

# ***Electrostatic Precipitator History & Fundamentals***

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# *Methods Of Particulate Capture*

## → *Mechanical*

- **Filtration (Baghouse)**
- **Cyclone**
- **Venturi Scrubber**
- **Impingement**

## → *Electrical (Electrostatic) Precipitation*



# *Discussion Points*

- **History of ESP Commercialization**
- **ESP Terminology**
- **Dry ESP Basics**
- **Wet ESPs for Utilities**
- **Basics of ESP O&M**

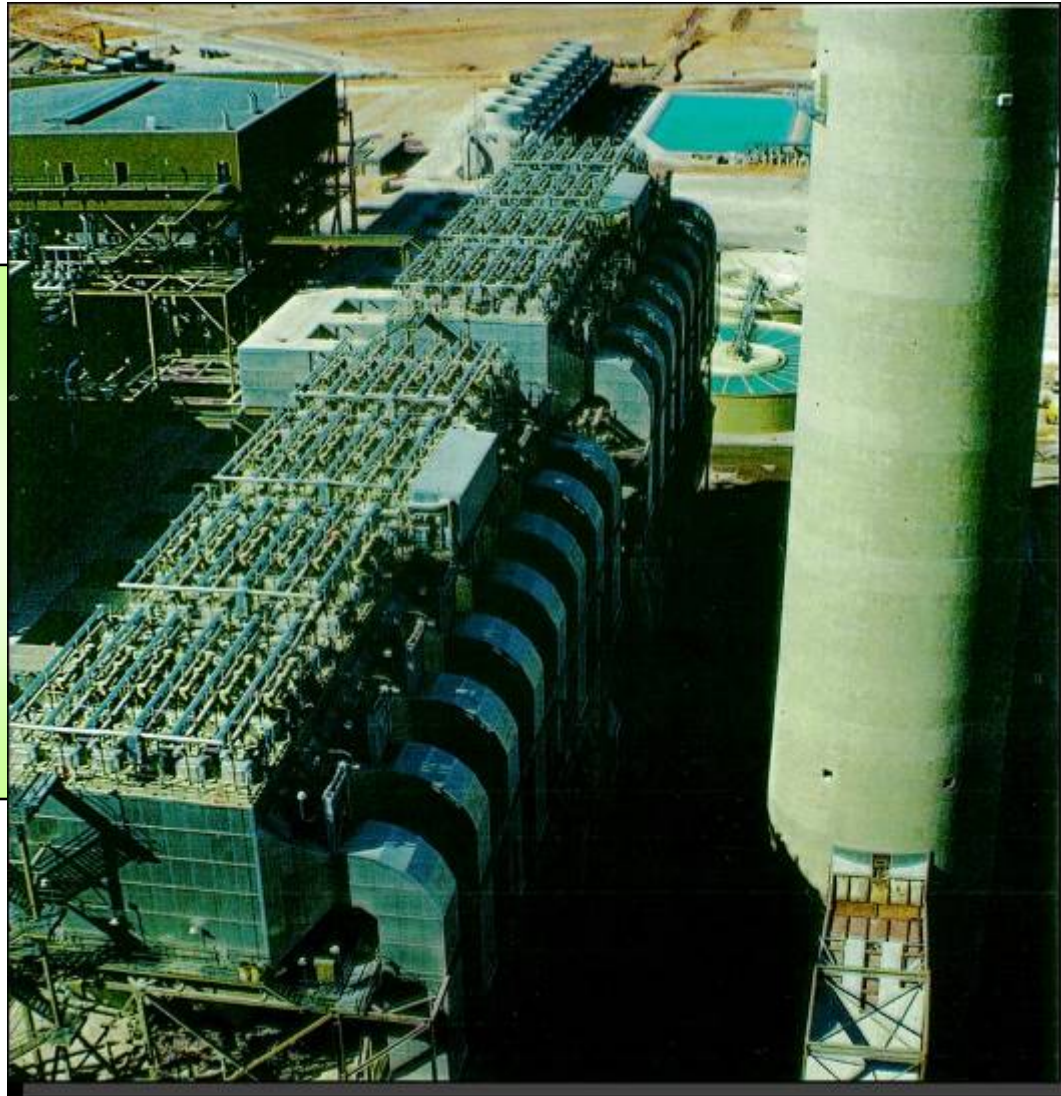


## *How are ESPs different?*

**The separation energy is applied only to the particles themselves instead of the entire gas stream.**

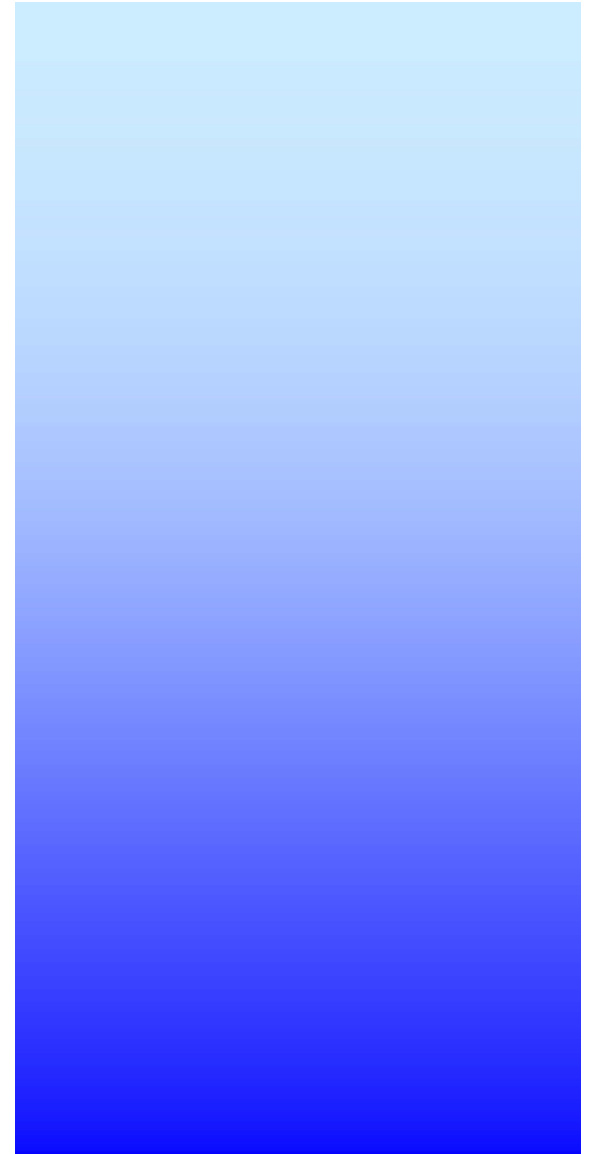


# *Electrostatic Precipitators*



# *What “Gave Birth” to ESPs?*

- **Technology advances in the late 1800s**
- **Industrial growth in the late 1800s / early 1900s**
- **Population growth in the late 1800s / early 1900s**
- **Lawsuits**



# ***Some Pre-1900 ESP Milestones***

- **600 B.C.**      **Greeks and Amber**
  
- **1600**            **William Gilbert**  
    **“Everything rushes towards electriks  
    excepting flame and flaming bodies and the  
    thinnest air...yet they entice smoke...  
    (that is) borne towards electriks in a straight line...”**
  
- **1745**            **Benjamin Franklin**  
    – points **“throwing off the electric fire...”**  
    **(corona discharge)**
  
- **1885**            **Sir Oliver Lodge/Walker & Hutchings**  
    – **lead smelter ESP, North Wales (failure)**



# Post - 1900



**Dr. Frederick G. Cottrell**  
**(1877 - 1948)**

- **Instructor & Electro-chemical researcher, University of California**
- **Developed the “Pubescent Electrode”**
- **Lab experiments at 10-15 kV**
- **First commercial ESP:  
Pinole, CA 1907  
SO<sub>3</sub> Mist (Fortunate)  
200 CFM**



# *Early Cottrell Installations*

- **Pinole Works and Selby Smelter - 1907**
- **Balaklala, Shasta CA – 1910**
  - **Zinc/Lead Smelter, 250,00 CFM**
- **Riverside, CA – 1912**
  - **Cement Kiln, 1,000,000 CFM**
- **Raritan Copper Works, NJ – 1913**
  - **Gold & Silver Fume Recovery, 10,000 CFM**
- **Anaconda Copper Smelter, Montana – 1919**
  - **2,000,000 CFM**
- **First Utility Flyash ESP - 1923**



# *The Research Corporation - 1912*

- Cottrell exited the field
- Non-profit to promote research in science
- Led to formation of Research-Cottrell and Western Precipitation  JOY  B&W
- Still in existence today  
(Cottrell Scholarships)

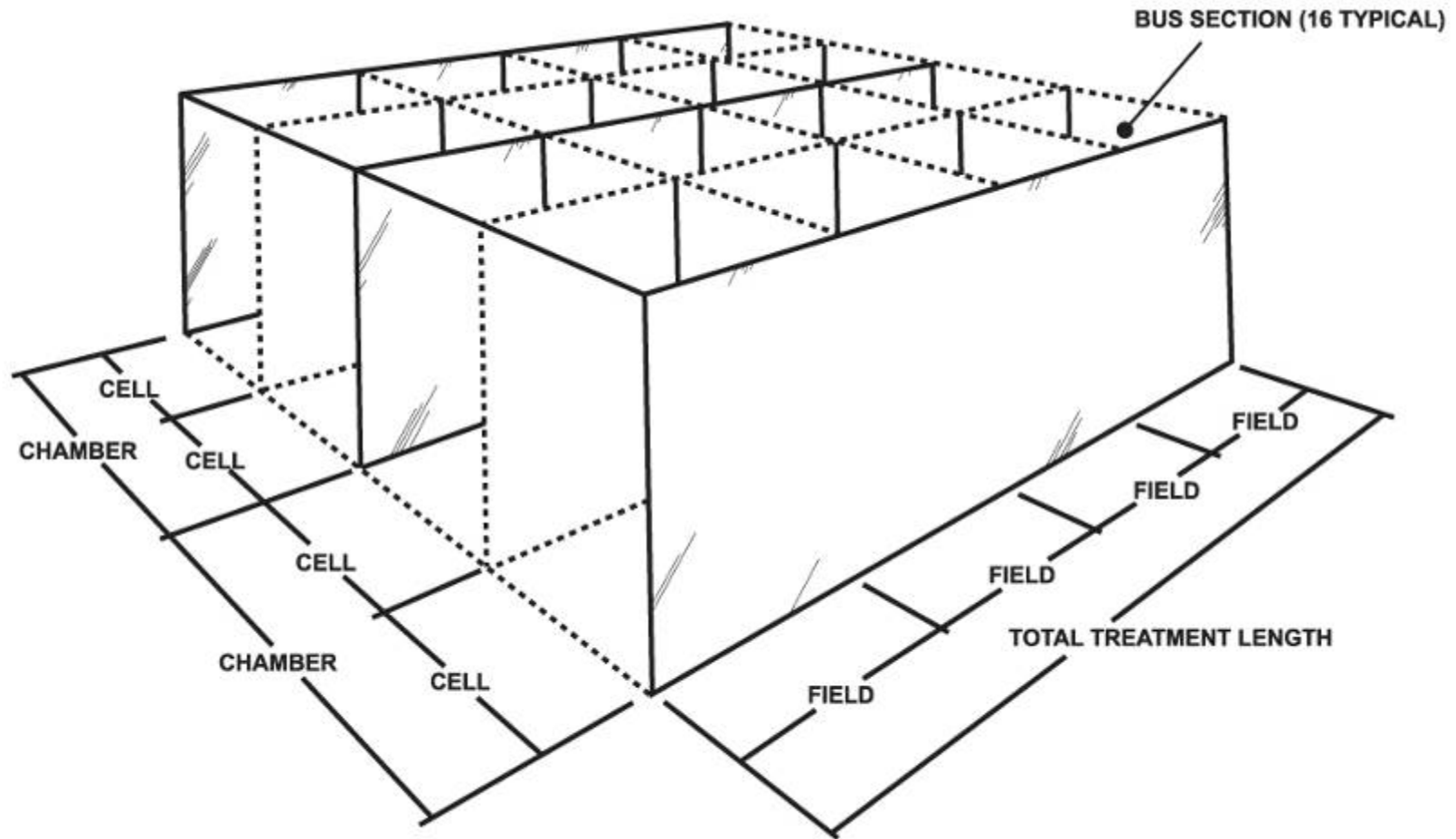


# *Major ESP Applications*

- **Electric Utilities (coal- & oil-fired boilers)**
- **Pulp & Paper (chemical recovery)**
- **Petrochemical (FCC - catalyst)**
- **Cement (kiln dust)**
- **Metallurgical (Cu, Pb, Zn, steel, etc.)**
- **Chemical / Industrial**



# ESP Terminology



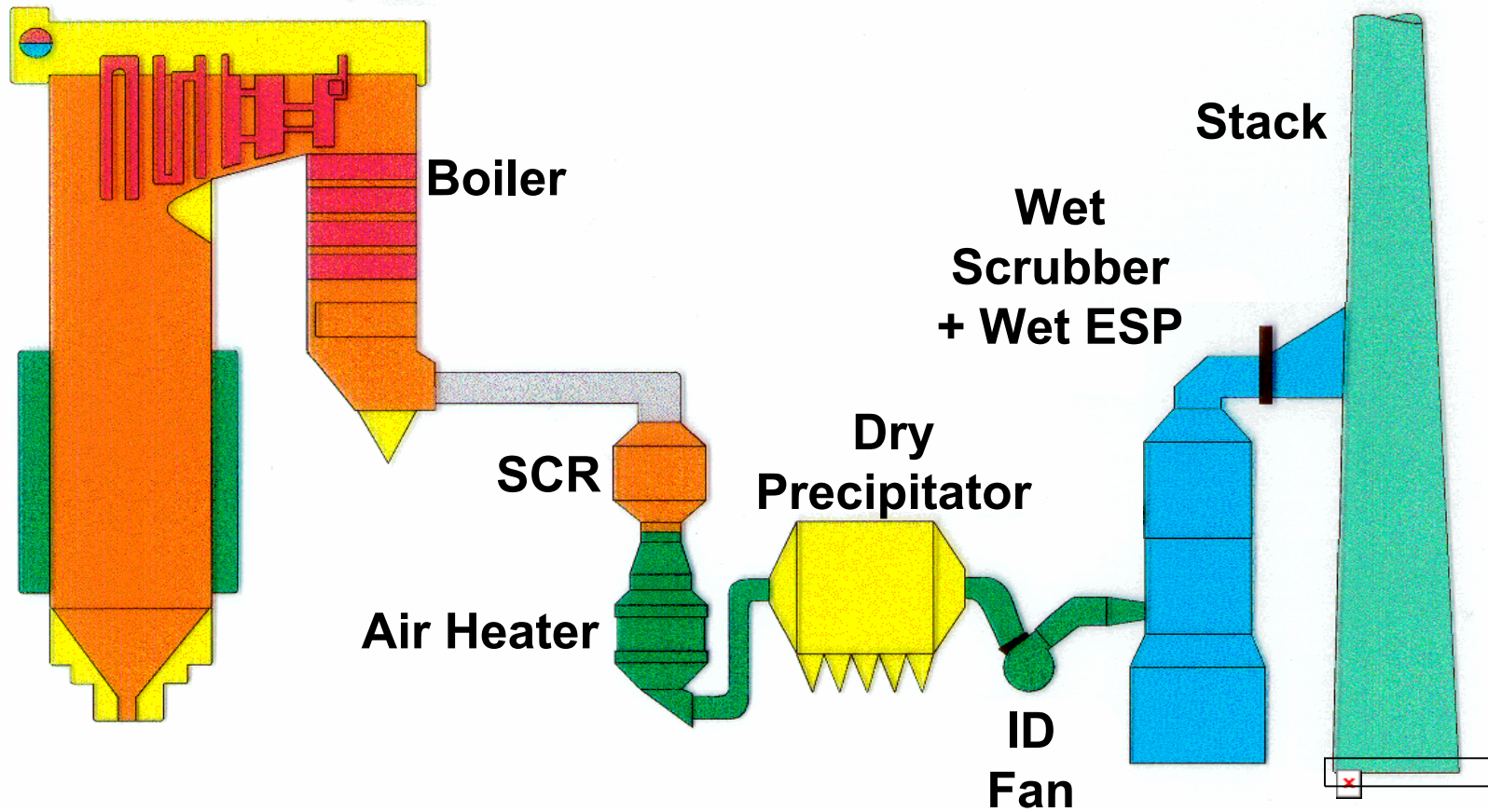
# ESP Types

**DRY** – Horizontal Gas Flow  
Parallel Plate  
Multi-Stage (Multi-Field)  
Mechanical Removal of Collected Material

**WET** – Vertical or Horizontal Gas Flow  
Tubular or Plate  
Smaller, Industrial Applications Common  
Drips/Washed (Not Rapped)



# Environmental Equipment for New Utility Boilers (Medium – High Sulfur Coal Plant)

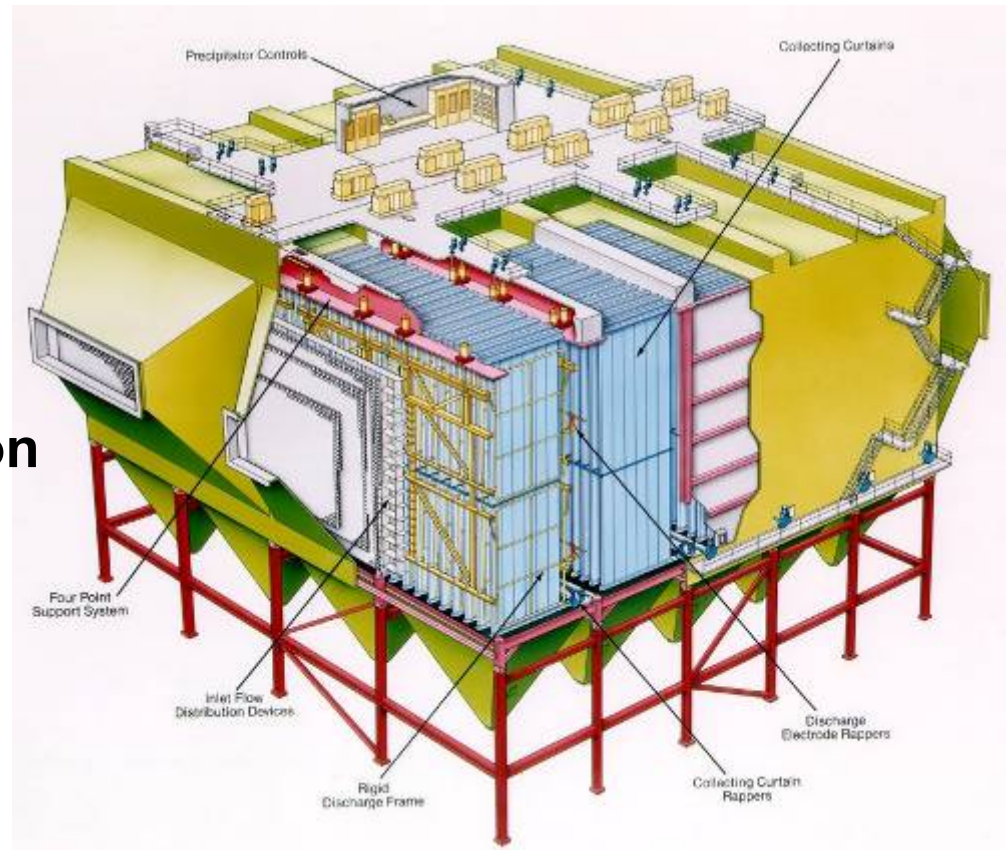


# Dry ESPs

- Dry ESPs - utility flyash, 90+% of market

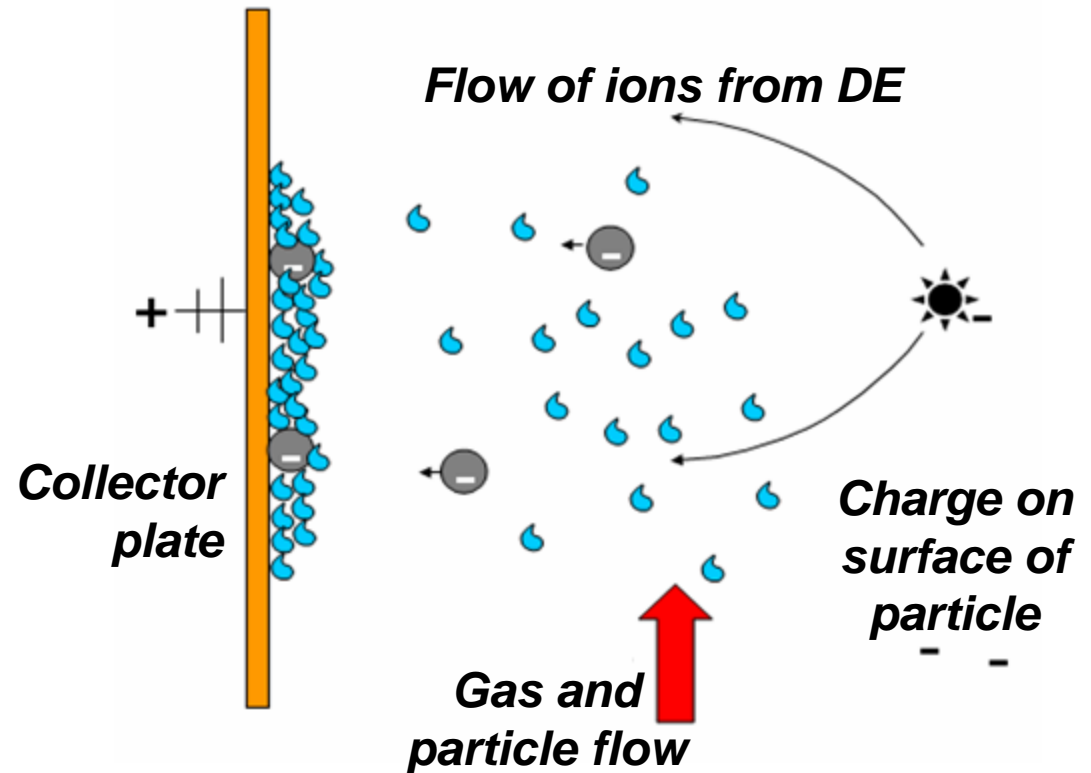
- Dry ESP

- a box with hoppers (or other) at bottom
- flue/ESP transitions, flow control devices
- multiple fields of collection zones
- rappers and auxiliary systems



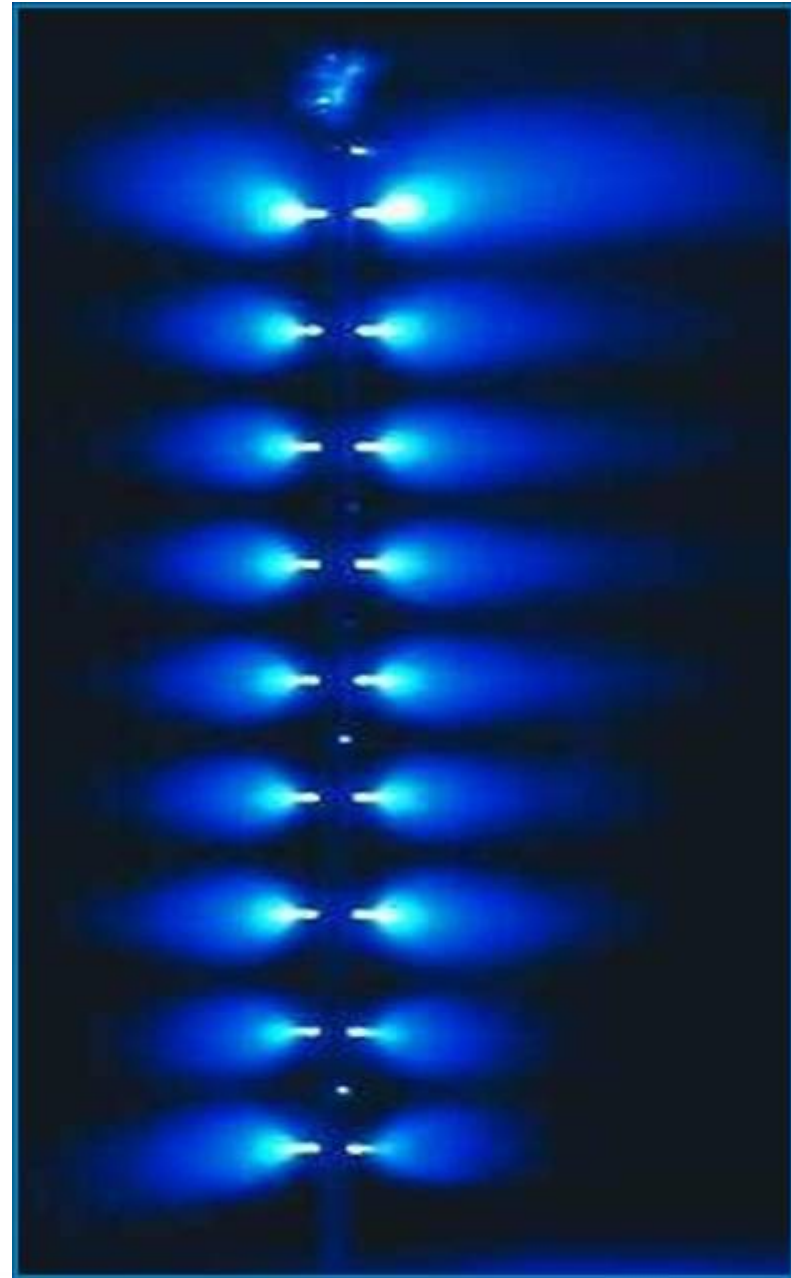
# Electrical Precipitation Steps

- Particle charging (Corona)
- Migration to collection surface electric field
- Agglomeration
- Removal from gas stream



# Corona

**The corona is the electrically active region of the gas stream formed by the electric field**



# *Main Electrical Parts of an ESP*

- **Collecting Electrode (CE)**
  - Tube (Wet) or Plate (Dry or Wet)
  - Anode (Grounded, Positive)
- **Discharge Electrode (DE)**
  - Wire, Spiked Pipe, etc.
  - Cathode (Negative, High Voltage)
- **Power Supply (Transformer-Rectifier, or T-R)**
  - 80 to 100 Kilovolts
  - 100 to 3000 Milliamps
  - Rectified AC
- **Removal System**



# ESP Casing



# *Discharge Electrodes*



# *Collection Electrodes*



# ESP Rappers



# *Transformer-Rectifiers (T-Rs) High Voltage Power Supplies*

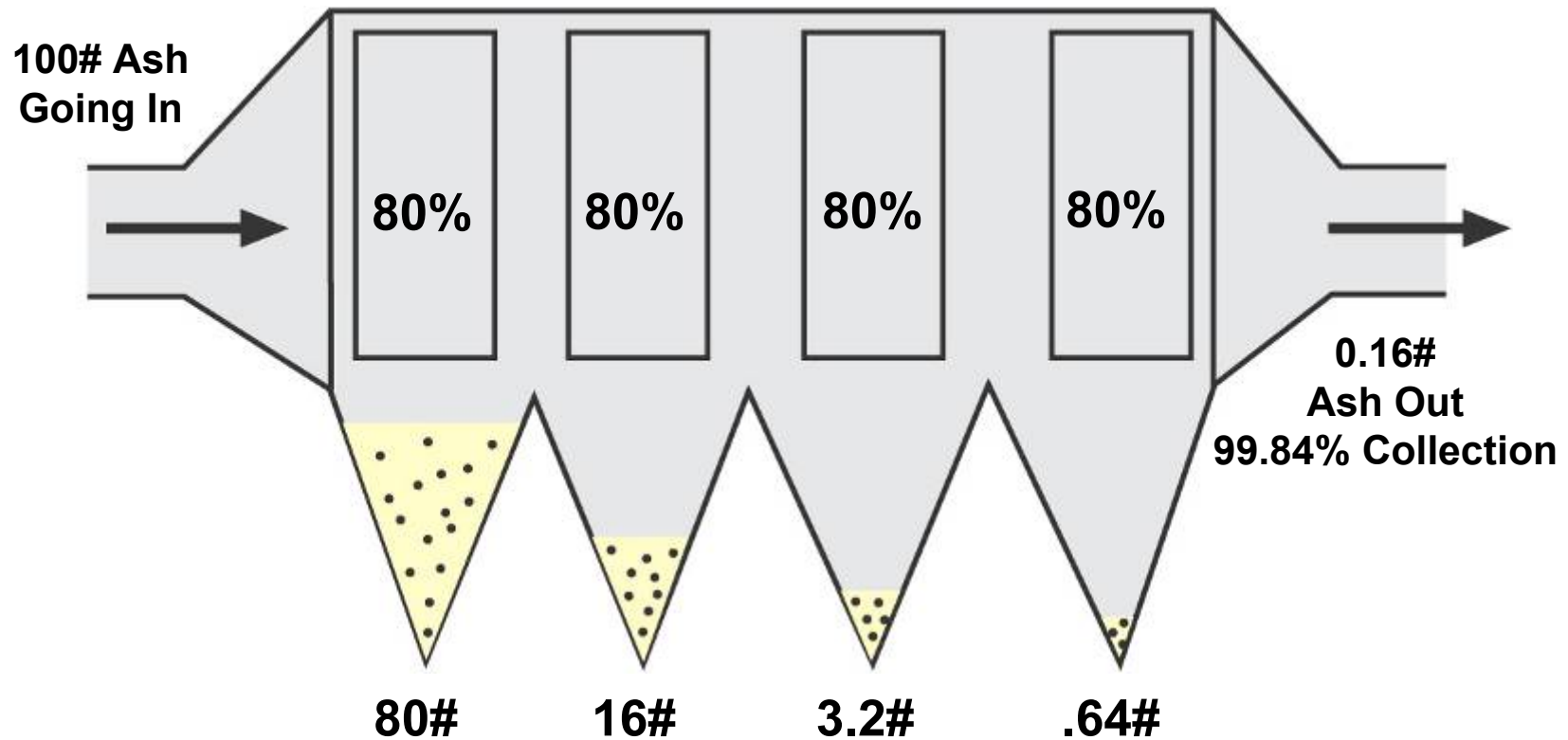


# *Basic ESP Design Considerations*

- **Size (specific collection area, SCA, A/V)**
- **Gas Flow Uniformity (and average velocity)**
- **Sectionalization (how many T-Rs)**
- **Aspect Ratio**  $\left[ \frac{\text{Treatment Length}}{\text{Treatment Height}} \right]$
- **Rapping System (type/effectiveness)**



# Typical ESP Geometric Collection



# *Impacts on ESP Performance*

- **Gas temperature**
- **Gas flow rate**
- **Plant elevation**
- **Particulate composition (chemical)**
- **Particulate size & loading (physical)**
- **Particle resistivity (electrical)**
  - **Function of coal and ash constituents**



# Particulate Resistivity

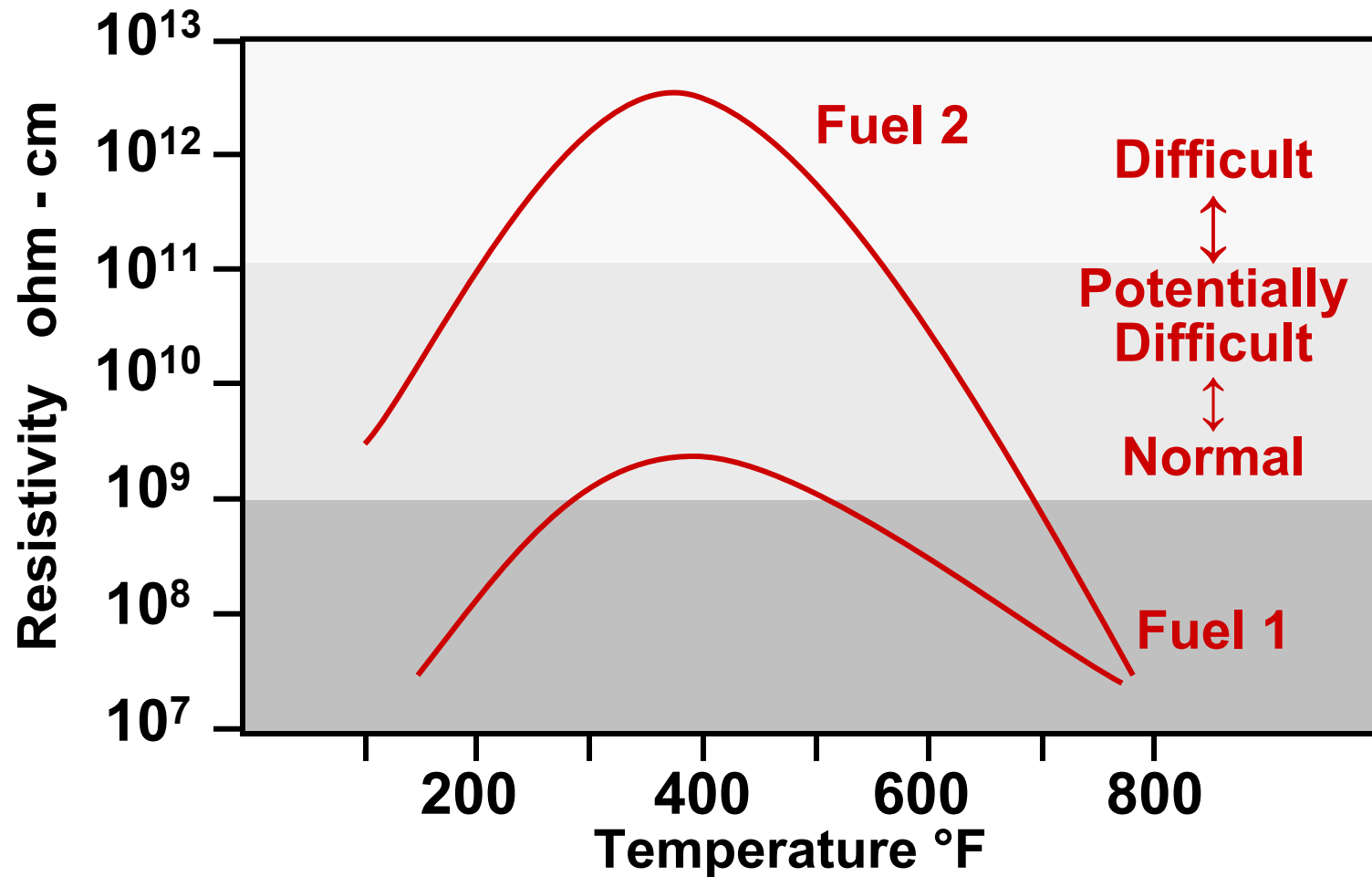
*How poorly/how well the particle conducts:*

$10^4 - 10^7$ OHM-CM	Low
$10^{12} - 10^{13}$ OHM-CM	High
$10^9 - 10^{11}$ OHM-CM	Optimum

- Major factors:
  - ash chemistry
  - $\text{SO}_3$
  - temperature
  - moisture



# Ash Resistivity



# Deutsch-Andersen Equation

$$E = 1 - e^{-(A\omega/V)}$$

**E** = Collection Efficiency

**V** = Flue Gas Volume – ACFM

**A** = Total Collection Area - ft<sup>2</sup>

**$\omega$**  = Average Migration Velocity - ft/sec



## *Migration Velocity, “ $\omega$ ”*

$$\omega = a \frac{E_o \times E_p}{2 \pi \gamma}$$

**a** = particle radius, microns

**E<sub>o</sub>** = charging field strength, volts per cm

**E<sub>p</sub>** = collecting field strength, volts per cm

**$\gamma$**  = gas viscosity, poises



# Hot Side vs. Cold Side ESP Factors

	Hot side	Cold side
<b>Location / Gas Temperature</b>	Prior to A/H, Gas Inlet Temperature 650° F - 850° F	After A/H, Gas Inlet Temperature 250° F – 400° F
<b>Ash Resistivity</b>	Bulk conduction prevails, metallic oxide content of ash	Surface conduction prevails, fuel sulfur / SO <sub>3</sub> content, flue gas moisture
<b>Advantages</b>	Can be used effectively on some low sulfur fuels without gas conditioning	Lower overall heat loss / higher efficiency of plant thermal, flue gas conditioning can be used to improve performance if necessary
<b>Disadvantages</b>	<ol style="list-style-type: none"> <li>1) Performance can degrade on certain fuels (some PRB) fuels required on outage to clean deposits on CEs &amp; DEs.</li> <li>2) Structural design and materials of construction are critical items</li> </ol>	Performance can deteriorate on fuels outside of design limits. There can be low temperature corrosion on high sulfur fuels as well as units where SCRs are added
<b>Commercial status</b>	Most units on western fuels have been replaced by cold side units or fabric filters due to performance degradation. Others on eastern fuels are still operating well. Could be a resurgence to sell ash in the future	Most prevalent today. Various upgrade approaches to improve performance (lower emissions/opacity, fuel switch, etc. drivers) are available



# ***“Hot Side” Dry ESPs for Utility Flyash***

- **Made use of “Bulk” conduction**
  - **Metallic ash components**
  - **High temperature - before air heater, 600 to 800F**
- **Western fuels (low sulfur)**
- **Performance degraded with time**
  - **(Sodium depletion?)**
- **Warranty problems - litigation - baghouses**
  - **1970s, 1980s**



# *ESP Sizing Sequence*

- **Determine sizing indicators**
- **Select migration velocity**
- **Determine surface arrangement**
- **Optimize arrangement**
- **Select TR set size**



# Precipitator Technical Data Sheet

Customer <u>x</u>	P <u>x</u>	Fuel Type <u>x</u>	
Plant <u>x</u>	Date _____	Proximate Anal. Perf.	Range -%
A/E _____	Engr. _____	Moisture _____	_____
		Volatile Matter _____	_____
		Fixed Carbon _____	_____
		Ash _____	_____
		Sulfur _____	_____
		HHV (BTU/lb) _____	_____
<u>Design Conditions</u>		<u>Ultimate Anal.</u>	
Gas Volume (acfm) <u>x</u>	_____	Sulfur _____	_____
Gas Temperature (F) <u>x</u>	_____	Hydrogen _____	_____
Collection Efficiency (%) <u>x</u>	_____		
Emissions (lbs/10E6 BTU) <u>x</u>	_____	Nitrogen _____	_____
Inlet Loading (gr/acf) <u>x</u>	_____	Oxygen _____	_____
Outlet Loading (gr/acf) <u>x</u>	_____	Ash _____	_____
Carbon _____	_____	Moisture _____	_____
<u>Sizing</u>		Chlorine _____	_____
# of ESP Casings _____			
# of Lanes per Casing _____			
Plate Height (m) _____			
# and Depth of Field (m) _____			
# and Size of TR Set (mA) _____	(per casing)		



# Precipitator Technical Data Sheet

<u>ESP Data</u>	<u>Ash Anal.</u>
Spare Surface <input checked="" type="checkbox"/> Lane Spacing (mm) _____	SiO <sub>2</sub>
Collection Surface (ft <sup>2</sup> ) _____	Al <sub>2</sub> O <sub>3</sub>
Migration Velocity (cm/sec) _____	TiO <sub>2</sub>
Gas Velocity (ft/sec) _____ Aspect Ratio _____	Fe <sub>2</sub> O <sub>3</sub>
SCA (ft <sup>2</sup> /Kacfm) _____	K <sub>2</sub> O
Fields with Pointed Strips _____	P <sub>2</sub> O <sub>5</sub>
Fields with Flat Strips _____	CaO
Type of Firing <input checked="" type="checkbox"/> _____	MgO
Carbon in Ash (%) <input checked="" type="checkbox"/> _____	Na <sub>2</sub> O
Moisture in Flue Gas (%) <input checked="" type="checkbox"/> _____	SO <sub>3</sub>
Sec. Voltage Rating (KV) _____	LiO <sub>2</sub>

Provide this data along with complete listing of fuel and ash analysis



# *Current Dry ESP Design (typical)*

<b>Gas velocity.....</b>	<b>3.5 - 5 ft/sec</b>
<b>SCA.....</b>	<b>300 - 500 ft<sup>2</sup>/kacfm</b>
<b>Collection efficiency.....</b>	<b>99.5 - 99.99 %</b>
<b>Number of fields.....</b>	<b>4 - 6</b>
<b>TR Sets.....</b>	<b>105 kV peak voltage</b>
<b>Rapping.....</b>	<b>magnetic impulse type</b>
<b>Rigid electrodes.....</b>	<b>pipe &amp; spike common</b>
<b>Wide plate spacing.....</b>	<b>up to 16" common</b>



# ***Dry ESP Improvements & Trends***

## ***1980s to Present***

- **Rigid (mast) discharge electrodes (1980)**
- **Microprocessor T-R & rapper controls (1982)**
- **Wider plate spacing (1980s)**
  - was 9" to 10"
  - early 1980s: 12"
  - standard now is 16" (T-Rs @ 100 + kV peak)



# *Dry ESP Improvements & Trends*

## *1980s to Present*

- **Computer performance models**
- **Computer flow models**
- **Skewed flow approaches**
- **Central controls & DCS tie-ins**
  - microprocessor controls
  - opacity feedback (energy management)
  - optimized rapping
  - data acquisition
  - SMPS (AC power supply)



# ***Wet ESPs for Electric Utilities***



# ***Wet ESPs Are Not New!***

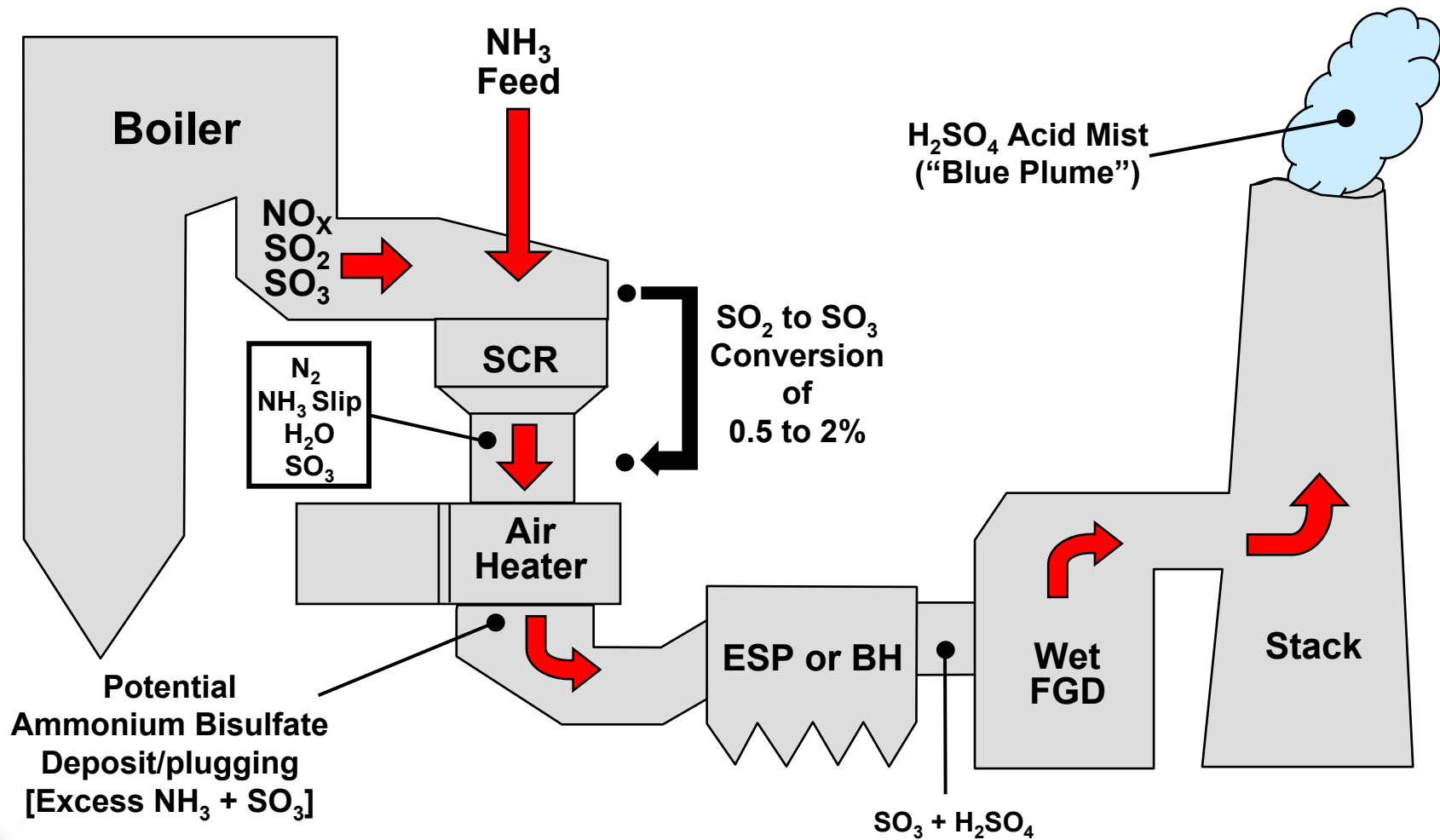
- **First commercial ESP was a wet unit put in service in 1907 in California for collection of acid mist**
- **Wet ESPs have been used in the following industries/applications:**
  - **Non-ferrous smelters**
  - **Steel industry**
  - **Spent acid plants**
  - **Paper industry**
  - **Incineration**
  - **Power plants burning unique fuels**

***Thousands of industrial Wet ESPs  
have been installed since 1907***

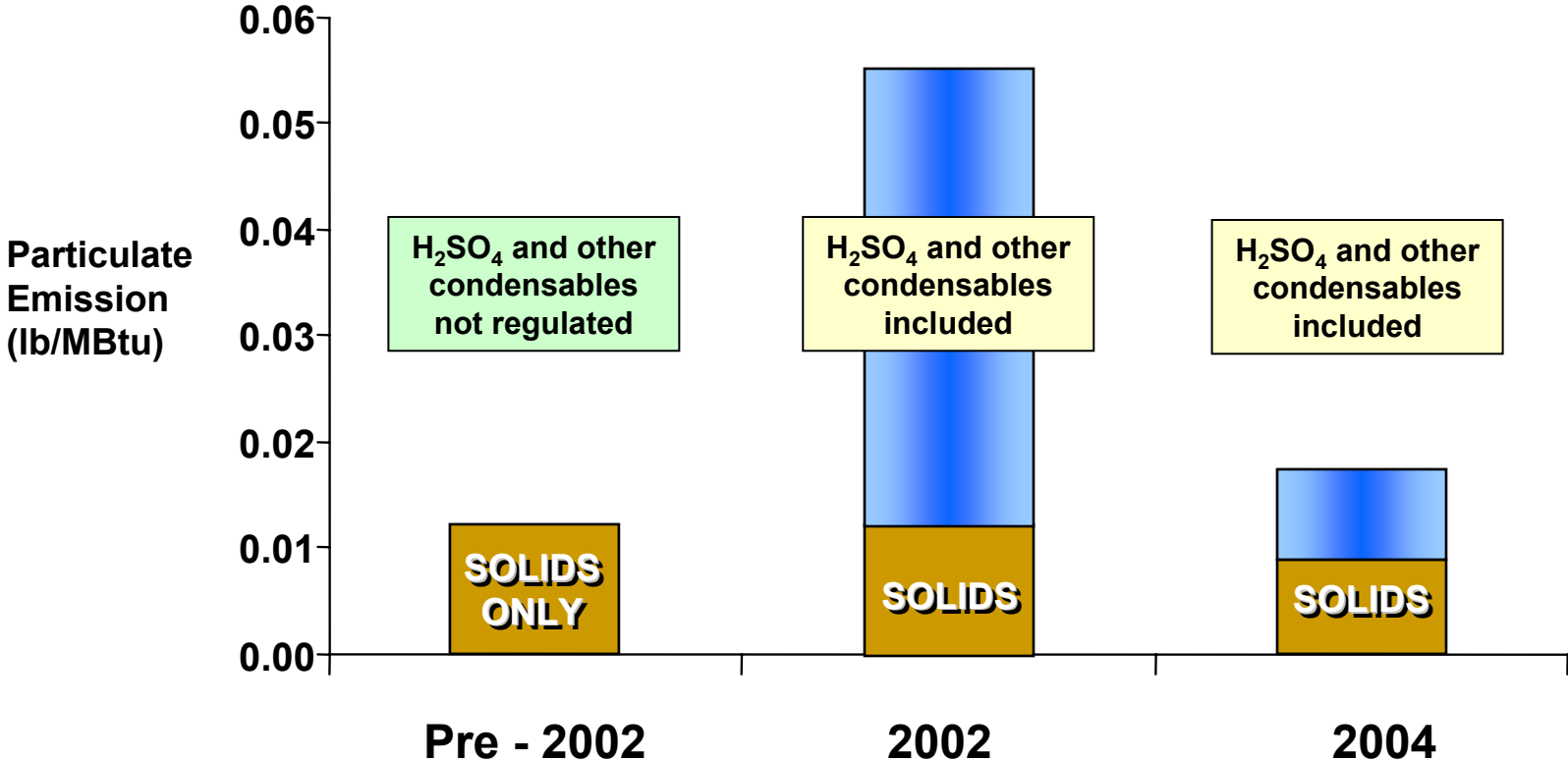


# Industry-Wide Issue:

## Acid Mist Emissions $SO_2$ to $SO_3$ Conversion



# Particulate Permit Requirements Redefined for New Power Plants



Total particulate permit requirement redefined

Permit levels for total particulate, including condensables, are significantly reduced



# *Sulfur Trioxide Issues*

## *Primary causes of SO<sub>3</sub> in flue gas:*

- **SO<sub>2</sub> and SO<sub>3</sub> are formed during combustion of sulfur containing fossil fuels**
- **Additional SO<sub>2</sub> to SO<sub>3</sub> conversion can be due to catalysis with metals such as iron and vanadium**
- **SCR catalyst (vanadium) increases SO<sub>3</sub> levels by catalytic oxidation**



# *Sulfur Trioxide Issues*

## *The Problem:*

- **SO<sub>3</sub> is a known culprit for corrosion of flues, air heaters, and other equipment**
- **Sulfur trioxide (SO<sub>3</sub>) forms an aerosol in a wet scrubber which contributes to a visible trailing plume**
- **A wet FGD collects very little SO<sub>3</sub> mist**
- **SO<sub>3</sub> mist may be considered PM<sub>2.5</sub> and may become regulated**
- **There can be more SO<sub>3</sub> mist than dry particulate in many wet scrubber stacks**
- **Control of SO<sub>3</sub> mist may be required for permits**



# Wet FGD Stack Particulate Emission

## ***Includes:***

- Flyash
- Gypsum carryover
- H<sub>2</sub>SO<sub>4</sub>

## ***Issues:***

- Emission limit new permits, regulations?
- Opacity – instrument vs. visible
- Stack blue haze – public relations



# *New Permits are Ratcheting Down Emissions and Guarantees*

## *Present: Wisconsin New Plant Requirement*

**Total Particulate – 0.015 lb/MMBtu**

**H<sub>2</sub>SO<sub>4</sub> Emissions – 0.009 lb/MMBtu**

**Visual Emissions – 15% Opacity**

## *AES Deepwater (state-of-the-art as of 1986)*

**Total Particulate – .012lb/MMBtu (VOCs excluded)**

**H<sub>2</sub>SO<sub>4</sub> Emissions – <0.009 lb/MMBtu**

**Visual Emissions – <10% Opacity (reheated)**



# ***Wet ESP Process Challenges***

- **Fine particulate**
- **SCR effects**
- **Corona suppression (space charge)**
- **Visual opacity and/or emissions**
- **Total particulate issue – new permits**



# Process Differences

## Wet ESPs vs. Dry ESPs

	Dry ESP	Wet ESP
Gas Temperature	250 - 850F range	Saturation temperature (typically 150F in Wet FGD)
Gas Humidity	< 10% typical	100%
Power Density	Variable with coal sulfur content and ash chemistry	Significantly higher than Dry ESP
Resistivity	Critical design factor	Not a design factor
Gas Velocity	5 fps $\pm$	10 fps $\pm$
Treatment Time	10 seconds $\pm$ typical	1-5 seconds $\pm$ typical
Re-entrainment	Important factor	Not a factor
Corrosion	Mild steel (typical)	Specialty metals and/or plastics



# Wet ESP Experience in North American Power Plant Applications

<b>Customer &amp; Location</b>	<b>Comm'l Operation</b>	<b>Fuel</b>	<b>Unit Size</b>	<b>Key Features of Wet ESP</b>
<b>Penn Power &amp; Light</b> Sudbury Station	1975	Coal (Anthracite)	Pilot	B&W (Joy) Wet ESP on Wet FGD VERTICALLY INTEGRATED <ul style="list-style-type: none"> <li>• Single Field</li> <li>• 85-92% solid particulate removal demonstrated</li> </ul>
<b>Getty Oil</b> Delaware City	1979	Petroleum Coke	220,000 ACFM	B&W (Joy) Wet ESP VERTICAL FLOW <ul style="list-style-type: none"> <li>• Two (2) Fields – Tubular Type</li> <li>• 95% acid mist removal guaranteed &amp; met</li> </ul>
<b>AES Deepwater Unit 1</b> Pasadena, TX	1986	Petroleum Coke (8% sulfur)	135 MW 634,000 ACFM	FLS (Fluid Ionics) Wet ESP after B&W Wet FGDs VERTICAL FLOW <ul style="list-style-type: none"> <li>• Three (3) Fields</li> <li>• 91% acid mist removal</li> <li>• 99% particulate removal</li> <li>• 0.005 lb/MMBtu guaranteed &amp; met</li> </ul>



# Wet ESP Experience in North American Power Plant Applications

<b>Customer &amp; Location</b>	<b>Comm'l Operation</b>	<b>Fuel</b>	<b>Unit Size</b>	<b>Key Features of Wet ESP</b>
<b>Northern States Power Sherco 1 &amp; 2</b> Becker, MN	1999 Start 2001 Finish	PRB Coal	2 X 750 MW 2,200,000 ACFM (each)	<ul style="list-style-type: none"> <li>• FLS retrofit into scrubbers</li> <li>• VERTICALLY INTEGRATED</li> <li>• 2- field – Tubular Type</li> <li>• Added after particulate scrubbers for opacity control</li> <li>• 95+% particulate removal</li> </ul>
<b>New Brunswick Power Dalhousie 1 &amp; 2</b> Dalhousie, NB	2000	Orimulsion® (2.9% Sulfur)	1 Wet FGD for 2 boilers 315 MW total 1,078,400 ACFM	EEC WESP - on top of B&W Wet FGD - VERTICALLY INTEGRATED <ul style="list-style-type: none"> <li>• Single Field – Tubular Type</li> <li>• Utilized existing space</li> <li>• Retrofit</li> </ul>
<b>New Brunswick Power Coleson Cove</b> Coleson Cove, NB	2004	Orimulsion® (2.9% Sulfur)	2 Absorbers for 3 boilers 550 MW each	B&W/FLS Wet FGD / Wet ESP VERTICALLY INTEGRATED <ul style="list-style-type: none"> <li>• 3 Fields – plate type</li> <li>• 90+% acid mist removal</li> </ul>



# *Types of Utility Wet ESP Installations*

- **Close-Coupled (Integrated) Wet ESP**
- **Wet FGD with Stand-Alone Wet ESP**



# *Stand-Alone Horizontal Wet ESP*



# Close-Coupled Wet ESPs



# *Ongoing ESP Requirements*

- **Materials of construction**
- **New testing methodology**
- **Opacity vs. loading data on wet stacks**



# *ESP*

## *Operation & Maintenance*



# ***ESP Maintenance – Wet & Dry***

- **Electrical readings w/ boiler data, opacity**
- **Walk-down – rappers, etc.**
- **Outage inspection**
  - **alignment**
  - **build-ups**
  - **corrosion**
  - **insulators**
- **Document – review/analyze**
- **Be proactive !**



# ***ESP Performance***

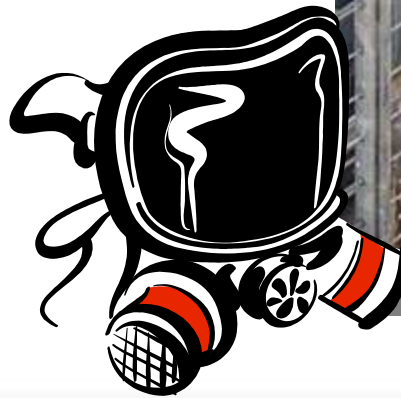
## ***Mechanical Impacts On Performance (Dry Flyash)***

- **Alignment**
  - **Original**
  - **With time**
- **Gas Distribution**
  - **Original**
  - **With time**
- **Re-entrainment**
  - **Rapper settings/maintenance**
  - **Fuel switch**



# *ESP Inspection*

- **Requires respirator**
- **Confined space certificate**
- **Lockout/grounding procedure**
- **Alignment, buildup & corrosion checks**
- **Insulator cleaning**
- **Adequacy of electrode rapping**
- **TR set air load**



# *ESP Diagnostics*

- **Original reports – mechanical acceptance, model study and field test, commissioning/airload, performance tests, etc. – establish original baseline**
- **Maintenance logs, electrical logs, etc.**
- **Look at process – fuel, temperatures, etc.**
- **Internal maintenance – alignment, insulators, build-ups**
- **Flow control – model study**



# *Remedies for ESP Performance Issues*

- **Tune-up / upgrade T-R, rapper controls**
- **Look at process – fuel, temperatures, etc.**
- **Internal maintenance – alignment, insulators, build-ups**
- **Flow control – model study**
- **Gas Conditioning –  $\text{SO}_3$ ,  $\text{NH}_3$**
- **Rebuild / enlarge**





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