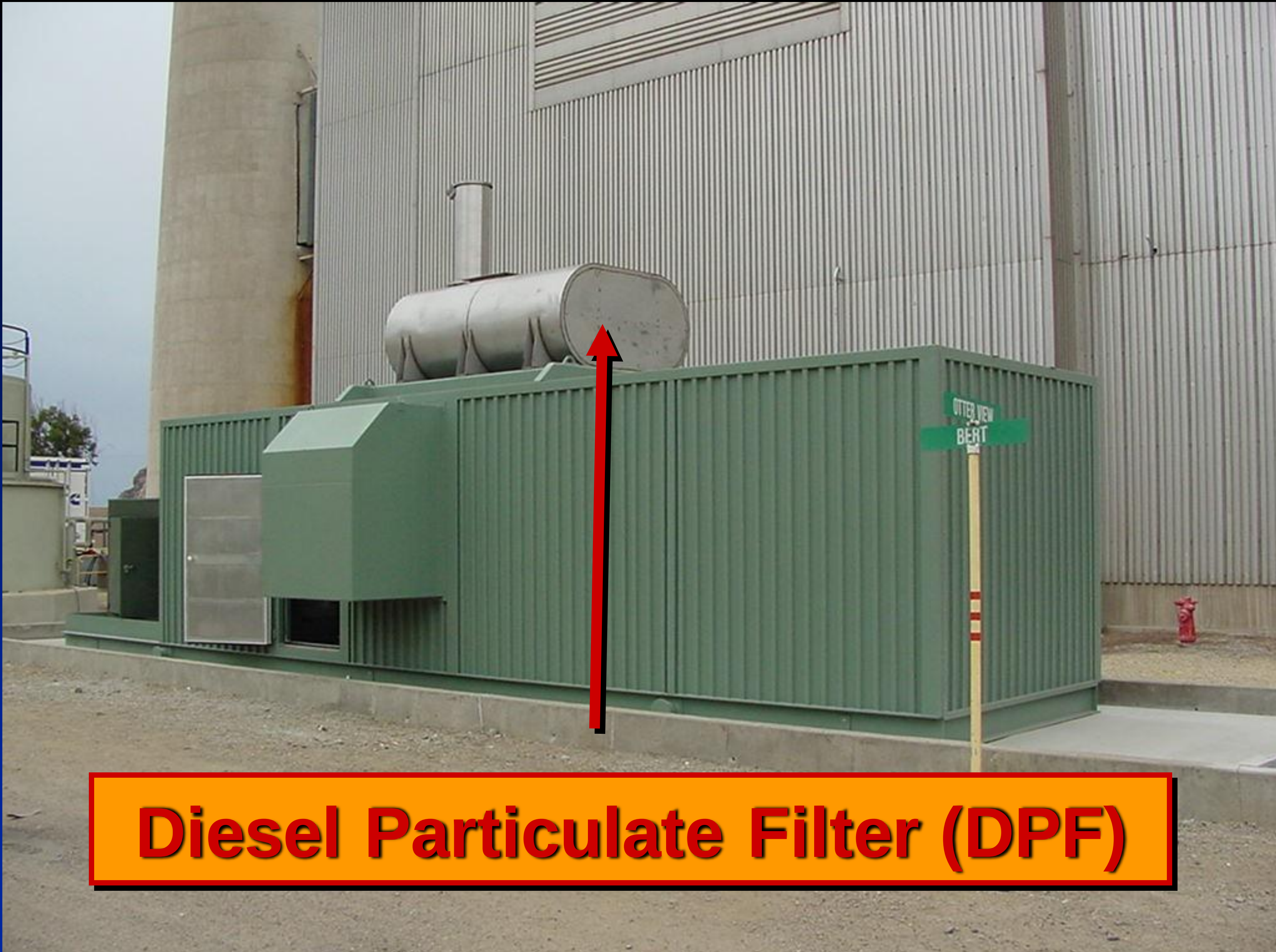
- Performance indicators
  - Pressure differential
  - Liquid flow rate
  - Gas flow rate
  - Scrubber outlet gas temperature
  - Makeup / blowdown rates
  - Scrubber liquid solids content (PM)

Scrubber Performance

- Performance indicators (continued)
  - Scrubber inlet gas and process exhaust gas temperature (PM)
  - Scrubber liquid pH (Acid gas)
  - Neutralizing chemical feed rate (Acid gas)
  - Scrubber liquid specific gravity (Acid gas)


Venturi
Scrubber
Exhaust

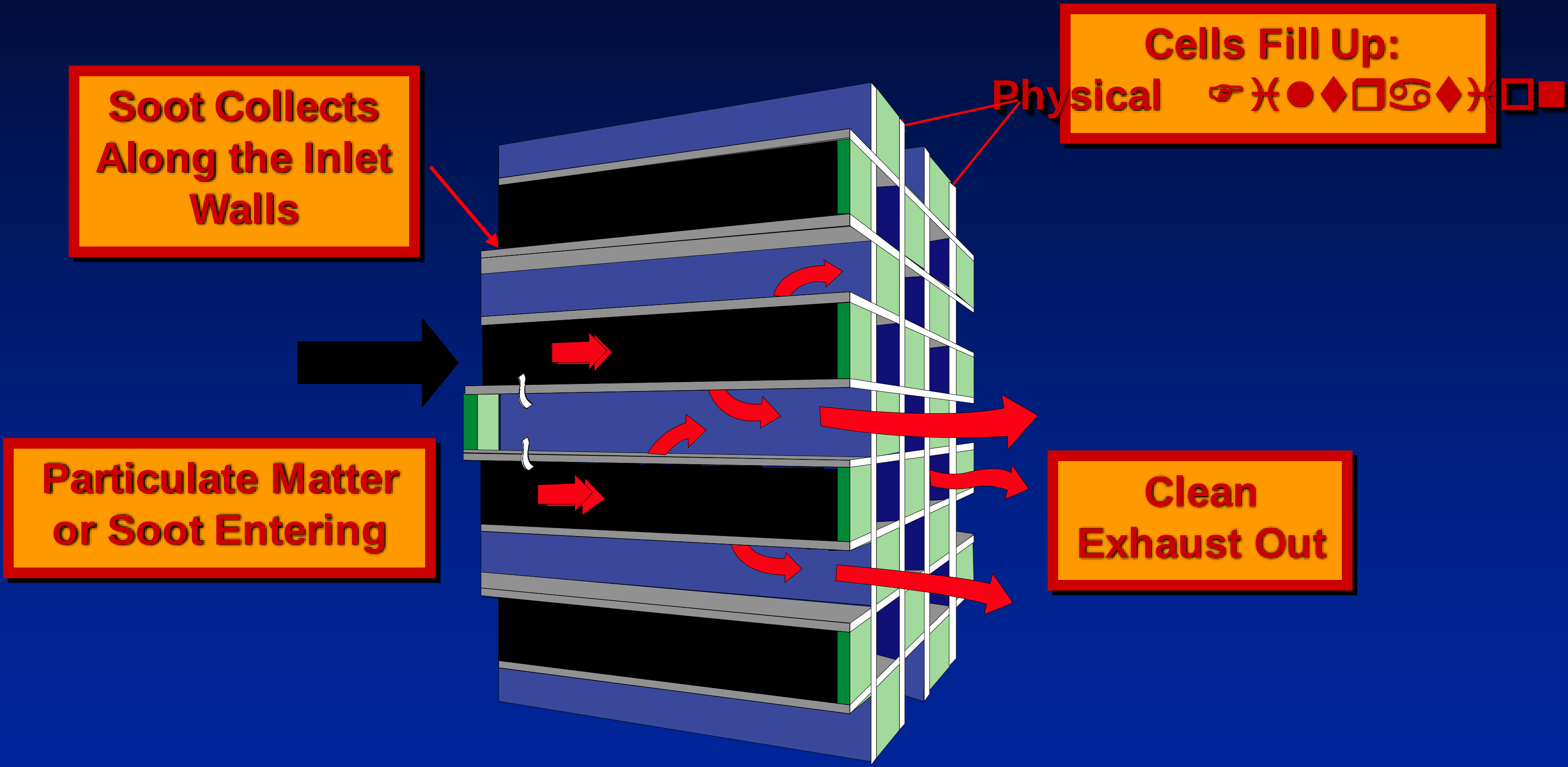
Let's Discuss Diesel Particulate Filters



Diesel Particulate Filter (DPF)

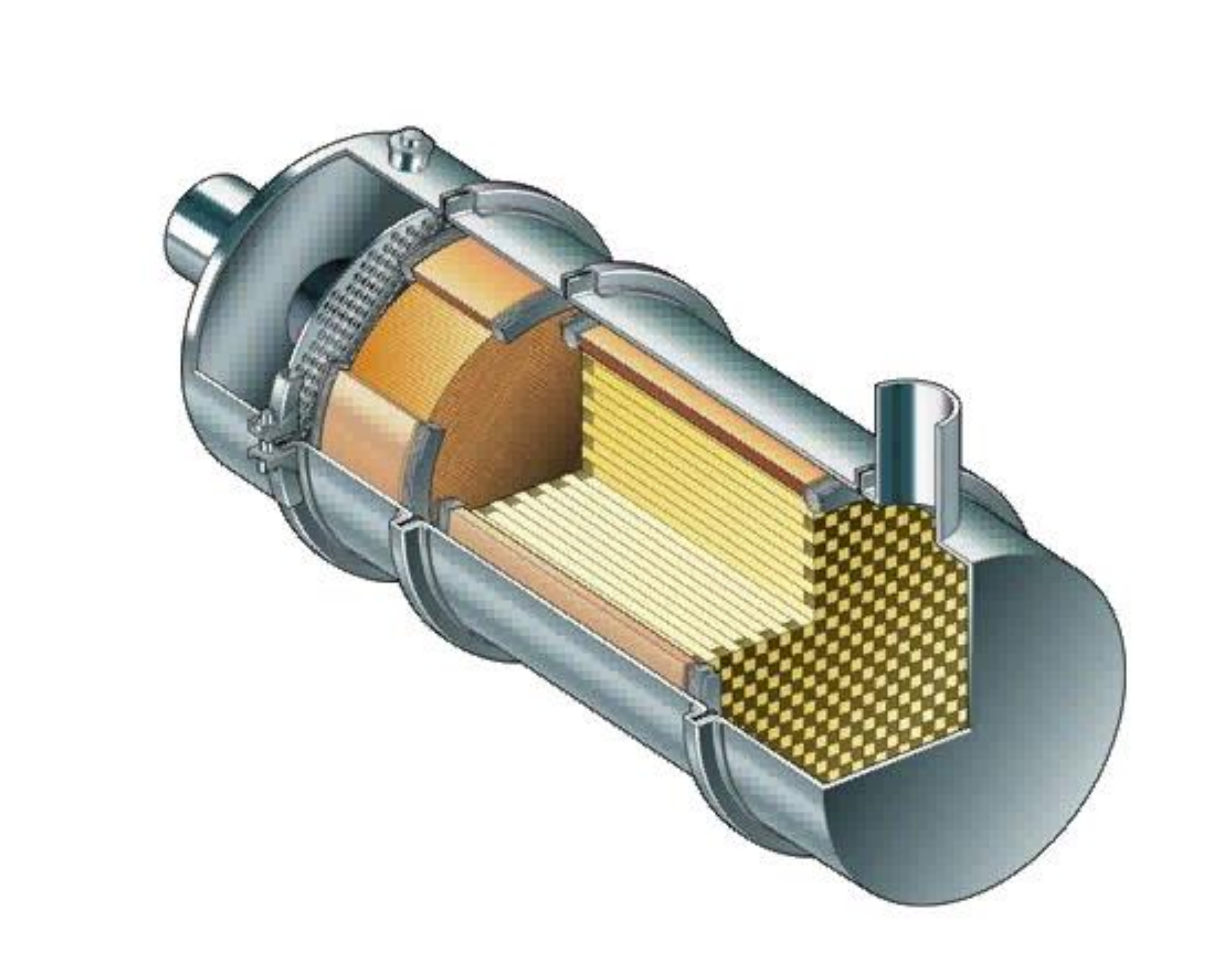
e Filter

What is a DPF



Soot Collects Along the Inlet Walls
Cells Fill Up: Physical ☞♓●♦❒♋♦♓❒■
Particulate Matter or Soot Entering
Clean Exhaust Out

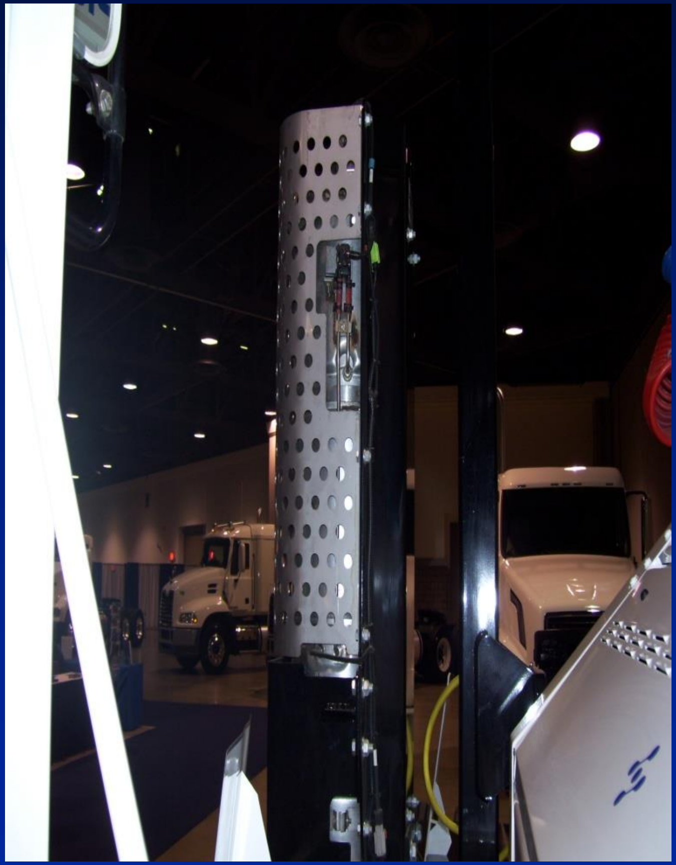
What is a DPF



Regeneration Strategies

Active

Passive



Diesel Particulate Filter (DPF)

- High temperature regeneration (600-650 ºC)
  $C + O_2 \rightarrow CO_2$
- Catalytic regeneration (~250 ºC)
- Oxidize NO to NO_2 → adsorbs → reduces regeneration temperature
- Fuel-borne catalyst
- Ceramic coatings
- Engine adjustments necessary
- Total PM efficiency > 90%

Active Regeneration

- Achieving 550ºC
  - Electrical Heater
  - Dosing (flame front)

Electrical Heater

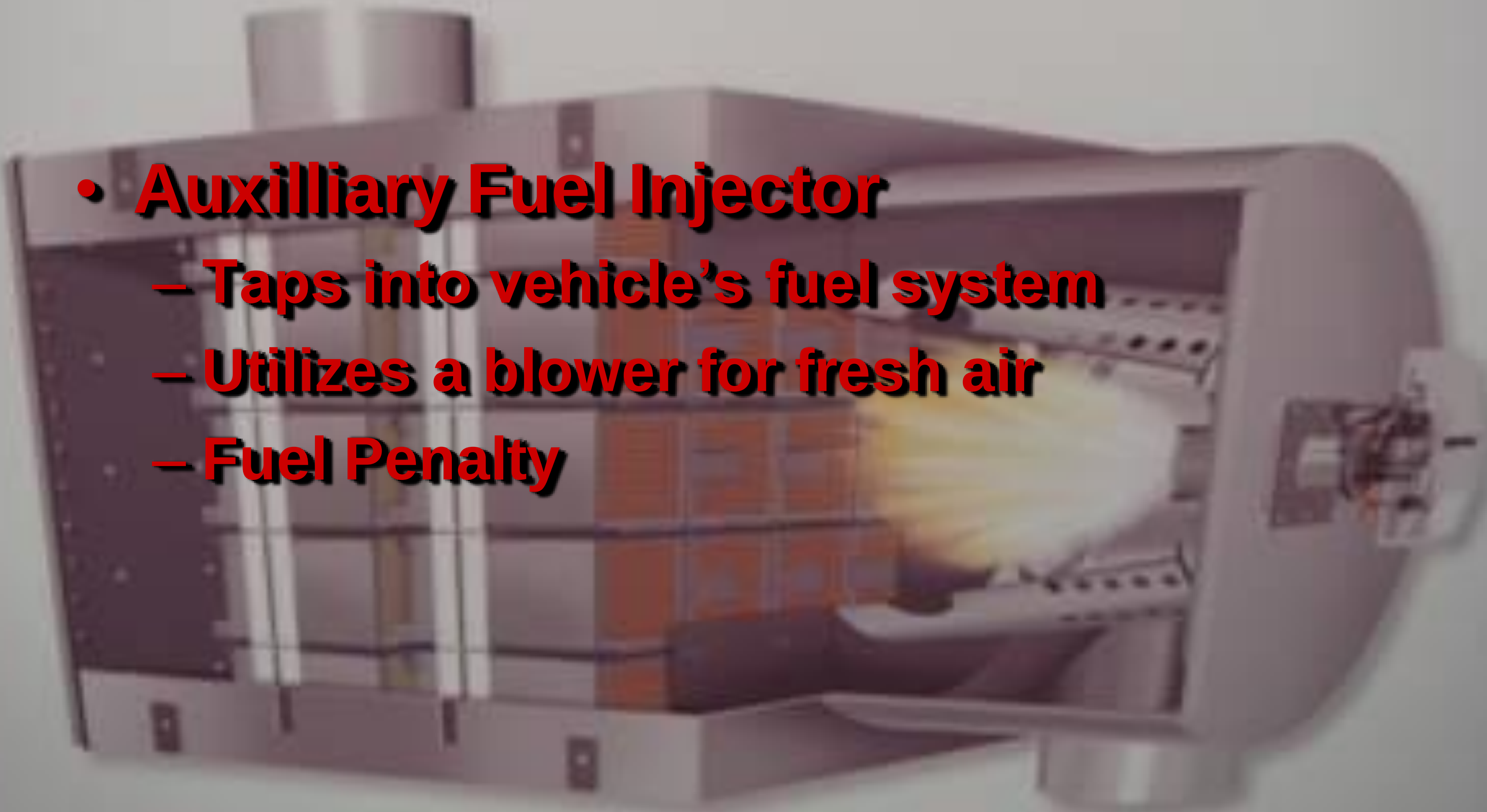
- Uses a heating element similar to an electric stove
- Performed while vehicle is offline

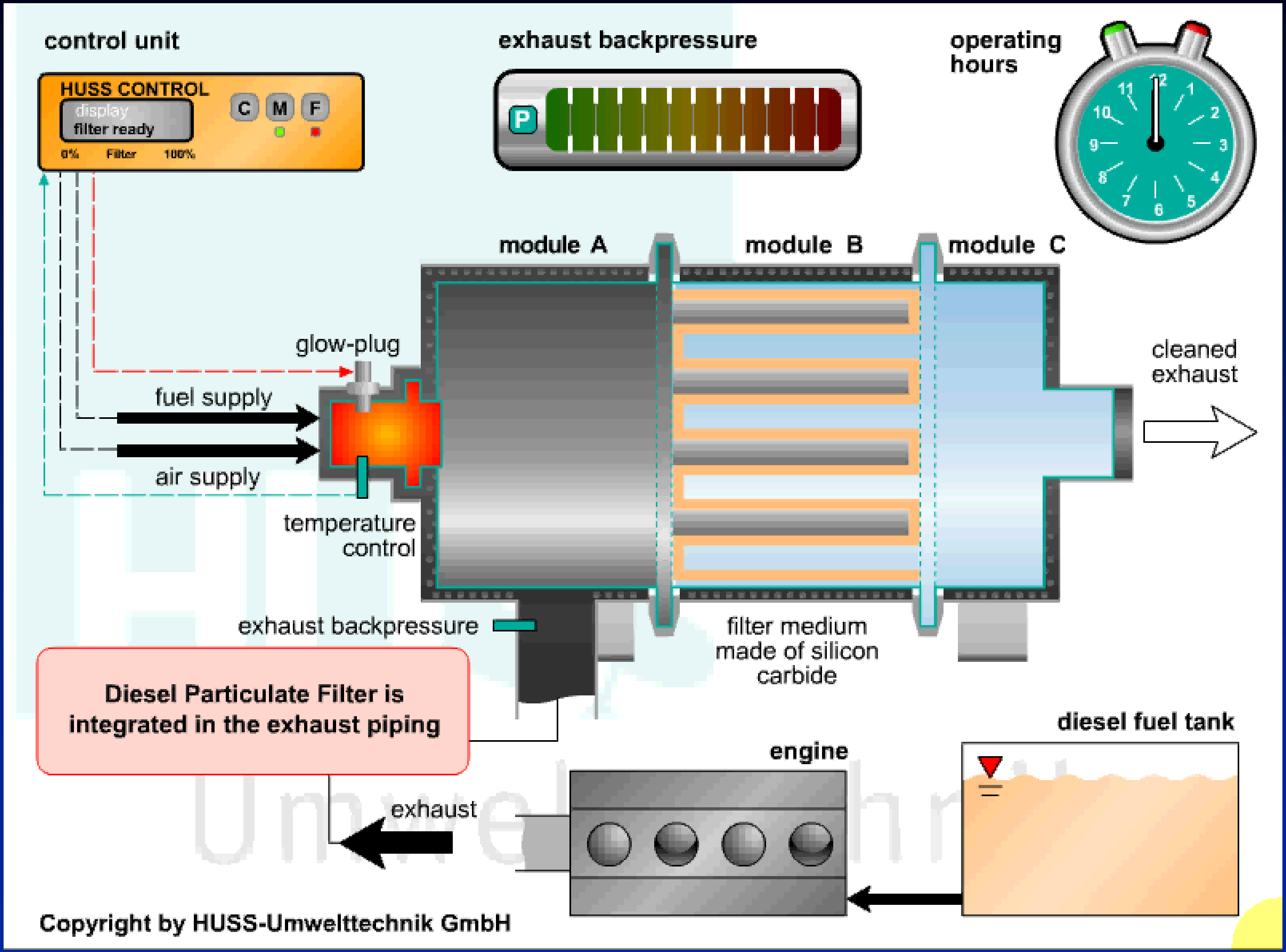
City Bus
Electrical Active Regeneration Cycle

Portable On-Board

Fuel Dosing

- Auxilliary Fuel Injector
  - Taps into vehicle's fuel system
  - Utilizes a blower for fresh air
  - Fuel Penalty



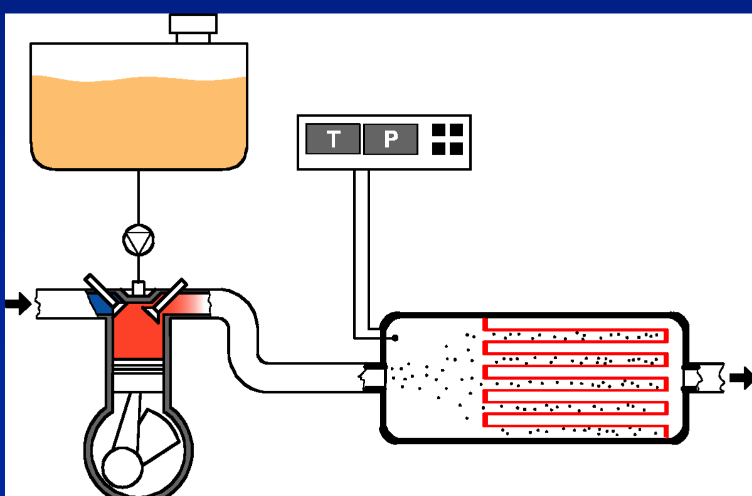

control unit
HUSS CONTROL
display
filter ready
C
M
F
0%
Filter
100%
exhaust backpressure
P
operating hours
module A
module B
module C
glow-plug
fuel supply
air supply
temperature control
cleaned exhaust
exhaust backpressure
filter medium made of silicon carbide
Diesel Particulate Filter is integrated in the exhaust piping
diesel fuel tank
engine
exhaust

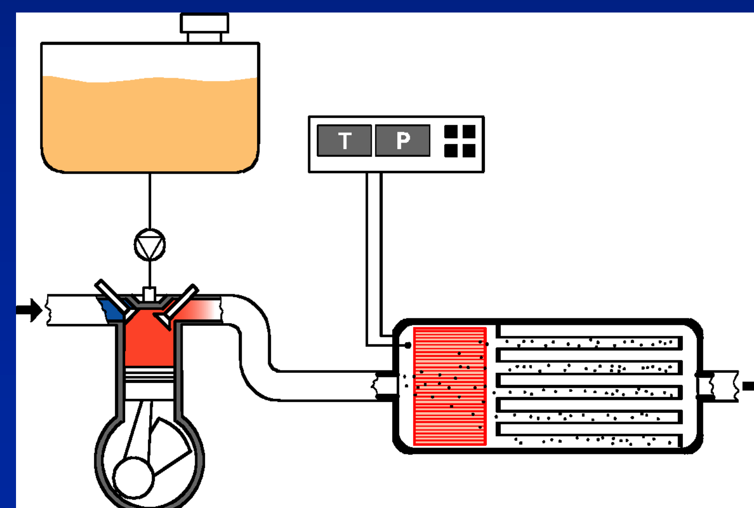
Active Regeneration (O_2 @ 550º C)

- Electrical
  - Online Electrical (Rypos)
  - Offline/Off-board
  - Offline/On-board
- Fuel Dosing
  - Flame front using auxiliary injector and vehicle's fuel supply
  - Air intake

Passive Regeneration

- NO2 oxidizes soot @ around 250º C
- NO2 generation
  - Diesel Oxidation Catalysts
  - Catalyzed Filters
  - Fuel Born Catalysts (FBC)?





Soot & Ash

Definition of Soot

Soot is a byproduct of incomplete combustion

Soot Cleaning

- DPF Collects the soot
- Elevated exhaust temperatures convert the soot to vapor

Definition of Ash

Ash is Noncombustible residue of a lubricating oil or fuel

Ash Cleaning

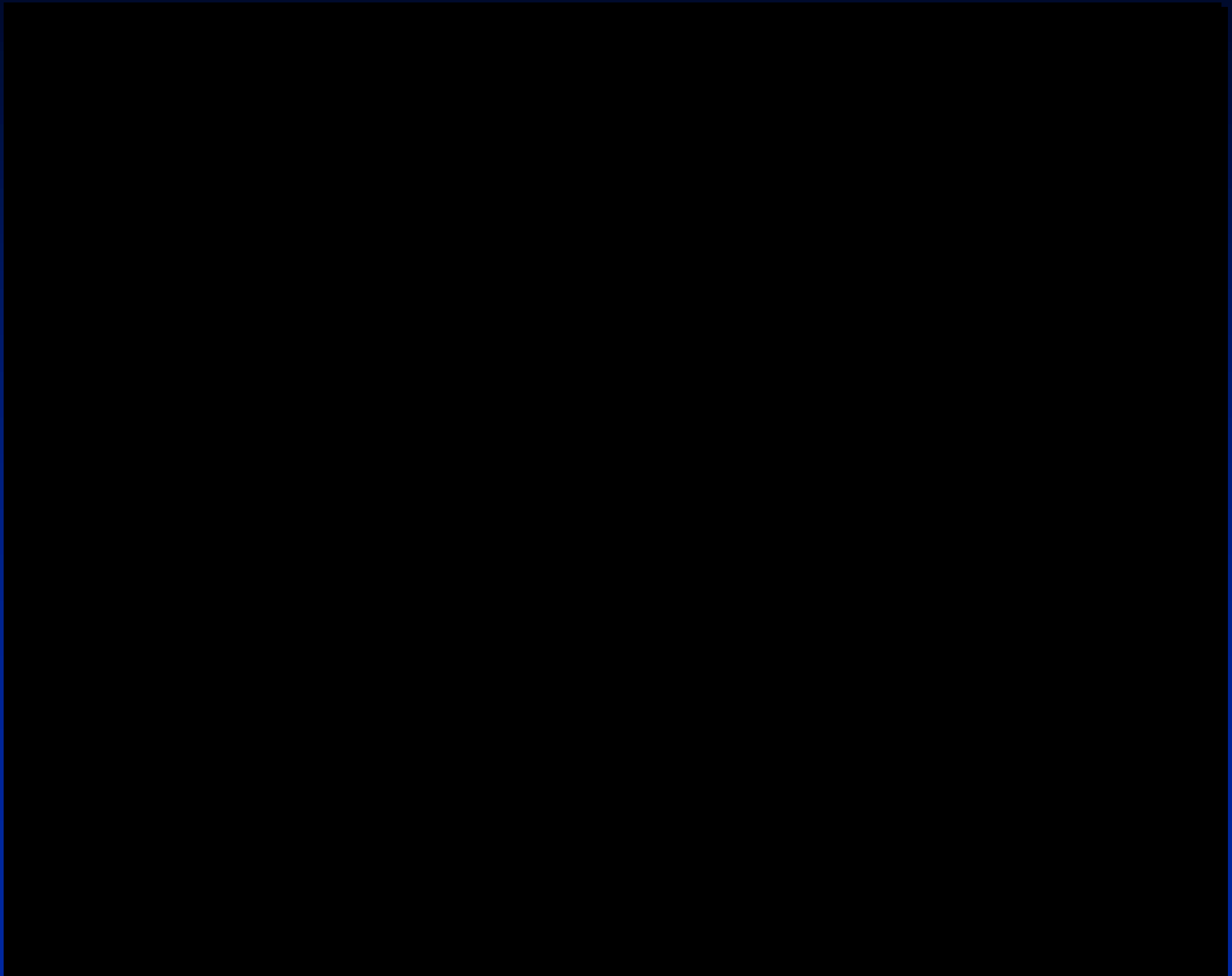
- DPF Collects the ash
- Ash is removed using a special service tool

Aftertreatment Regeneration Device (ARD)

- **What is ARD?**
  - **ARD is the device that increases exhaust gas temperature to enable regenerate the DPF**

- **What are the benefits of the CRS System?**
  - **Regenerates under all conditions**

Comical Relief



Typical PM Spray Booth


Spray Booth
Filter Inspection


Spray Booth
Filter Inspection


Spray Booth
Filter Inspection


PM Control: Wet Suppression

PM Control: Wet Suppression

Gas Fired I.C. Engine Controls

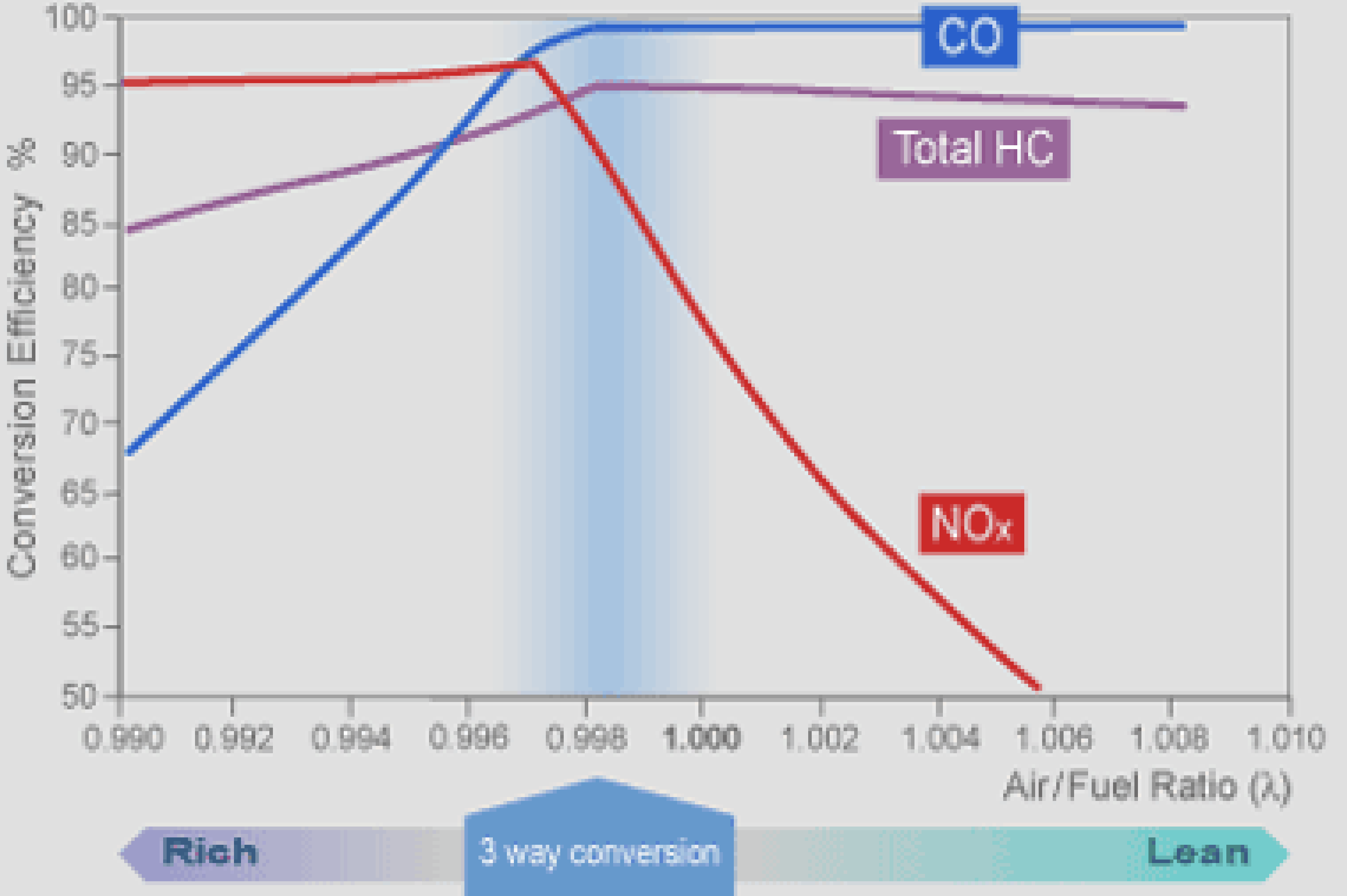
Gas Fired I.C. Engines

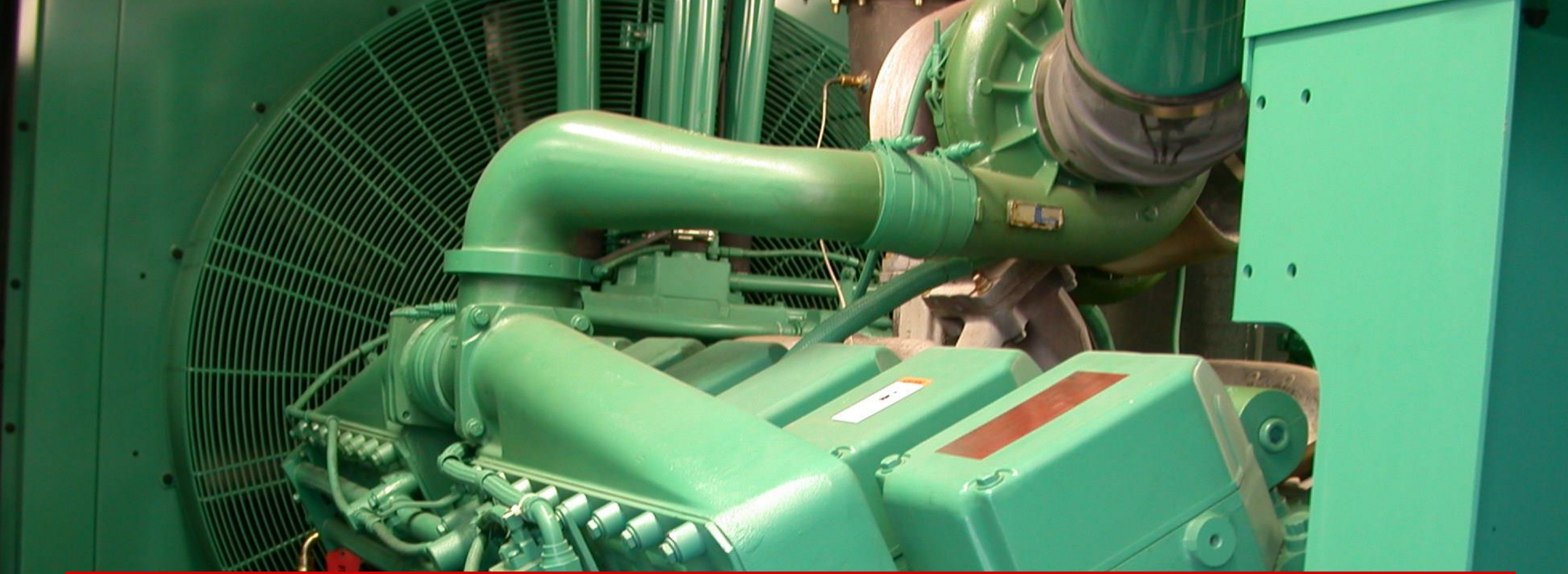
3-way Catalyst:
Non-Selective Catalytic Reduction

3-way Catalyst:
Non-Selective Catalytic Reduction

- Rich burn/NG fired engine
- $2CO + 2NO \rightarrow 2CO_2 + N_2$
- $NO + HC + O_2 \rightarrow N_2 + CO_2 + H_2O$
- 98% control for NO_X & CO

Rich/Lean Catalyst Conversions





- Issues with NSCR:
  - Air/Fuel ratio (AFR) controller required
  - O_2 sensor to maintain AFR
  - Inlet gas temp. range : 800-1200°F
  - Sulfur levels should be < 200 ppmv


SCR Catalyst for IC Engines

https://www.epa.gov/catc/clean-air-technology-center-products

https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors

The End