

# Reinhold Environmental Ltd.



## 2006 APC Round Table & Expo Presentation

***July 16-18, 2006, Columbus, OH***

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# ***“Coal and the Environment”***

2006 APC Round Table & Expo

17-18 July 2006

Hyatt Regency Hotel  
Columbus, Ohio

Tony Widenman  
Technological Specialist-Fuel & Fuel Engineer  
DTE Energy, Detroit Edison



# Welcome & Good Morning!

## Objective:

To deliver a basic understand of coal  
and it effects on the environment



In the immediate future the electric power industry needs to meet tightening air quality emission limits without significantly reducing availability or derating existing generating units... How?

Fuel switching?

Fuel blending?

Cofiring?

Precombustion coal treatment?

Combustion treatment?

Post combustion treatment?

Magic?



## Fuel Switching

### Back-end Flue Gas Clean-up

- ♦ SCR, SNCR, amine scrubbers, sorbent injection, flue gas additives
- ♦ Capital intensive, increased O&M, possible loss of MW<sub>n</sub>

### Pre-combustion and Combustion Clean-up

- ♦ Combustion tuning, advanced boiler controls, LNO<sub>x</sub> burners, OFA,  $\mu$ -pulverized coal, advanced coal cleaning, MagMill<sup>®</sup>, PepTec<sup>®</sup>, ...
- ♦ Immature or non-power generation technologies
  - ♦ ClearStack<sup>®</sup>, Phenix, Oxygen Enhanced Combustion (OEC), Coal-Water Slurry (CWS), ...
- ♦ Fuel additives, combustion additives,
- ♦ Less capital than back-end clean-up
- ♦ Back-end clean-up still required, but as a polisher; therefore smaller installations



## Fuel Switching

- ♦ Only some users can benefit
- ♦ Issues
  - ♦ Transportation logistics or costs
  - ♦ Plant reliability
  - ♦ Unacceptable O&M
  - ♦ Unfavorable fuel economics
  - ♦ May rerate unit
  - ♦ Fuel availability
    - ♦ Low-rank coals (lignite, subbituminous [PRB], mid-vol coals, international coals)
  - ♦ Off-design fuels, equipment constraints
    - ♦ Coal handling flexibility
    - ♦ e.g., PRB coals — pulverizer capacity, coal fineness, fan capacity, firebox size, emissions control equipment, tube spacing, number of sootblowers, sootblowing air capacity, sootblowing frequency vs. tube erosion
    - ♦ Cofiring — biomass, gas, oil, syngases (gas, oil, coal), waste coals (~4-5 B-tons), waste oils



## Fuel Blending

- ♦ Often an economic and performance compromise
  - ♦ Usually decreases delivered fuel cost relative to original fuel (\$/MBtu)
  - ♦ Usually increases fuel cost relative to fuel switching (e.g. 100% PRB)
  - ♦ Reduces O&M relative to fuel switching
  - ♦ Reduces derates relative to fuel switching
  - ♦ Adds another fuel to coal handling
  - ♦ Near homogeneous blending is very critical



Unfortunately, none of this can be fully evaluated unless basic coal science is understood. Without this understanding:

- ◆ Operators make bad-decisions
- ◆ Engineers over/under engineer the design
- ◆ Management may be lead in the wrong or less than optimum direction
- ◆ Regulators interpret laws based on a the lack of knowledge of what can/cannot be done
- ◆ Lawmakers make laws not based on science, but on pseudo-science and inaccurate information from biased lobbyists and staff members
- ◆ Overseers make reactive statements and misinform the public
- ◆ Public is given either incorrect or only partially correct information and react accordingly



What do we need to know before we can control emissions to the environment ...

We must understand basic combustion

We must understand how pollutants are formed

Let's start with the basics ...

What is coal?



Hypothesized Coal Structures

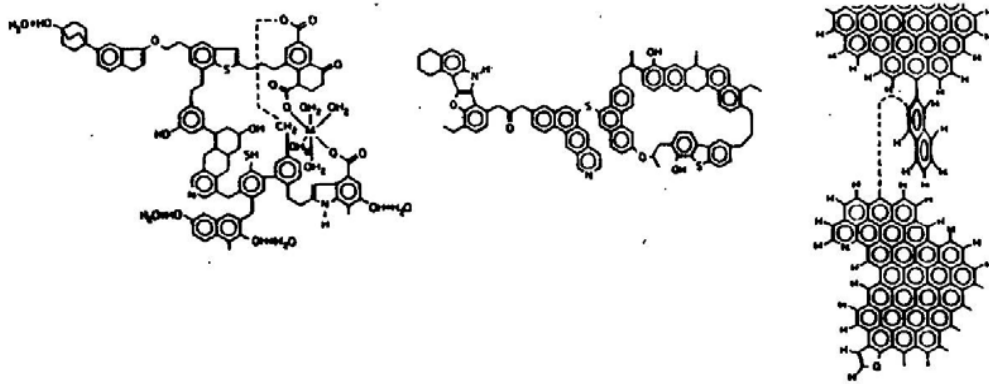


Figure 13. Spiro and Kosky (1982) models for a low-, intermediate-, and high-rank coal.

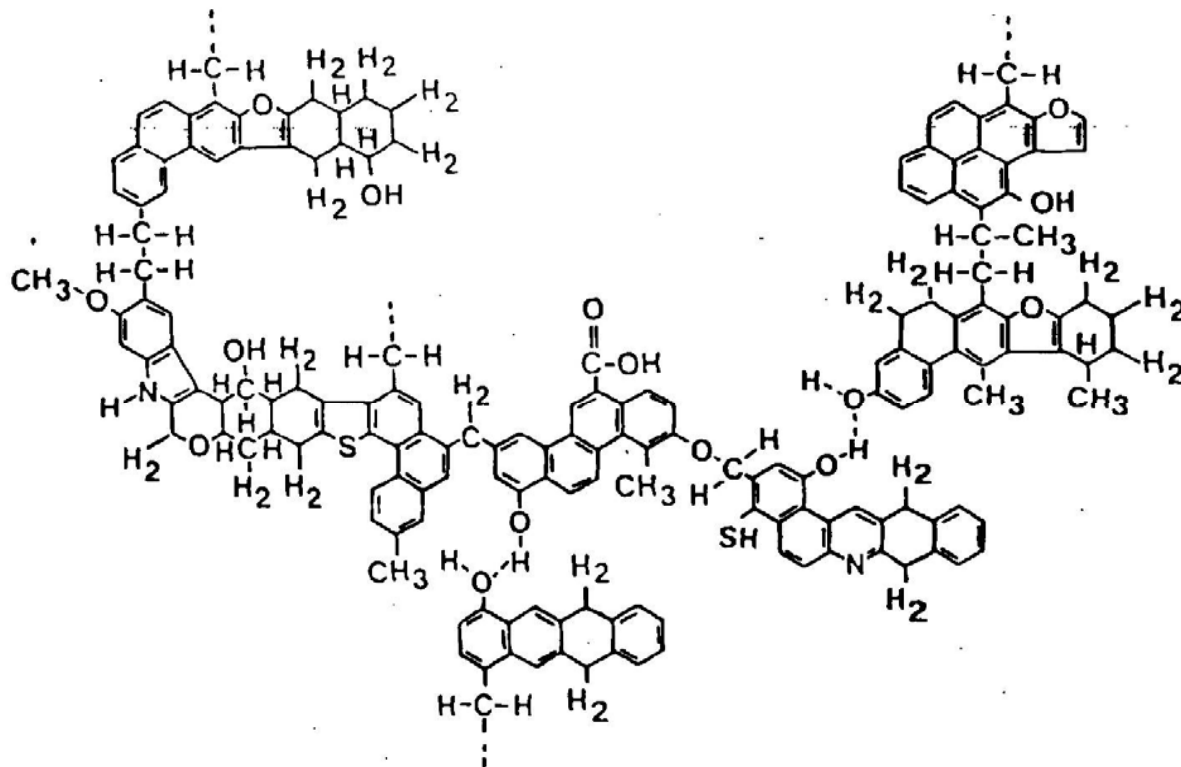


Figure 12. The Solomon (1981) model of a Pittsburgh high-volatile bituminous coal.



## Definitions of Coal

- A brown or black combustible sedimentary rock (in the geological sense) composed principally of consolidated and chemically altered plant remains. (ASTM D121)
- Coal is a rock, a sediment, a conglomerate, a biological fossil, a complex colloidal system, an enigma in solid-state physics and an intriguing object for chemical and physical analyses (*van Krevelen*)
- A solid, brittle, more or less distinctly stratified **combustible, carbonaceous rock**
- A black, **inhomogeneous**, organic fuel formed largely from partially **decomposed** and **metamorphosed plant materials**
- The natural, rocklike, brown or black derivative of **forest-type plant material**, usually accumulated in peat beds and progressively compressed and indurated until it is finally altered in graphite or graphite-like material
- Coal is a **chemically and physically heterogeneous, "combustible," sedimentary rock consisting of both organic and inorganic material** (Miller)



## *"Coal and the Environment" — 2006 APC Round Table & Expo*

- Coal
  - Black (or brown, gray)
  - Burns (usually with difficulty)
- Age & Geology
  - 20 million – 325-250 million years

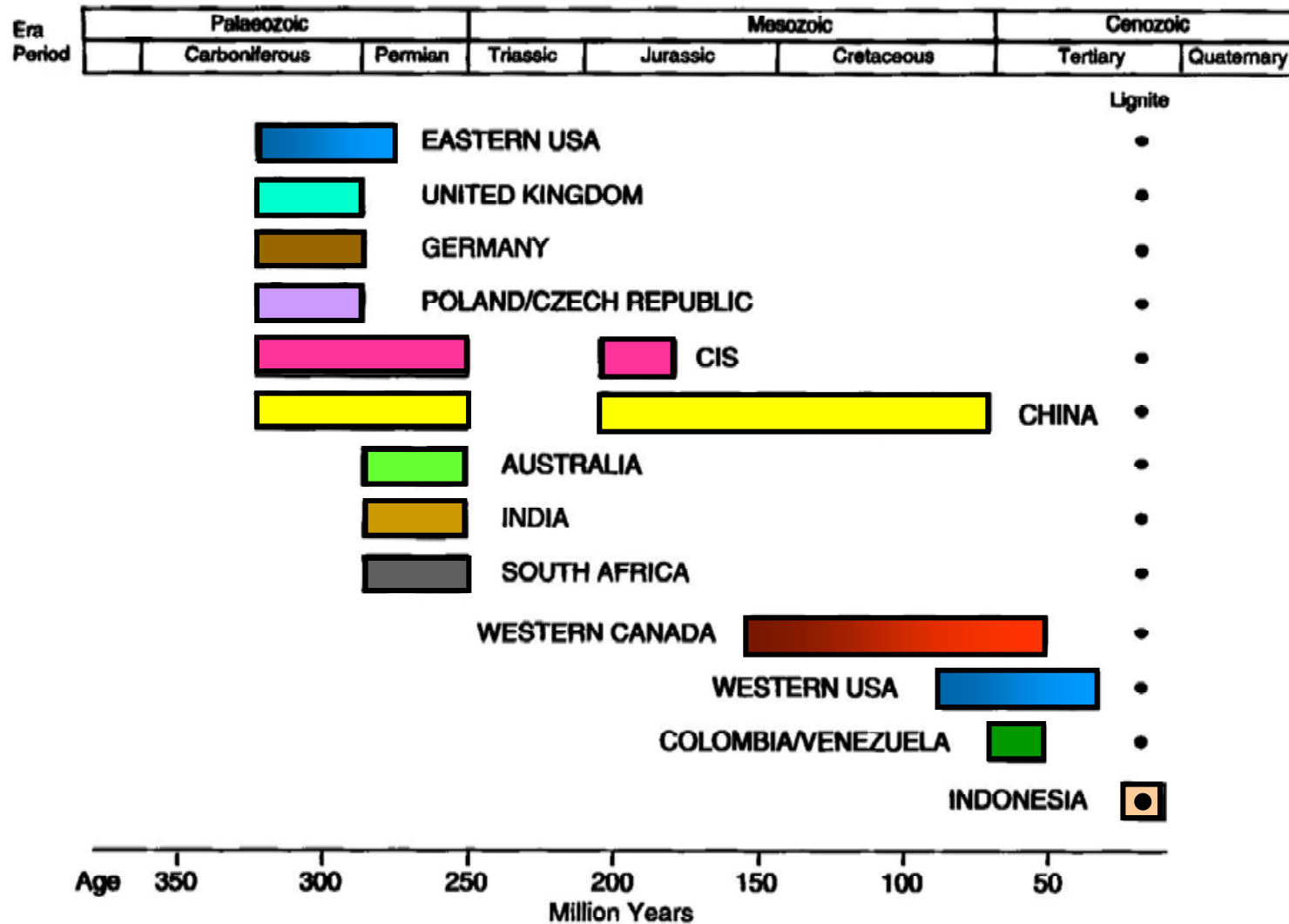
### Coalification

Era	Period	Approximate mean age (10 <sup>6</sup> years)	Class
Upper Paleozoic	Carboniferous	250	Anthracite
	Permian	210	Carbonaceous/Anthracite
Mesozoic	Triassic	180	Bituminous
	Jurassic	150	Bituminous
	Cretaceous	100	Sub-Bituminous/Bituminous
Tertiary	Eocene	60	Lignite/Sub-Bituminous
	Oligocene	40	Lignite
	Miocene	20	Lignite
Quaternary	Pleistocene	1	Peat



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Geological Ages — Coal & Lignite



**FIGURE 1-1.** Comparison of the geological ages of the world's hard coal and lignite deposits. (From Walker, S., *Major Coalfields of the World*, IEA Coal Research, London, 2000. With permission.)



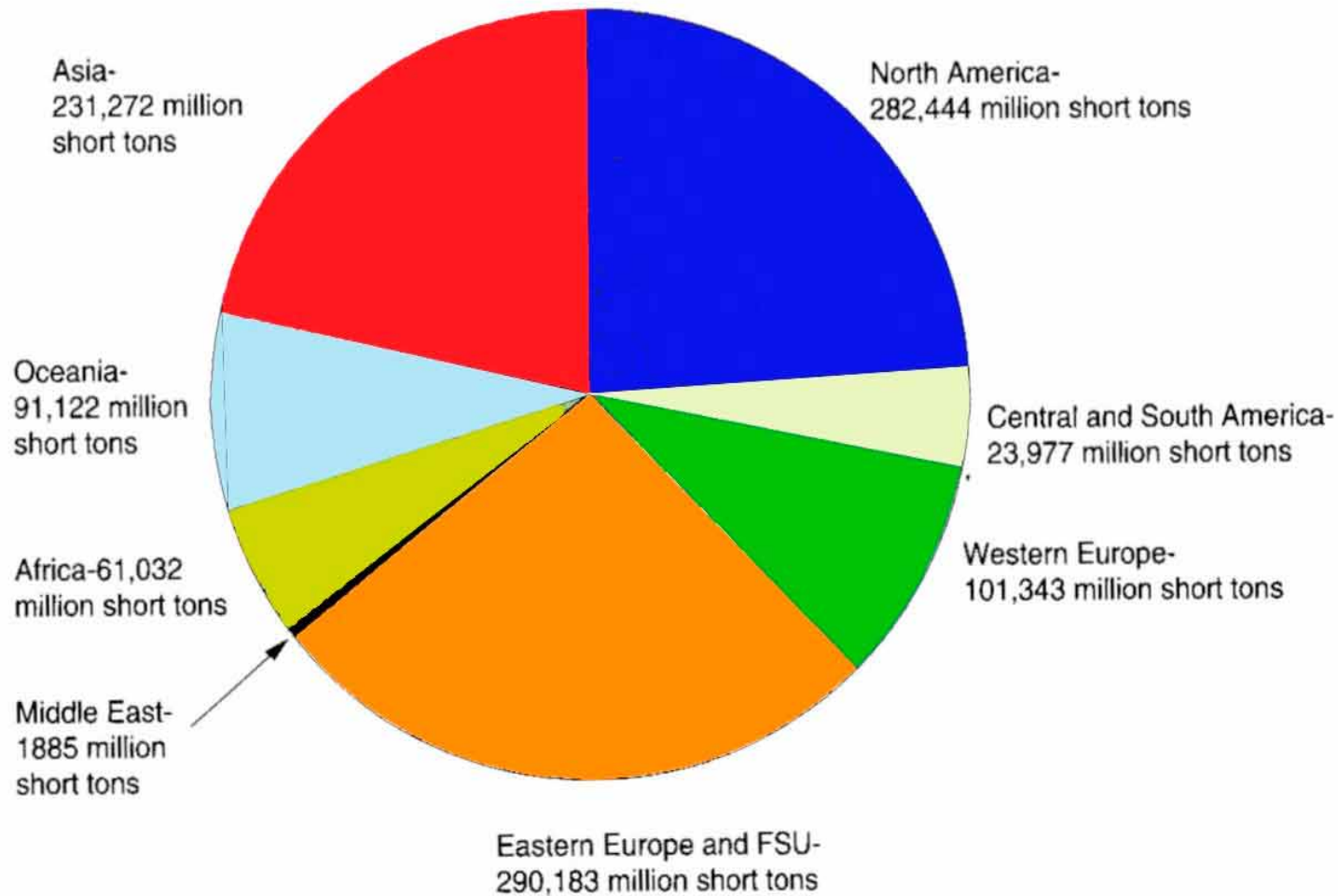
Coalification Process

Materials	Partial Processes	Main Chemical Reactions
Decaying ↓ Vegetation ↓ Peat ↓ Lignite ↓ Bituminous coal ↓ Semianthracite ↓ Anthracite	Peatification  Lignitification  Bituminization  Preanthracitization  Anthracitization  Graphitization	Bacterial and fungal life cycles  Air oxidation, followed by decarboxylation and dehydration  Decarboxylation and hydrogen disproportioning  Condensation to small aromatic ring systems  Condensation of small aromatic ring systems to larger ones; dehydrogenation  Complete carbonification

FIGURE 1-2. The coalification process. (From Van Krevelen, D. W., *Coal: Typology-Physics-Chemistry-Constitution*, Third ed., Elsevier Science, Amsterdam, 1993. With permission).



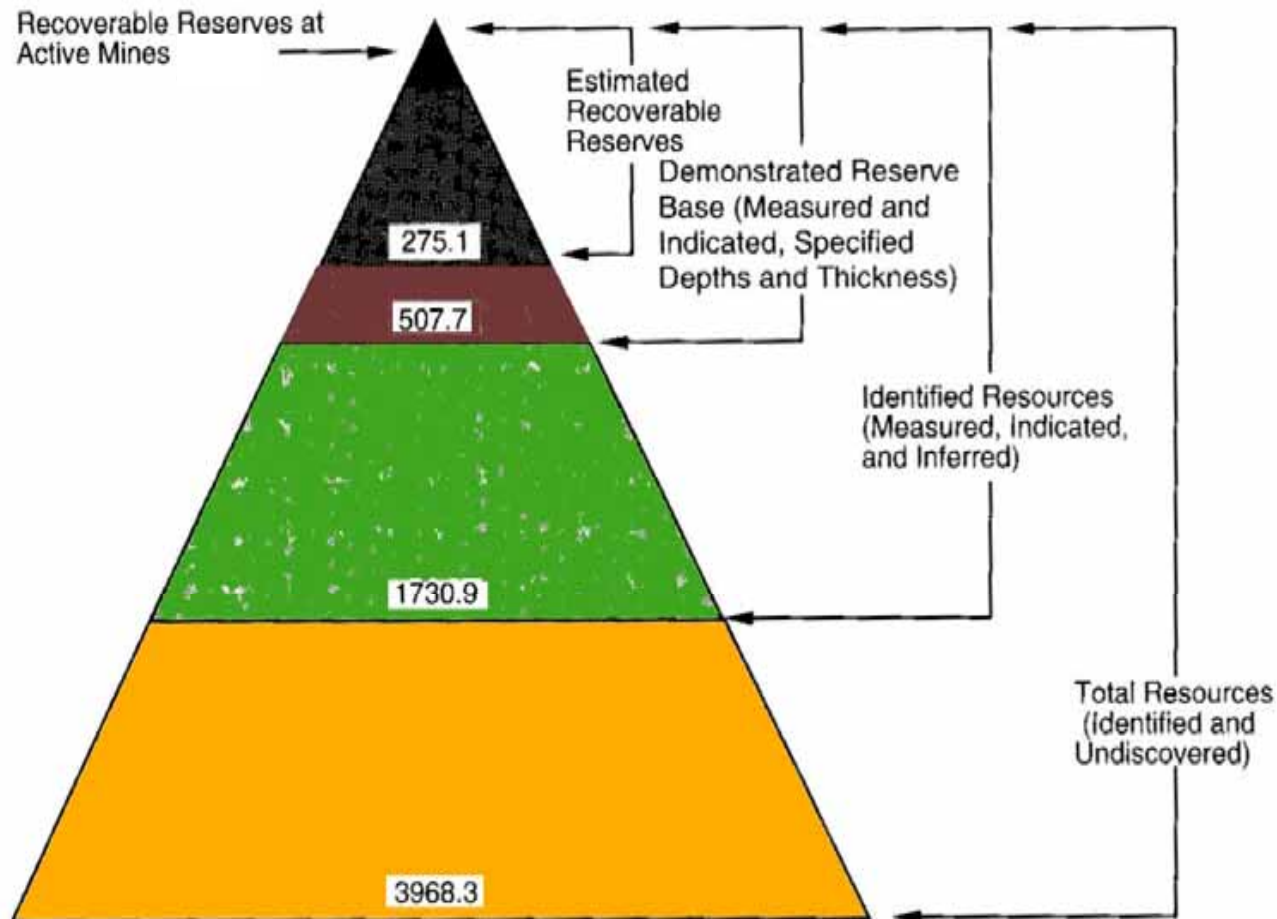
Recoverable Coal Reserves



Distribution of recoverable coal reserves in the world.



US Coal Resources & Reserves

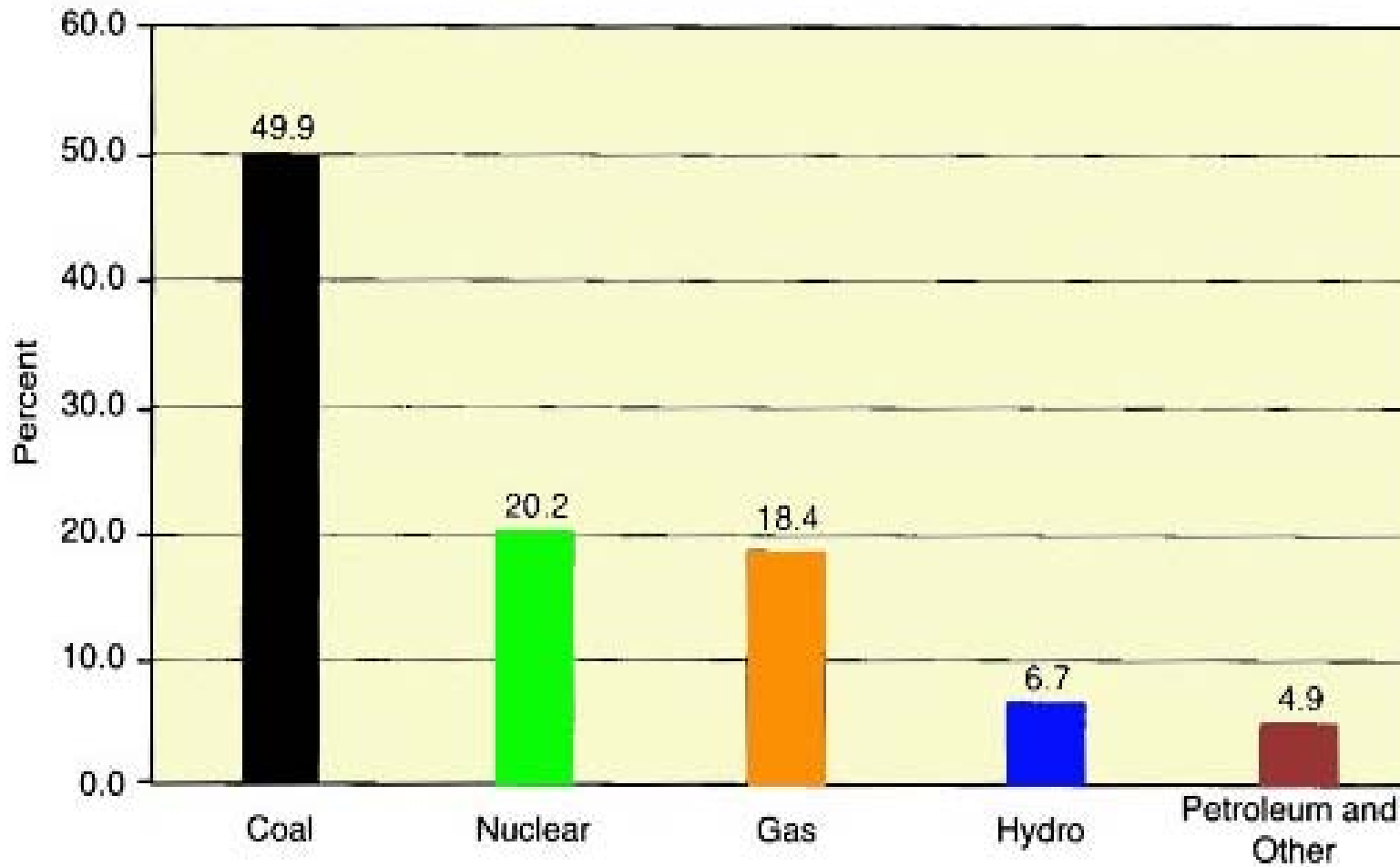


United States coal resources and reserves in billion short tons.  
(From EIA, *U.S. Coal Reserves: 1997 Update*, U.S. Department of Energy, Energy Information Administration, Washington, D.C., February 1999, p. 5, Appendix A.)





Electricity Production by Fuel Source



Production of electricity in the United States in 2002 by fuel source.  
(From Freme, F., *U.S. Coal Supply and Demand: 2002 Review*, U.S. Department of Energy, Washington, D.C., 2002.)



## Typical Coal Analyses

- ◆ **Proximate**
  - ◆ Moisture, ash, volatile, fixed carbon, sulfur, HHV
  - ◆ SO<sub>2</sub>, ash load, volatile/fixed carbon
- ◆ **Ultimate**
  - ◆ C, H, N, O in the coal maceral
- ◆ **Ash Mineral (oxides of major elements)**
  - ◆ Acids: Si, Al, Ti
  - ◆ Bases: Fe, Ca, Mg, K, Na
  - ◆ Minor: S, P, Ba, Sr, Mn
  - ◆ Base/Acid
  - ◆ ESP Index
- ◆ **Ash Fusion**
  - ◆ Oxidizing & reducing atmospheres
  - ◆ Initial deformation, spherical deformation, hemispherical deformation, fluid
  - ◆ Plastic range & fusion box
  - ◆ Eutectics
- ◆ **Trace Elements**



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## COMMERCIAL TESTING & ENGINEERING CO.

GENERAL OFFICES: 1919 SOUTH HIGHLAND AVE., SUITE 210-B, LOMBARD, ILLINOIS 60148 • (312) 953-8300

KEITH RISTINEN  
MANAGER  
NORTHWEST DIVISION



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609 CHARLES ST., BILLINGS, MT 59102  
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PRB MT-CROM

July 30, 1985

AWS 29 AUG '85

NCE

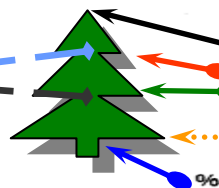
Kind of sample reported to us: **Coal**  
 Sample taken at:   
 Sample taken by: **CT&E**  
 Date sampled: **7/2/85**  
 Date received: **7/11/85**

### PROXIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	22.92	xxxxx
% Ash	5.14	6.67
% Volatile	32.84	42.61
% Fixed Carbon	39.10	50.72
	100.00	100.00
Btu/lb.	9590	12442
% Sulfur	0.38	0.49

### ULTIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	22.92	xxxxx
% Carbon	54.85	71.16
% Hydrogen	3.97	5.15
% Nitrogen	0.83	1.08
% Chlorine	0.05	0.06
% Sulfur	0.38	0.49
% Ash	5.14	6.67
% Oxygen (diff)	11.86	15.39
	100.00	100.00



Energy Sink -  
Energy Sink -  
Energy Source +  
Energy Source +

Moisture, Ash-free Btu = 13331

### SULFUR FORMS

	As Received	Dry Basis
% Pyritic Sulfur	0.12	0.15
% Sulfate Sulfur	0.00	0.00
% Organic Sulfur (Diff)	0.26	0.34
% Total Sulfur	0.38	0.49

### FUSION TEMPERATURE OF ASH

	Reducing	Oxidizing
Initial Deformation	1980 °F	2350 °F
Softening (H = W)	2020 °F	2380 °F
Softening (H = 1/2W)	2100 °F	2400 °F
Fluid	2160 °F	2430 °F

V/FC 0.84

% EQUILIBRIUM MOISTURE = 22.1

FREE SWEELING INDEX = xxxxx  
SJJ/lc

Original Copy Watermarked For Your Protection

Respectfully submitted,  
COMMERCIAL TESTING & ENGINEERING CO.

*Steve Judd*  
Manager, Billings Laboratory



Charter Member

OVER 40 BRANCH LABORATORIES STRATEGICALLY LOGATED IN PRINCIPAL COAL MINING AREAS, TIDEWATER AND GREAT LAKES PORTS, AND RIVER LOADING FACILITIES

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(313) 897-1354 or (313) 897-1296

## COAL ANALYSIS

Organization: Fuel Supply  
 Report for:  
 Project/Report No.:

Mine:  
 Supplier: **Pittsburgh Seam-Washed**  
 Train ID/Vessel Name:

Sampling Location: Mine Comparison  
 Sampling Area: As-Shipped  
 Sampling Method: Mechanical  
 Sampling Date:

Sample Receipt Date: **02/26/1999**

Sample Weight: 33,547.0 grams

Sul. > 1.70

### Proximate

	AS-RECEIVED	DRY	MAF
Total Moisture	4.52		
Ash	6.78	7.10	
Volatile	34.31	35.95	38.68
Fixed Carbon	54.39	56.99	61.32
Sulfur	2.05	2.14	
Btu	13376	14010	15080
Air-Dry Loss	2.30		
Residual Moisture (1-gram)	2.27		
SO2 (fuel maximum)	3.06		
Ash Loading (fuel maximum)	5.07		
V/FC	0.63		

### Ultimate

	AS-RECEIVED	DRY
Carbon	75.23	78.82
Hydrogen	5.00	5.24
Nitrogen	1.45	1.52
Oxygen	4.97	5.21



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## PRB-WY CROM

Sample Date: 05-Oct-2003

Material Type Fuel: Coal

Sampling Method: Rotary Splitter

<u>Moisture</u>	<u>Procedure</u>	<u>Units</u>	<u>Value</u>
Total Sample Size	ASTM D2013	grams	99.30
Air-Dry Loss	ASTM D2013	%	6.98
Residual	ASTM D3173	%	12.88

<u>Short Proximate</u>			<u>As Received</u>		<u>Dry</u>	<u>MAF</u>
Total Moisture	ASTM D3302	%	18.96	Energy Sink -		
Ash	ASTM D3180	%	6.05	Energy Sink -	7.47	
Volatile	ASTM D3175	%	33.18	Energy Source +	40.94	44.25
Fixed Carbon-A/R	ASTM D3175	%	41.81	Energy Source +	51.59	55.75
Sulfur	ASTM D4239	%	0.40		0.49	
Calorific Value	ASTM D5865	Btu/lb	9,612		11,860	12,818
SO2 (fuel maximum)		lbs/MBtu	0.83			
Ash Load (fuel max)		lbs/MBtu	6.30			
V/FC Ratio			0.79			

<u>Ultimate</u>				
Carbon	ASTM D3176	%	56.01	69.11
Hydrogen	ASTM D3176	%	3.73	4.60
Nitrogen	ASTM D3176	%	0.89	1.10
Oxygen	ASTM D3176	%	13.96	17.22

Energy Sink -  
Energy Sink -  
Energy Source +  
Energy Source +



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**CApp hvAb**

Sample Date: 06/12/2003

Material Type Fuel: Sampling Method: Manual

Sample Type: As-Requested Sampled By:

Unit:

<i>Moisture</i>	<i>Procedure</i>	<i>Units</i>	<i>Value</i>
Total Sample Size	ASTM D2013	grams	11230.0
Air-Dry Loss	ASTM D2013	%	6.25
Residual	ASTM D3173	%	1.47

<i>Short Proximate</i>	<i>As Received</i>		<i>Dry</i>	<i>MAF</i>
Total Moisture	ASTM D3302	%	7.63	
Ash	ASTM D3180	%	9.21	9.97
Volatile	ASTM D3175	%	29.23	31.65
Fixed Carbon-A/R	ASTM D3175	%	53.93	58.38
Sulfur	ASTM D4239	%	1.46	1.58
Calorific Value	ASTM D5865	Btu/lb	12,711	13,762
SO <sub>2</sub> (fuel maximum)		lbs/MBtu	2.30	
Ash Load (fuel max)		lbs/MBtu	7.24	
V/FC Ratio			0.54	

<i>Ultimate</i>				
Carbon	ASTM D3176	%	70.66	76.49
Hydrogen	ASTM D3176	%	4.42	4.78
Nitrogen	ASTM D3176	%	1.21	1.31
Oxygen	ASTM D3176	%	5.41	5.86

<i>Ash Fusion</i>			<i>Reducing</i>	<i>Oxidizing</i>
Initial	ASTM D1857	°F	2,500	2,610
Spherical		°F	2,520	2,645
Hemispherical		°F	2,565	2,665
Fluid		°F	2,625	2,700



# "Coal and the Environment" — 2006 APC Round Table & Expo

Sample Date: 06/12/2003

CApp hvAb

Material Type Fuel:

Sampling Method:

Sample Type: As-Requested

Sampled By:

Unit:

<u>Ash Mineral</u>	<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>
Silcon Dioxide, SiO2	%	50.33	Acid	%	81.17			
Alum Oxide, Al2O3	%	27.34	Base	%	18.83			
Titanm Dioxide, TiO2	%	1.25	Base Acid Ratio		0.23			
			Ash Ratio		0.17			
Iron Oxide, Fe2O3	%	12.91	Ash Type		Bituminous			
Calcium Oxide, CaO	%	1.24	Silica Ratio		0.77			
Magnesium Oxide, MgO	%	0.99	Silica Alumina Ratio		1.84			
Potassium Oxide, K2O	%	2.62	Iron Calcium Ratio		10.41			
Sodium Oxide, Na2O	%	0.55	Dolomite Percentage	%	11.84			
			ESP Index		77.67			
Mang Oxide, Mn3O4	%	0.03	Undetermined	%	0.32			
Sulfur Trioxide, SO3	%	1.16						
Phos Pentoxide, P2O5	%	0.97						
Barium Oxide, BaO	%	0.15						
Strontium Oxide, SrO	%	0.14						
<u>Trace Elements</u>	<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>
Sb, Antimony	ppm	0.11	Pb, Lead	ppm	8.24	Ag, Silver	ppm	0.067
As, Arsenic	ppm	11.97	Mn, Manganese	ppm	18.9	Tl, Thallium	ppm	0.62
Ba, Barium	ppm	104	Hg, Mercury	ppm	0.082	V, Vanadium	ppm	30.1
Be, Beryllium	ppm	2.2	Mo, Molybdenum	ppm	1.12	Zn, Zinc	ppm	14.5
Cd, Cadmium	ppm	0.061	Ni, Nickel	ppm	13.61			
Cl, Chlorine	ppm	957.28	Se, Selenium	ppm	3.22			
Cr, Chromium	ppm	12.4						
Co, Cobalt	ppm	6.21						
Cu, Copper	ppm	15.8						
F, Fluorine	ppm	<10						



*Coal Characteristics*

*Its Properties & Effects*



## Coal

- ♦ Mechanical combination of coal + mineral matter
- ♦ **Coal Matrix** (bark, sap, leaves)
  - ♦ Complex aromatic hydrocarbon
  - ♦ C, H, N, O, S, ...
  - ♦ **Hydrophobic** (rejects water)
- ♦ **Mineral Matter** (ash)
  - ♦ Mostly minerals of the following oxides
    - ♦ Si, Al, Ti, Fe, Ca, Mg, K, Na, S, P, Ba, Sr, Mn, Cl, + ...
    - ♦ 76 of the first 92 elements
  - ♦ **Hydrophilic** (accepts water)



## Coal Rank

### ◆ Bituminous

- ◆ "Eastern" — Appalachian (eastern KY, WV, PA, OH, NY, VA, TN, AL)  
Illinois Basin ( IL, IN, western KY) , CO, UT, NM + others
- ◆ Typical classifications
  - ◆ Low Sulfur (<1.67 lbs SO<sub>2</sub>/MBtu)
  - ◆ Mid-Sulfur (<3 lbs SO<sub>2</sub>/MBtu)
  - ◆ High-Sulfur (>3 lbs SO<sub>2</sub>/MBtu)

### ◆ Subbituminous

- ◆ Western
- ◆ PRB: MT (high Na, moderate Ca), WY (low Na, high Ca)
- ◆ Other (Hanna River, Green River, Big Horn regions, etc.)

### ◆ Other Ranks

- ◆ Meta-anthracite (PA, UT), ↑
- ◆ Anthracite (PA, UT), ↑
- ◆ Lignite ↓ (ND, SD, NE, OK, TX, MT, AL, MS)
  - ◆ In Germany called "Brown Coal", now classified as Lignite B
- ◆ Peat, ↓ ↓ (Ireland)



# ASTM D388 Classification of Coals by Rank

TABLE 1 Classification of Coals by Rank<sup>A</sup>

Class/Group	Fixed Carbon Limits (Dry, Mineral-Matter-Free Basis), %		Volatile Matter Limits (Dry, Mineral-Matter-Free Basis), %		Gross Calorific Value Limits (Moist, <sup>B</sup> Mineral-Matter-Free Basis)				Agglomerating Character
	Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Btu/lb		Mj/kg <sup>C</sup>		
					Equal or Greater Than	Less Than	Equal or Greater Than	Less Than	
Anthracitic:									
Meta-anthracite	98	...	...	2	...	...	...	...	} nonagglomerating
Anthracite	92	98	2	8	...	...	...	...	
Semianthracite <sup>D</sup>	86	92	8	14	...	...	...	...	
Bituminous:									
Low volatile bituminous coal	78	86	14	22	...	...	...	...	} commonly agglomerating <sup>E</sup>
Medium volatile bituminous coal	69	78	22	31	...	...	...	...	
High volatile A bituminous coal	...	69	31	...	14 000 <sup>F</sup>	...	32.6	...	
High volatile B bituminous coal	...	...	...	...	13 000 <sup>F</sup>	14 000	30.2	32.6	
High volatile C bituminous coal	...	...	...	...	11 500	13 000	26.7	30.2	
					10 500	11 500	24.4	26.7	} agglomerating
Subbituminous:									
Subbituminous A coal	...	...	...	...	10 500	11 500	24.4	26.7	} nonagglomerating
Subbituminous B coal	...	...	...	...	9 500	10 500	22.1	24.4	
Subbituminous C coal	...	...	...	...	8 300	9 500	19.3	22.1	
Lignitic:									
Lignite A	...	...	...	...	6 300 <sup>G</sup>	8 300	14.7	19.3	} nonagglomerating
Lignite B	...	...	...	...	...	6 300	...	14.7	

<sup>A</sup>This classification does not apply to certain coals, as discussed in Section 1.

<sup>B</sup>Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.

<sup>C</sup>Megajoules per kilogram. To convert British thermal units per pound to megajoules per kilogram, multiply by 0.002 326.

<sup>D</sup>If agglomerating, classify in low volatile group of the bituminous class.

<sup>E</sup>It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and that there are notable exceptions in the high volatile C bituminous group.

<sup>F</sup>Coals having 69 % or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of gross calorific value.

<sup>G</sup>Editorially corrected.



## Composition

(wt% DMMF Basis)

	C	H	O
Wood	49	7	44
Peat	60	6	34
Lignite	70	5	25
Subbituminous	75	5	20
Bituminous	85	5	10
Anthracite	94	3	3

- Increasing Aromatization & Loss of Oxygen with Time



## Typical Fossil Fuel Analyses

<b>Analysis</b>	<b>Natural Gas</b>	<b>Fuel Oil</b>	<b>Bituminous Coal</b>
Nitrogen (N, %)	0.8	0.5	1.2-1.9
Oxygen (O, %)	1.8	0.9	2-9
Carbon (C, %)	74	88	72-82
Ash (%)	0	0.04	2-40 <sup>+</sup>
Sulfur (S, %)	Trace	0.04-1	0.5-6
Hydrogen (H, %)	23.8	10	3-5.5
Moisture (%)	0	0	2-12
Calorific Value (HHV, Btu/lb)	23,100 (1000 Btu/ft <sup>3</sup> )	18,200 (137,000 Btu/gal)	11,200-14,200



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## Coal Structural Characterization

**Polycyclic Aromatic Hydrocarbons Identified in the A-2 Fractions of  
Upper Freeport, Wyodak, Illinois #6, Pittsburgh, Pocahontas #3, and Beulah-Zap**

<b>Peak no.</b>	<b>Proposed structure</b>	<b>Peak no.</b>	<b>Proposed structure</b>
1.	Naphthalene	24.	tert-Butyl-C <sub>1</sub> -biphenyl
2.	2-Methylnaphthalene	25.	2-Phenylnaphthalene
3.	1-Methylnaphthalene	26.	C <sub>2</sub> -phenanthrenes
4.	Biphenyl	27.	Fluoranthene
5.	C <sub>2</sub> -naphthalenes	28.	C <sub>1</sub> -phenylnaphthalenes
6.	C <sub>1</sub> -biphenyls	29.	Pyrene
7.	C <sub>2</sub> -naphthalenes	30.	C <sub>2</sub> -phenanthrenes
8.	Fluorene	31.	Benzo[a]fluorene
9.	3-Methylfluorene	32.	Benzo[b]fluorene and/or benzo[c]fluorene
10.	C <sub>2</sub> -biphenyls	33.	Retene (7-isopropyl-1- methylphenanthrene)
11.	C <sub>4</sub> -naphthalenes	34.	Methyl-9,10-dihdropyrene
12.	2-Methylfluorene	35.	C <sub>1</sub> -benzofluorenes
13.	1-Methylfluorene	36.	Chrysene
14.	C <sub>2</sub> -naphthalenes	37.	C <sub>2</sub> -benzofluorenes
15.	Phenanthrene	38.	C <sub>1</sub> -chrysenes
16.	C <sub>2</sub> -fluorenes	39.	C <sub>1</sub> -benzofluorenes
17.	C <sub>2</sub> -biphenyls	40.	C <sub>2</sub> -chrysenes
18.	C <sub>2</sub> -naphthalenes	41.	Benzo[fluoranthene]
19.	2-Methylphenanthrene	42.	Benzo[e]pyrene
20.	3-Methylphenanthrene	43.	Benzo[a]pyrene
21.	4-Methylphenanthrene and/or 9-methylphenanthrene	44.	C <sub>1</sub> -252
22.	1-Methylphenanthrene		
23.	tert-Octyl-C <sub>2</sub> -naphthalene		



Hypothesized Coal Structures

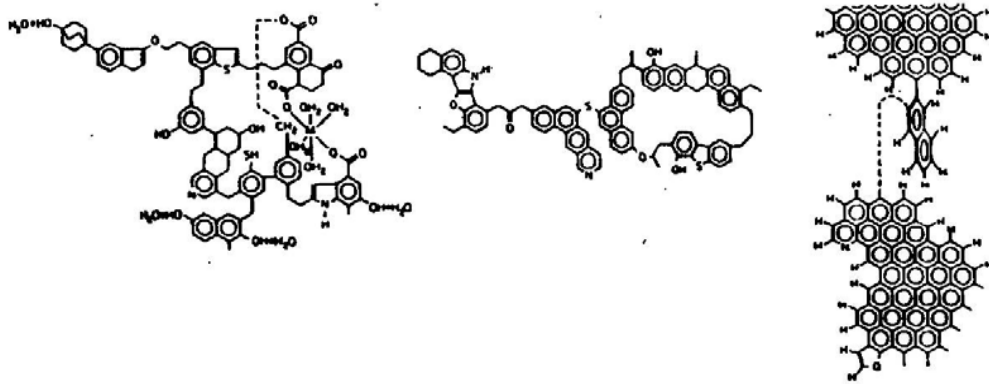


Figure 13. Spiro and Kosky (1982) models for a low-, intermediate-, and high-rank coal.

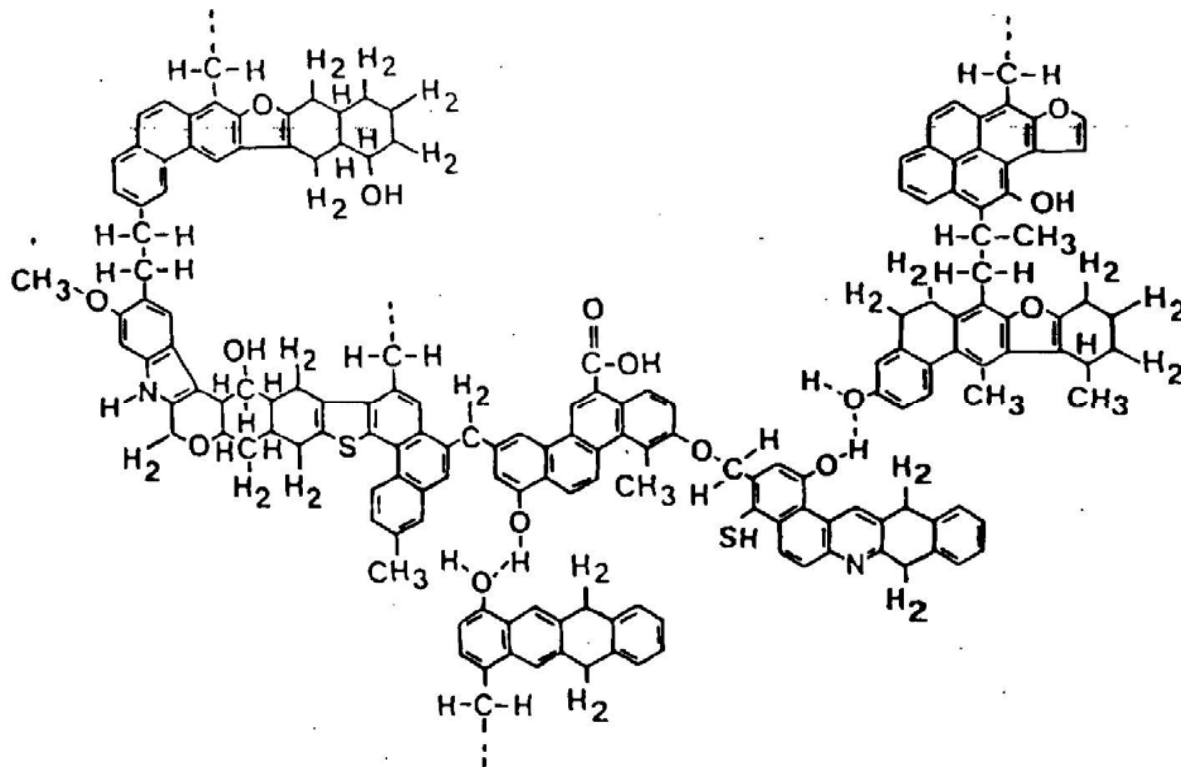
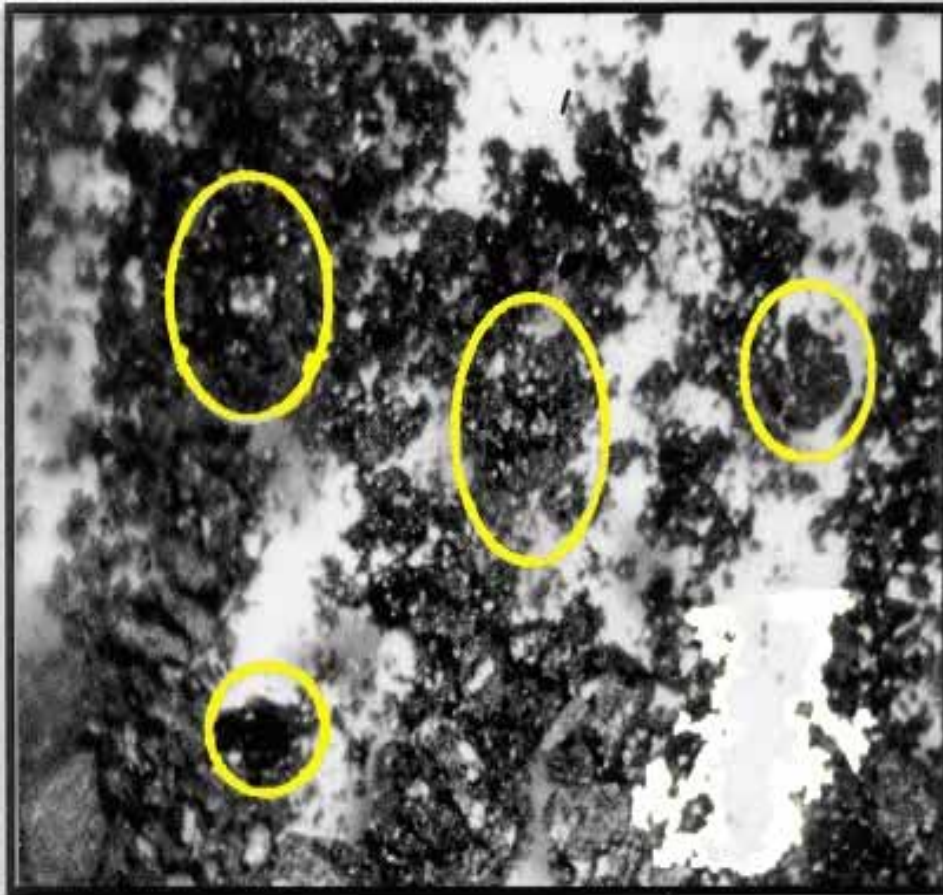


Figure 12. The Solomon (1981) model of a Pittsburgh high-volatile bituminous coal.



Photomicrograph of PRB Coal Particles

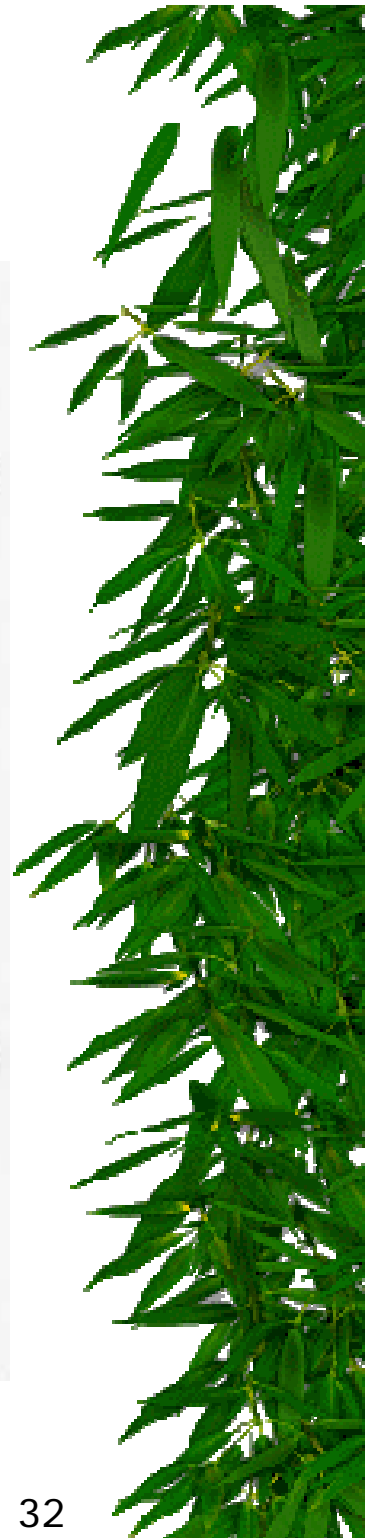


20X, stereo-photomicrograph  
Sub-Bituminous Coal from St.Clair  
Power Plant

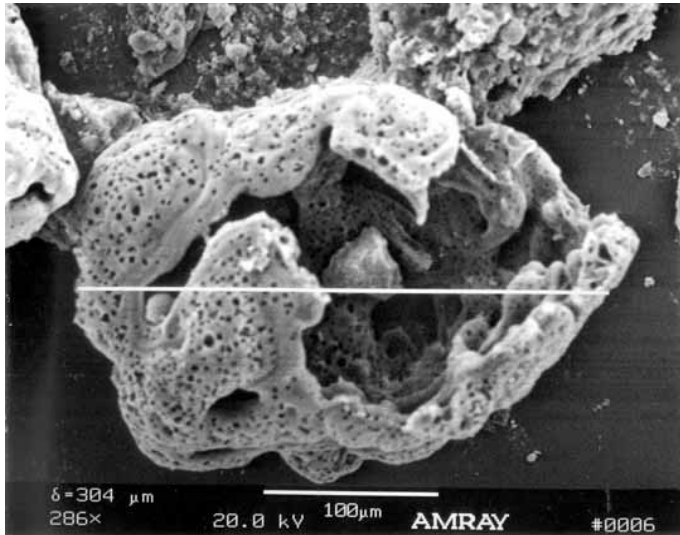
Observations:

Typical sub-bituminous coal, a.k.a. Western coal. Sample was taken from a St. Clair Power Plant stockpile.

Raw coal particles have defined edges and often reflective surfaces. Examples of larger such particles are circled in yellow. Larger particles with rough surfaces are agglomerations of small particles with a large particle.



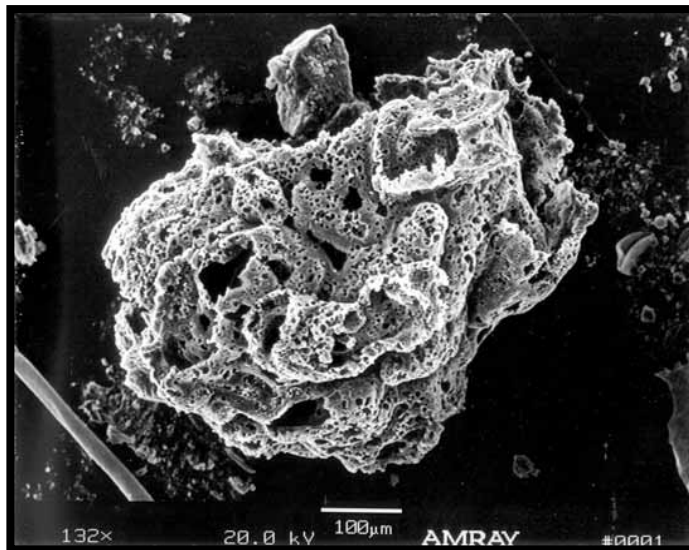
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286X, SEM-photomicrograph  
Partially Burned Coal Particle

Partially burned coal. Note the “popcorn” appearance.

Particle is about 304- $\mu\text{m}$  across. Note the small seed-like ash particle in the center. Holes on the surface are made by escaping gases during combustion.

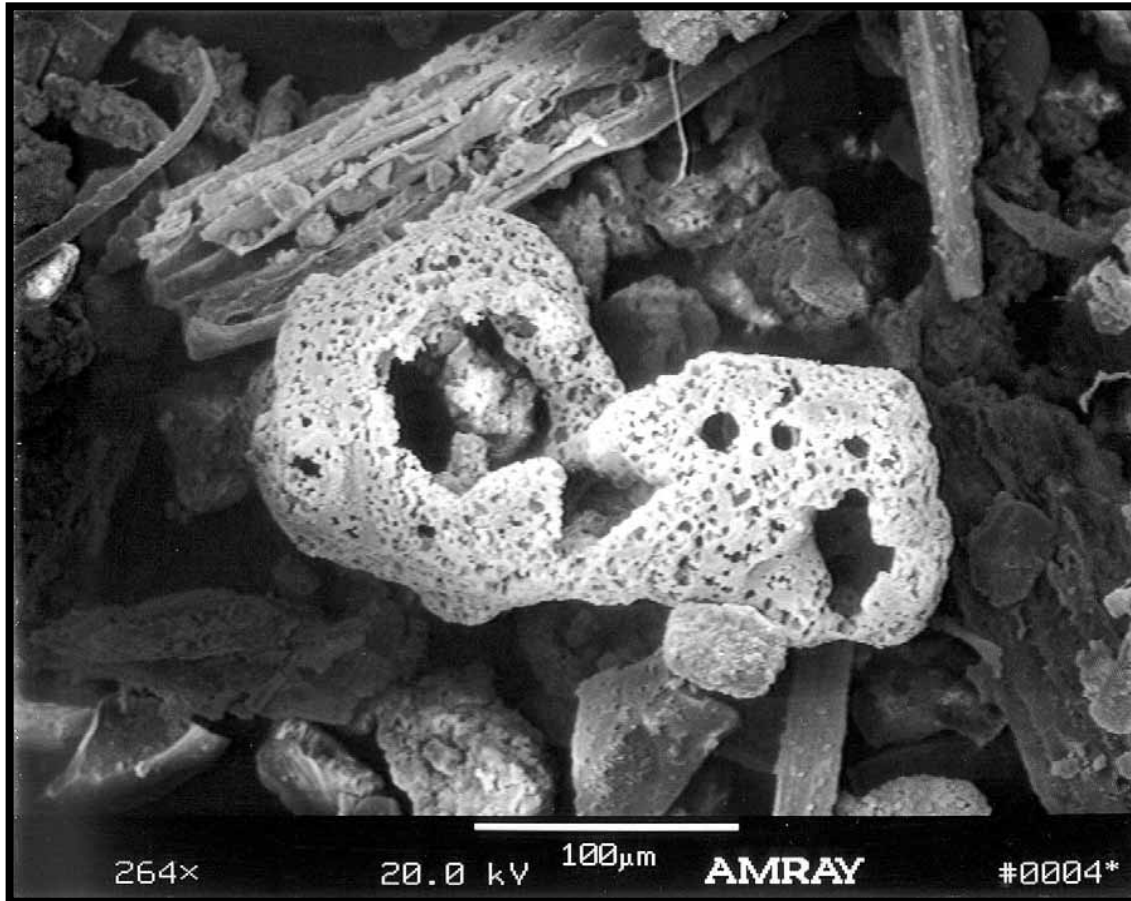


132X, SEM-photomicrograph  
Partially Burned Coal Particle

Partially burned coal.

Particle is about 580- $\mu\text{m}$  across, very porous and hollow. Initial combustion likely occurred at the right end where there is a large hole. Smaller holes on the surface were made by escaping gases during combustion.





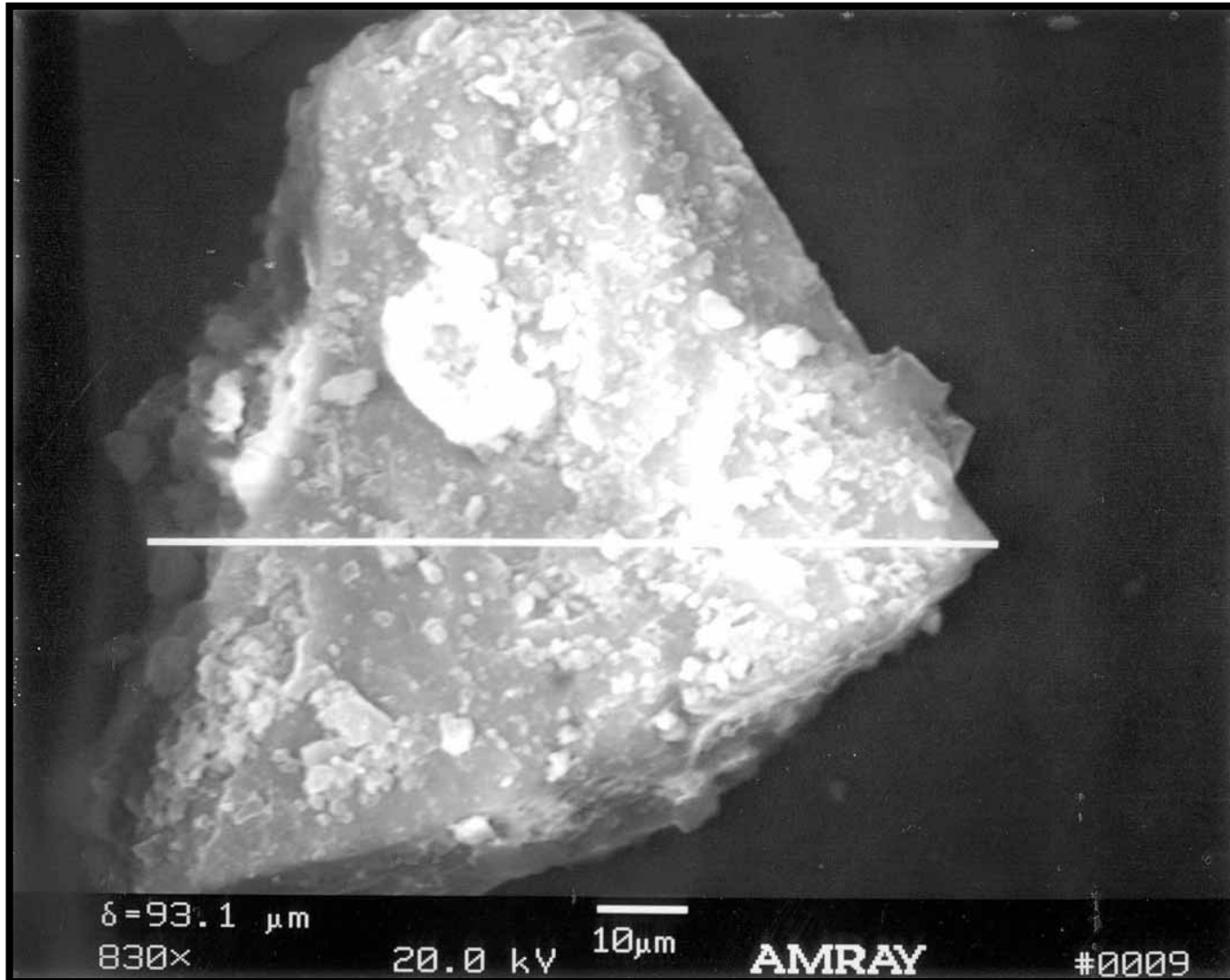
**Partially Burned Coal Particle**

264X, SEM-photomicrograph

Porous particle in the center is partially burned coal about 260-µm wide. Large holes were created when expanding gases explosively escaped the particle during heating; small holes on the surface are from gases escaping from the viscous carbonaceous surface. The particle is surrounded by sand, dirt and plant matter.



SEM Photomicrograph of Coal Particle



Sub-bituminous coal particle, about 93- $\mu\text{m}$  across.

Note the defined edges, the shape and texture of the particle



## Coal Mineral Types

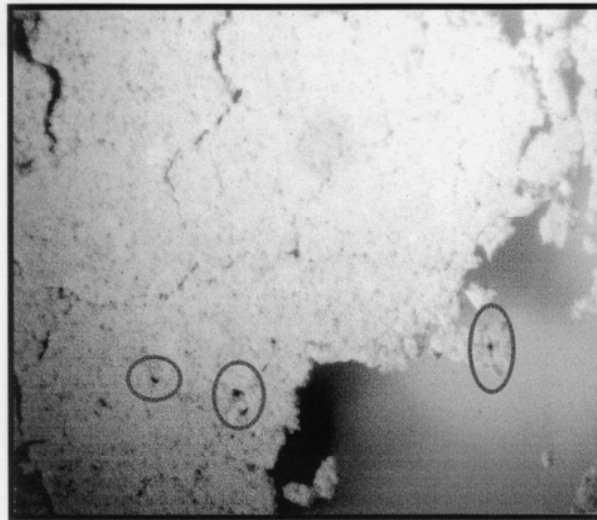
**TABLE 51.** Mineral Types Observed in the Recommended Coals by CCSEM

Mineral type	Chemical formula <sup>a</sup>
Quartz	SiO <sub>2</sub>
Al-silicate (kaolinite)	Al <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>
Fe-aluminosilicate	Fe <sub>r</sub> Al <sub>y</sub> Si <sub>z</sub>
K-aluminosilicate (illite)	K(Al, Fe) <sub>4</sub> (Si, Al) <sub>8</sub> O <sub>20</sub> (OH) <sub>4</sub>
Ca-aluminosilicate	Ca <sub>r</sub> Al <sub>y</sub> Si <sub>z</sub>
Iron oxide	Fe <sub>2</sub> O <sub>3</sub>
Pyrite	FeS <sub>2</sub>
Gypsum	CaSO <sub>4</sub> · 2H <sub>2</sub> O
Calcite	CaCO <sub>3</sub>
Rutile	TiO <sub>2</sub>
Barite	BaSO <sub>4</sub>
Ankerite	Ca(Mg, Fe, Mn) (CO <sub>3</sub> ) <sub>2</sub>
Siderite	FeCO <sub>3</sub>
Crandallite	CaAl <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>5</sub> · H <sub>2</sub> O
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>
Calcium aluminate	Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>
Apatite	Ca <sub>5</sub> F(PO <sub>4</sub> ) <sub>3</sub>
Spinel	(Fe, Al, Mg)O <sub>4</sub>
Calcium silicate	CaSiO <sub>3</sub>
Pyrrhotite/iron sulfate	FeS
Ca-rich	—
Si-rich	—

<sup>a</sup> Actual molar ratios will vary due to limits of the CCSEM technique.  
 Source: Zygarlicke *et al.* (1990a).

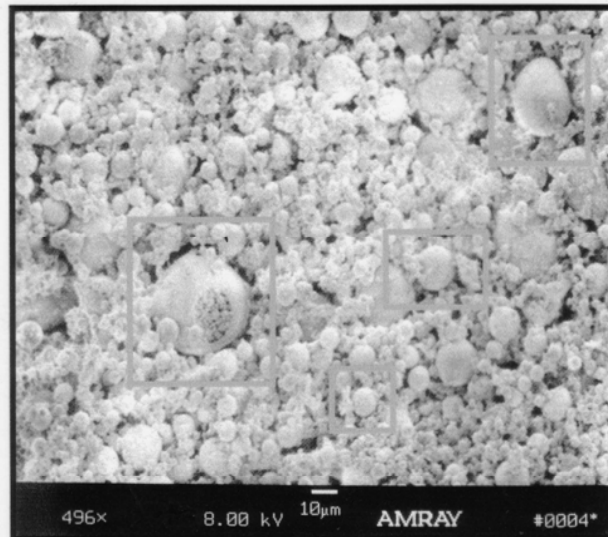


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20X, stereo-photomicrograph  
Fly-ash from Belle River Power Plant  
Fly-Ash Silo

Observations:  
Fly-ash produced primarily  
from sub-bituminous coal.  
Black particles, circled in  
red, are unburned carbon.

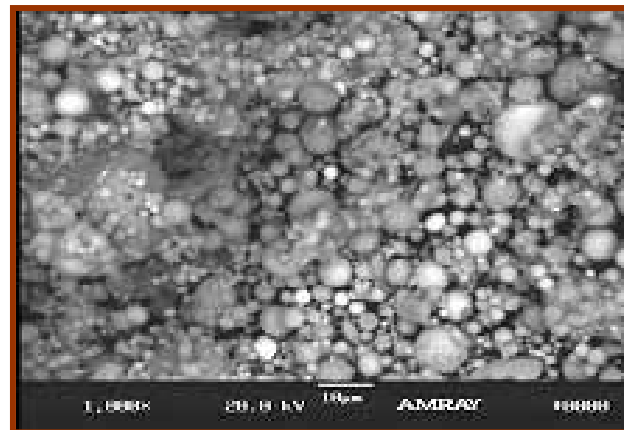
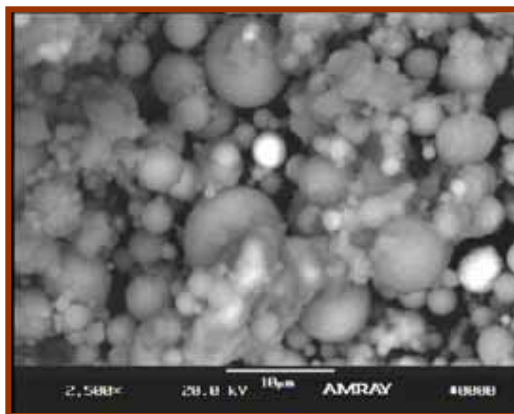
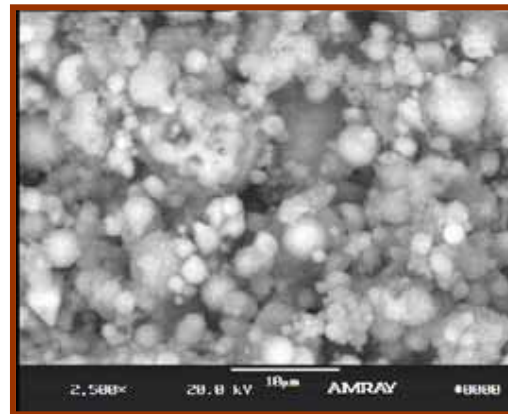
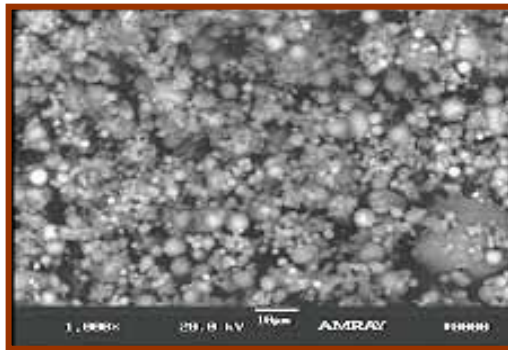


496X, SEM photomicrograph  
Fly-ash from St. Clair Power Plant  
South Fly-Ash Silo

Observations:  
Fly-ash produced primarily  
from sub-bituminous coal.  
Note the abundance of fly-ash  
cenospheres. Examples are  
enclosed by blue rectangles.



SCR & ESP



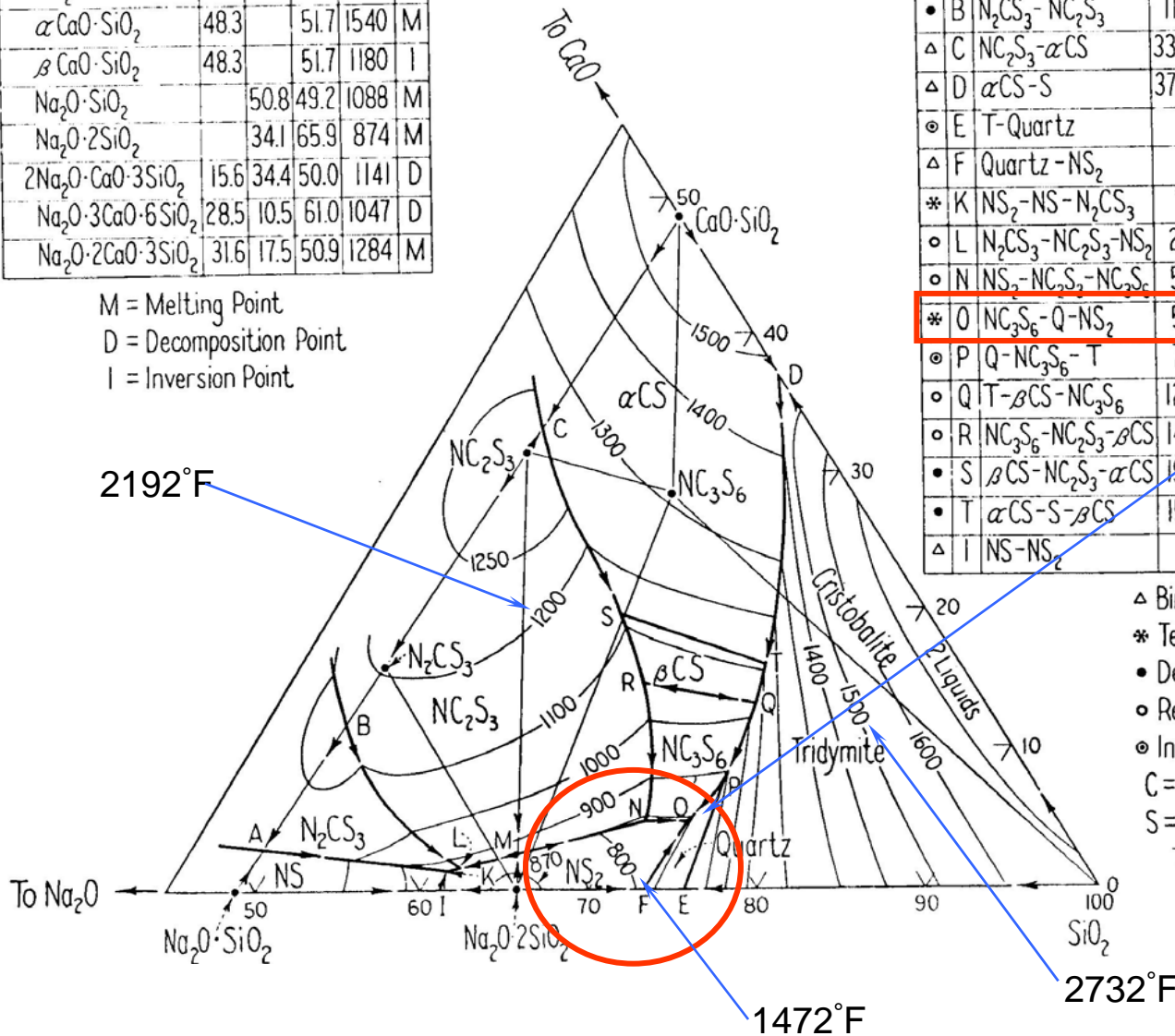
Example CaO and SiO<sub>2</sub> with Na<sub>2</sub>O

Compounds	CaO	Na <sub>2</sub> O	SiO <sub>2</sub>	Temp.	
SiO <sub>2</sub>			100.0	1710	M
α CaO · SiO <sub>2</sub>	48.3		51.7	1540	M
β CaO · SiO <sub>2</sub>	48.3		51.7	1180	I
Na <sub>2</sub> O · SiO <sub>2</sub>		50.8	49.2	1088	M
Na <sub>2</sub> O · 2SiO <sub>2</sub>		34.1	65.9	874	M
2Na <sub>2</sub> O · CaO · 3SiO <sub>2</sub>	15.6	34.4	50.0	1141	D
Na <sub>2</sub> O · 3CaO · 6SiO <sub>2</sub>	28.5	10.5	61.0	1047	D
Na <sub>2</sub> O · 2CaO · 3SiO <sub>2</sub>	31.6	17.5	50.9	1284	M

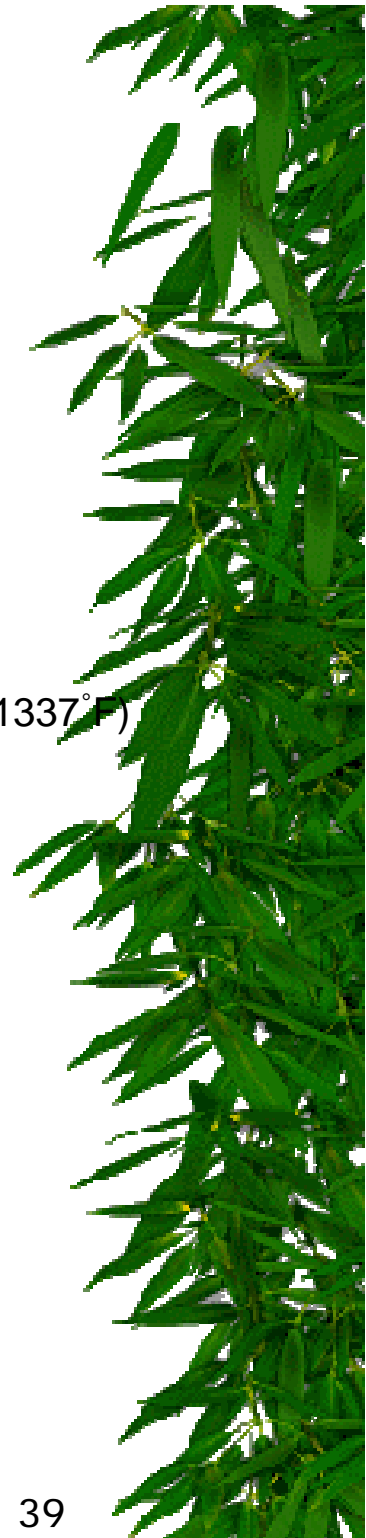
M = Melting Point  
D = Decomposition Point  
I = Inversion Point

Point	Crystal Phases	CaO	Na <sub>2</sub> O	SiO <sub>2</sub>	Temp.
△ A	NS - N <sub>2</sub> CS <sub>3</sub>	3.0			1060
• B	N <sub>2</sub> CS <sub>3</sub> - NC <sub>2</sub> S <sub>3</sub>	11.5			1141
△ C	NC <sub>2</sub> S <sub>3</sub> - αCS	33.0			1280
△ D	αCS - S	37.0		63.0	1436
⊙ E	T-Quartz		24.3	75.7	870
△ F	Quartz - NS <sub>2</sub>		26.4	73.6	790
* K	NS <sub>2</sub> - NS - N <sub>2</sub> CS <sub>3</sub>	18	37.5	60.7	821
⊙ L	N <sub>2</sub> CS <sub>3</sub> - NC <sub>2</sub> S <sub>3</sub> - NS <sub>2</sub>	2.0	36.6	61.4	827
⊙ N	NS <sub>2</sub> - NC <sub>2</sub> S <sub>3</sub> - NC <sub>3</sub> S <sub>6</sub>	5.2	24.1	70.7	740
* O	NC <sub>3</sub> S <sub>6</sub> - Q - NS <sub>2</sub>	5.2	21.3	73.5	725
⊙ P	Q - NC <sub>3</sub> S <sub>6</sub> - T	7.0	18.7	74.3	870
⊙ Q	T - βCS - NC <sub>3</sub> S <sub>6</sub>	12.9	13.7	73.4	1035
⊙ R	NC <sub>3</sub> S <sub>6</sub> - NC <sub>2</sub> S <sub>3</sub> - βCS	14.5	19.0	66.5	1030
• S	βCS - NC <sub>2</sub> S <sub>3</sub> - αCS	18.5	17.7	62.8	1110
• T	αCS - S - βCS	15.6	11.4	73.0	1110
△ I	NS - NS <sub>2</sub>		38.0		840

△ Binary Eutectic  
\* Ternary Eutectic  
• Decomposition Point  
⊙ Reaction Point  
⊙ Inversion Point  
C = CaO N = Na<sub>2</sub>O  
S = SiO<sub>2</sub> Q = Quartz  
T = Tridymite



(1337°F)



*Fuel Characteristics*

*Its Properties & Effects*

*Flags & Evaluation Criteria*



## Evaluation Criteria

### – Proximate

- [-] Moisture
- [-] Ash (Mineral Matter)
- [+] Volatile
- [+] Fixed Carbon
- Sulfur
- HHV
- SO<sub>2</sub> (lbs SO<sub>2</sub>/MBtu)
- Ash loading (lbs ash/MBtu)
- Volatile / Fixed Carbon

### – Ultimate

- C + H + N + O ⇔ Volatile & Fixed Carbon

### – Ash Mineral

- [Si, Al, Ti], [Fe, Ca, Mg, K, Na]
- Base-Acid Ratio
- Na<sub>2</sub>O (%) & Na<sub>2</sub>O loading (lbs Na<sub>2</sub>O/MBtu)

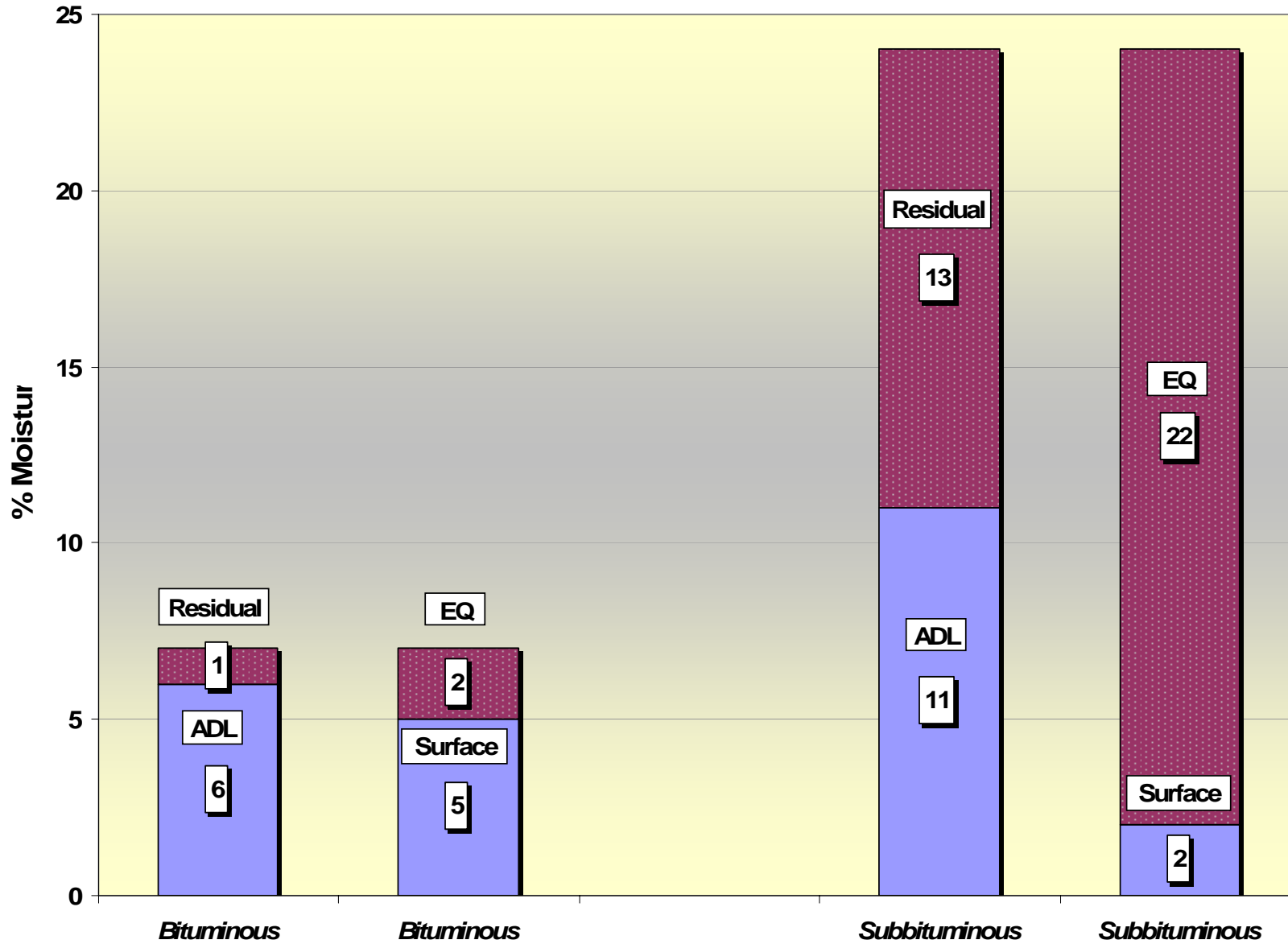


## Moisture

- ◆ Laboratory characteristic
  - ◆ **Residual + Air-Dry Loss (ADL)  $\approx$  Total**
  - ◆ On every lab report (Certificate of Analysis)
  
- ◆ Physical characteristic
  - ◆ **Equilibrium (Inherent, Bed) + Surface  $\approx$  Total**
  - ◆ Difficult & infrequently determined
  - ◆ Valuable reference value



Moisture Components



**Ash With Your Coal?**



## Ash (Mineral Matter)

- ♦ Slagging / Fouling Parameters
  - ♦ Fe, Na, Ca, Mg, K (plastic-phase deposition)
  - ♦ Na (vapor deposition, especially PRB-MT)
  - ♦ Fe acts as a flux to depress ash's melting temperature
    - ♦ S generally trends with Fe
- ♦ Base-Acid Ratio
  - ♦  $(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}) / (\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2)$
  - ♦ Minimum fusion temperature, B:A ~0.7-0.8
  - ♦ High slagging potential, B:A ~0.5-1.2
- ♦ Silica vs Silicates
  - ♦ "Glass" vs. clay
  - ♦ Material handling & combustion considerations
- ♦ Na, organic vs. inorganic compounds



♦ Ash ESP Ash Parameters

♦ Ash Loading (Grain Loading)

♦  $\text{Lbs ash/MBtu} \equiv \text{ash\%} * 10,000 / \text{HHV (Btu/lb)}$

♦ Not all ash travels to the ESP

♦  $f(\text{ash viscosity, ash fusion temperatures, furnace atmosphere})$

♦  $\text{S } [SO_3], \text{ Na, Fe, Li}$  (> improves ESP collection efficiency)

♦  $\text{SiO}_2 + \text{Al}_2\text{O}_3 < \sim 80\%$  (ESP Index)

♦  $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 < \sim 98\%$ , else ESP reentrainment

♦ Fly Ash Sales effected by S, Ca, Na+Mg, C,  $SO_3$

♦ Air Toxics

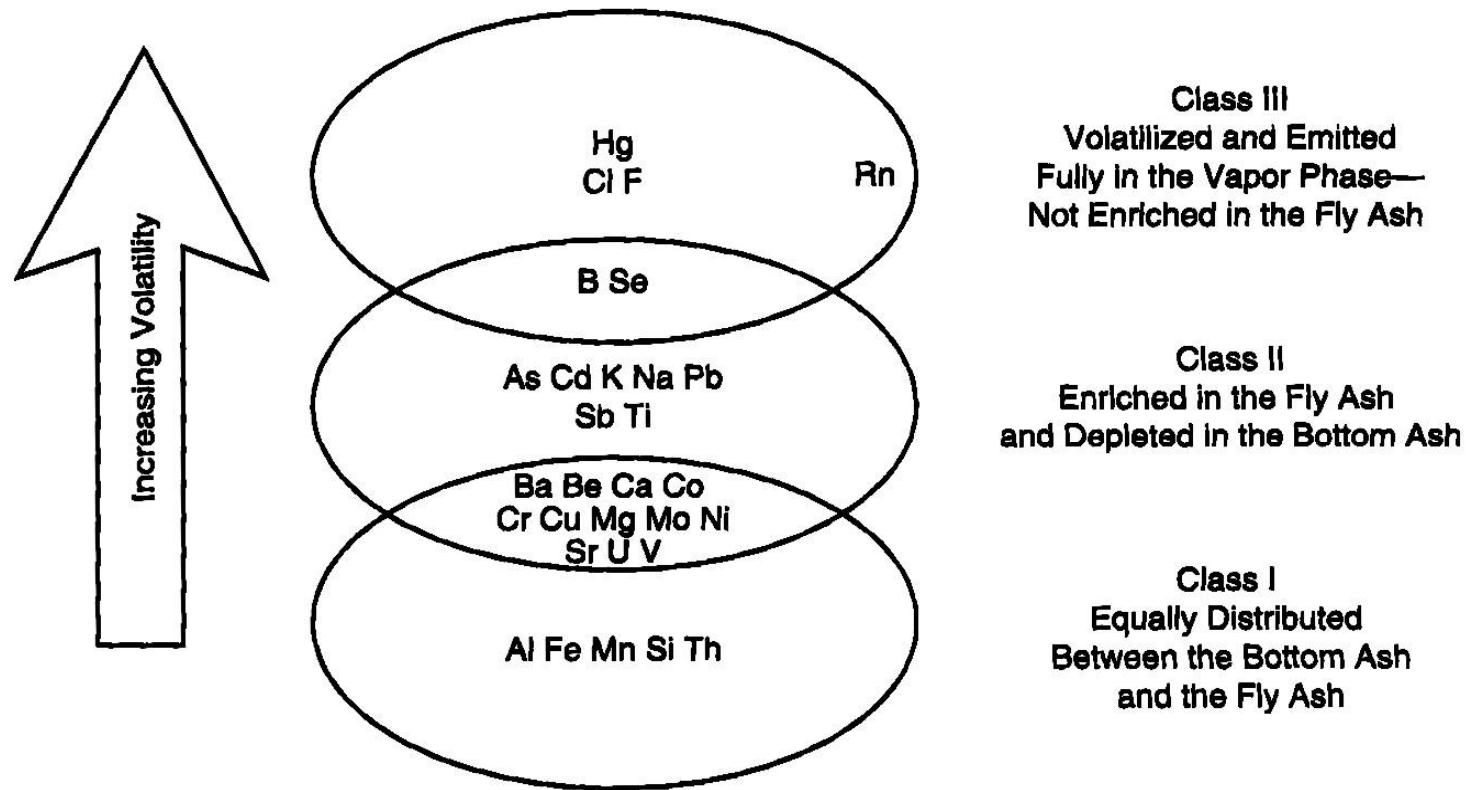
♦ Hg

♦ Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Mo, Ni, Se, Ag, V, Tl, Zn

♦ Cl, F (source of HCl & HF emissions)



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Classification scheme for selected trace elements relative to their volatility and partitioning in power plants. (Adapted from Miller *et al.* [37] and Clarke and Sloss [40].)



## Volatility (as-fired basis)

- ♦ High-vol (>28%) [steam coal, some met coals]
- ♦ Mid-vol (20%-28%) [met coals, sometimes steam coal]
- ♦ Low-vol (<20%) [met coals]
- ♦ Volatile/FC ["fireball" location]
  - ♦ Higher value moves fireball lower in furnace
  - ♦ Lower value moves fireball higher in furnace



## Sulfur

- ♦ **SO<sub>2</sub>**
  - ♦ **Lbs SO<sub>2</sub>/MBtu  $\equiv$  S% \* 20,000 / Heating Value (Btu/lb)**
    - ♦ 1.0% S @12,000 Btu/lb = 1.67 lbs SO<sub>2</sub>/MBtu
    - ♦ 1.1% S @13,200 Btu/lb = 1.67 lbs SO<sub>2</sub>/MBtu
    - ♦ 0.9% S @10,800 Btu/lb = 1.67 lbs SO<sub>2</sub>/MBtu
    - ♦ Power plants around the country may have tighter emission limits due to local or state consent orders
  
- ♦ **Sulfur Forms**
  - ♦ **Organic S**
    - ♦ Part of coal matrix
    - ♦ Not economically removable (today)
    - ♦ Released in flame zone, converts to SO<sub>2</sub> & SO<sub>3</sub>, sulfate deposition
  - ♦ **Pyritic S**
    - ♦ Component of ash, mostly FeS<sub>2</sub>, some HgS
    - ♦ Removable by physical coal cleaning
      - ♦ Balanced by economics & contractual requirements
    - ♦ Deeper cleaning removes more ash
      - ♦ Pyritic S and trace elements incrementally removed
    - ♦ May release in furnace, stay in ash as slag, sulfate deposition, fouling deposit or fly ash
  - ♦ **Sulfate S**
    - ♦ Oxidized sulfur, existing sulfates
    - ♦ Usually <0.01%



## HHV (Higher Heating Value, Gross Calorific Value)

- ◆ HHV (gross HV); as-received, dry & MAF bases
  - ◆ **As-Received**
    - ◆ Contractual, performance calculations
    - ◆ Includes moisture and ash as energy sinks
  - ◆ **Dry**
    - ◆ Lab comparison, removes moisture bias
    - ◆ Includes ash as the energy sink
  - ◆ **MAF**
    - ◆ Fingerprint, total energy from volatile & fixed carbon
    - ◆ Energy sources



## Ultimate (C,H,N,O + [Ash+S+Cl])

- ♦ C, O (dry basis)
- ♦ Function of coal rank
  - ♦ ↑ Rank: ↑ C, ↓ O, ↓ H
  - ♦ ↓ Rank: ↓ C, ↑ O, ↓ N
- ♦ C – total C in coal maceral
- ♦ H – total H in coal maceral
- ♦ N – total N in coal maceral
- ♦ O – total O in coal maceral (assumed by difference)
- ♦ H:C (molar basis) – indicator of coal reactivity
- ♦ O:C (molar basis) – indicator of coal reactivity
- ♦ N:C (molar basis) – indicator of fuel N reactivity



## HGI (Hardgrove Grindability Index)

- ♦ Indicator of power required to pulverize coal to -200 mesh
- ♦ HGI @x% moisture
  - ♦ Critical value for low-rank coals
  - ♦ Higher moisture, higher apparent HGI ; coal less friable
  - ♦ Lower moisture, lower apparent HGI ; coal more friable
- ♦ Index based on coal from Pocahontas Seam (set = 100)
  - ♦ Typical mined range: 35-110+ (harder  $\Rightarrow$  softer)
  - ♦ Typical range used by utilities: 37-75
- ♦ Effects of HGI extremes
  - ♦ For example, given 50 as design value
  - ♦ Low HGI (e.g., 39)
    - ♦ Coal harder than design
    - ♦ Increased wear on mill internals, increased O&M, reduced availability, increased burner-line erosion, reduced throughput, increased pyrites
  - ♦ High HGI (e.g., 80)
    - ♦ Coal softer than design
    - ♦ Reduced wears on mill internals, increased O&M, reduced availability, increased burner-line leaks, increased throughput, decreased pyrites, increased dust loading inside mill



## Mill Fineness

- ♦ Mill fineness and balance is one of the most important factors for proper combustion & burner line distribution; everything downstream is effected by coal particle size and particle distribution across the boiler
- ♦ Many negative environmental, combustion & performance factors can be traced back to mill performance
  - ♦ E.g., CO, NO<sub>x</sub>, slagging, UBC, LOI , waterwall corrosion, furnace erosion, O<sub>2</sub> mal-distribution, increased H-C emissions, opacity
- ♦ Mill Throughput Factors
  - ♦ Input coal size
  - ♦ Moisture
  - ♦ Pyrite concentration
  - ♦ Coal recirculation
  - ♦ Desired final particle size range



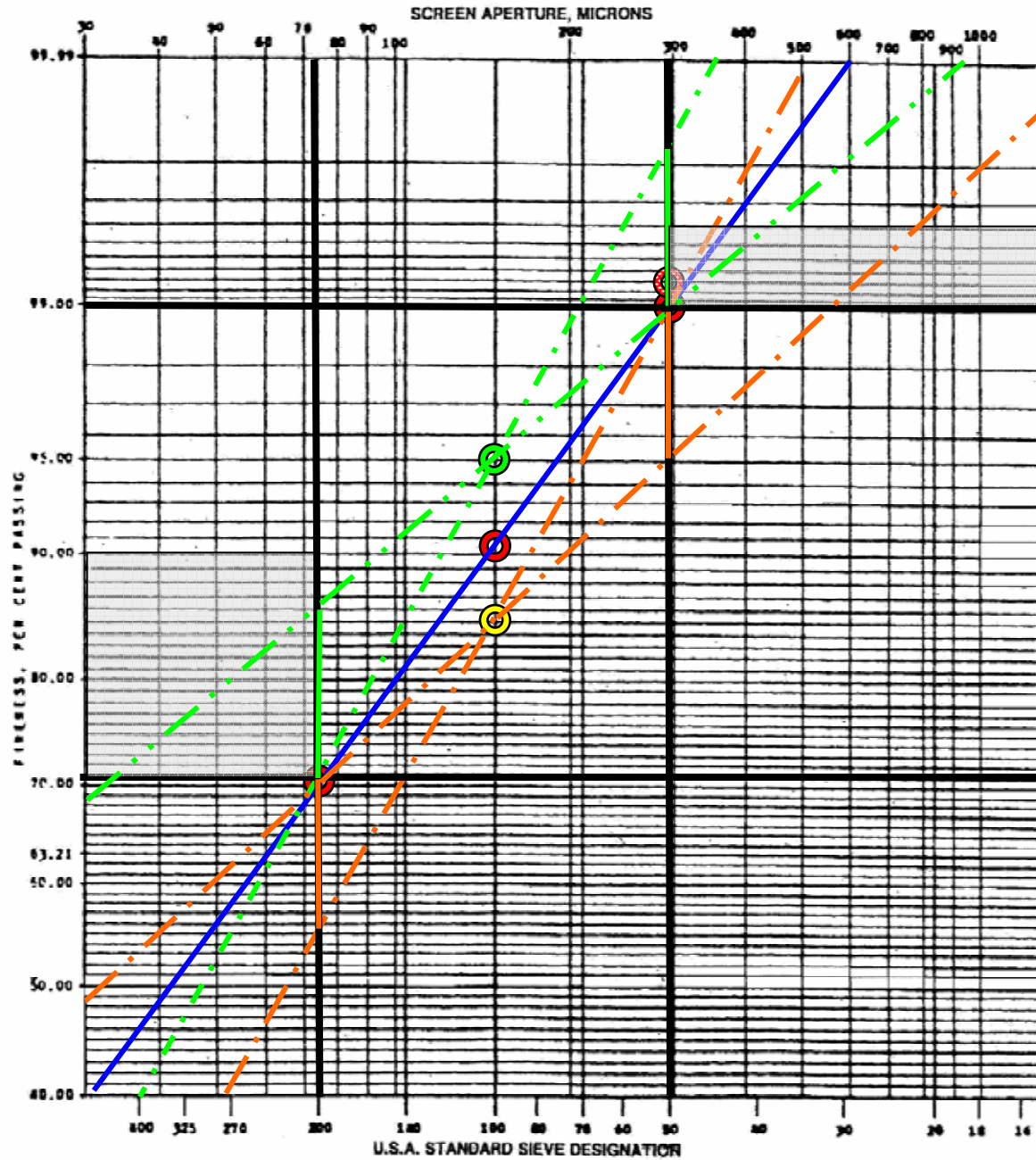
## Mill Fineness

- ♦ Impacts of Output Fineness
  - ♦ **Coarse** — Delayed combustion, combustion higher in furnace, higher unburned C (UBC), higher CO, higher O<sub>2</sub> requirement, increased mill throughput, slagging higher in furnace, decreased mill maintenance, larger burner-line bias (particle momentum vs. density), burner-line layout
  - ♦ **Micro Pulverized** — Rapid combustion, combustion lower in furnace, reduced unburned C (UBC), lower CO, reduced O<sub>2</sub> requirement, reduced mill throughput, increased mill maintenance, too rapid burnout, (decreased NO<sub>x</sub>?)





Rosin-Rammler Chart



Plot of Rosin and Rammler Equation for Use with Pulverized Coal



## Combustion Characteristics for Pulverized Coal Furnaces

---

### Particle size

~Top size	180 $\mu\text{m}$
Average size	45 $\mu\text{m}$
Furnace temperature	>2200°F
Particle heating rate	$10^3$ - $10^6$ °F/sec

### Reaction times

Volatiles	<0.1 sec
Char	<1 sec
Reactive element	Chemically controlled combustion



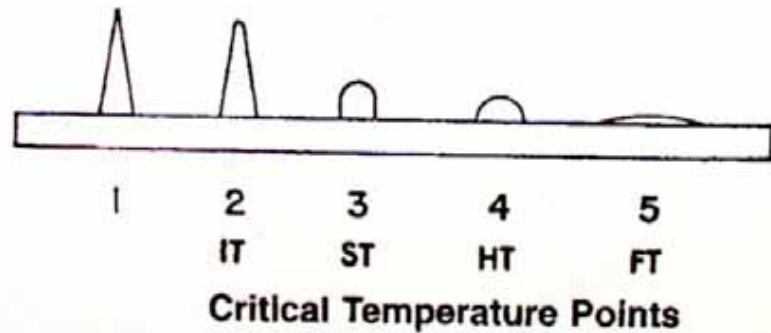
## Ash Fusion Temperatures

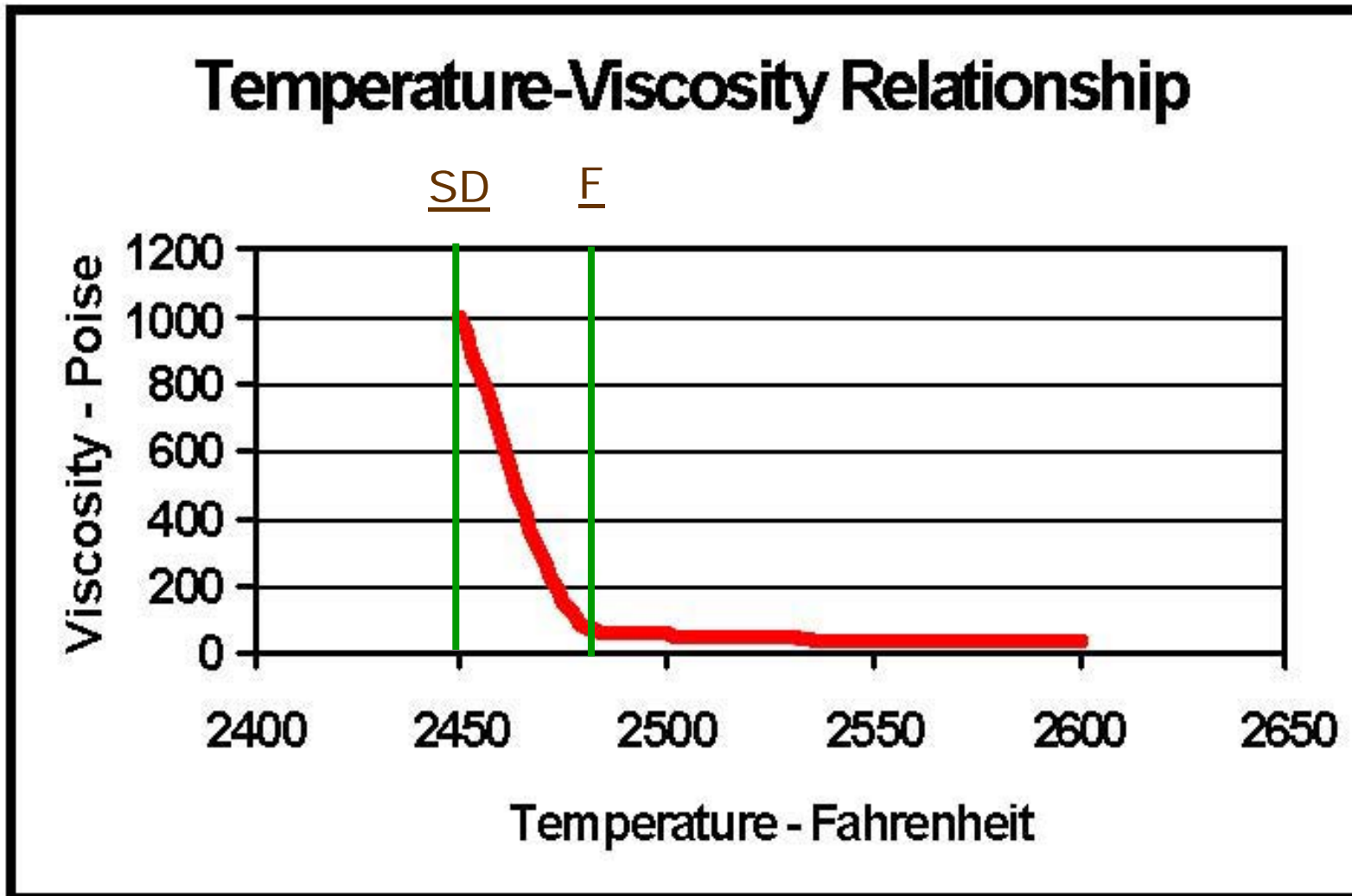
- ◆ Reducing & oxidizing atmospheres (CO/CO<sub>2</sub> vs. air)
  - ◆ **Initial, Spherical, Hemispherical, Fluid**
- ◆ Plastic range (fusion box)
  - ◆ Fluid - Initial
- ◆ Ash melting temperatures follows a hysteresis curve (lab vs operating boiler)
- ◆ **Eutectics** in blends
- ◆ Need to correlate with unit operation
  - ◆ Compare relative changes
  - ◆ Cannot always use absolute values



## Ash Fusion

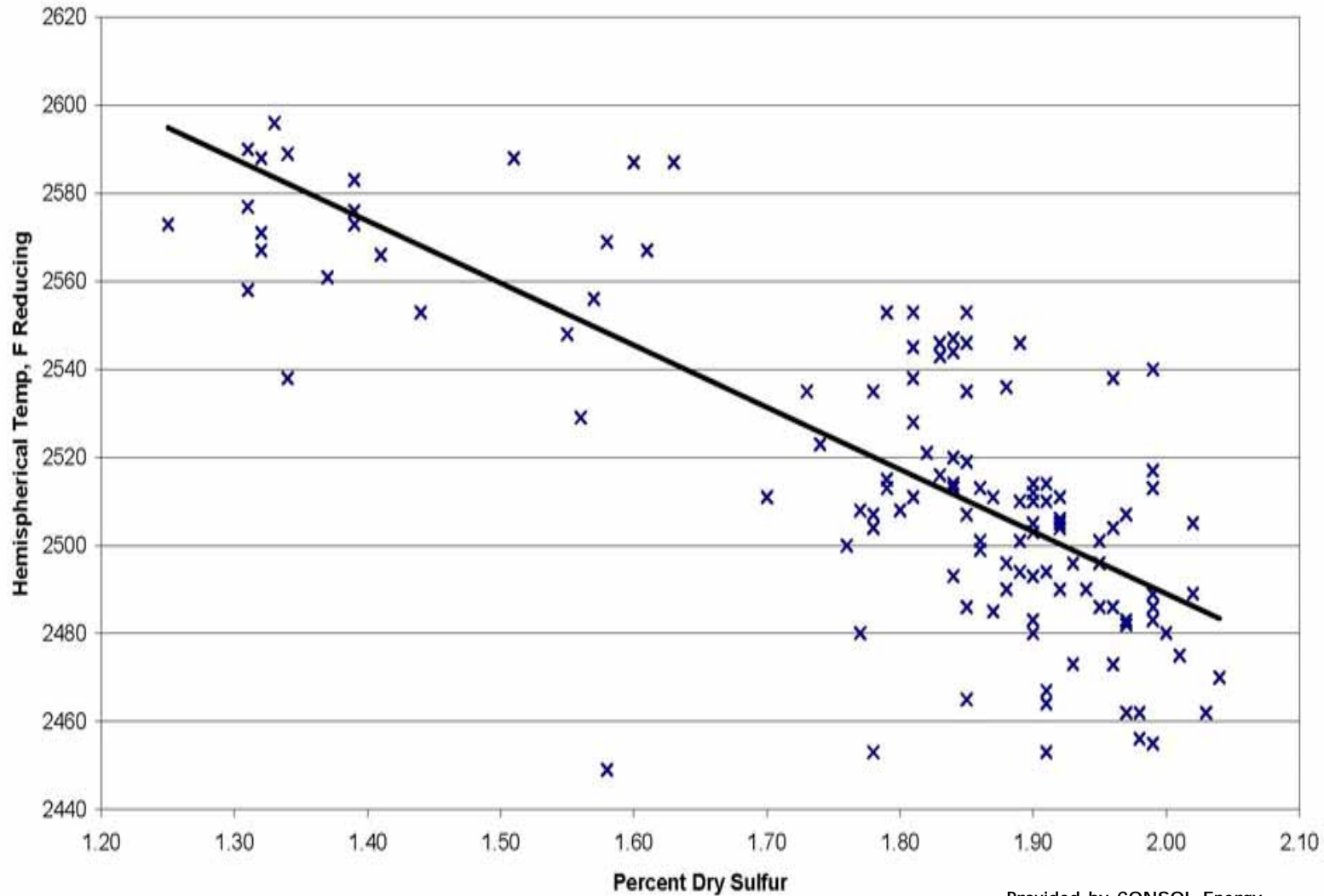
- Slagging & Fouling Predictors
- Eutectic Predictor





Sulfur vs. Ash Fusion Temperature

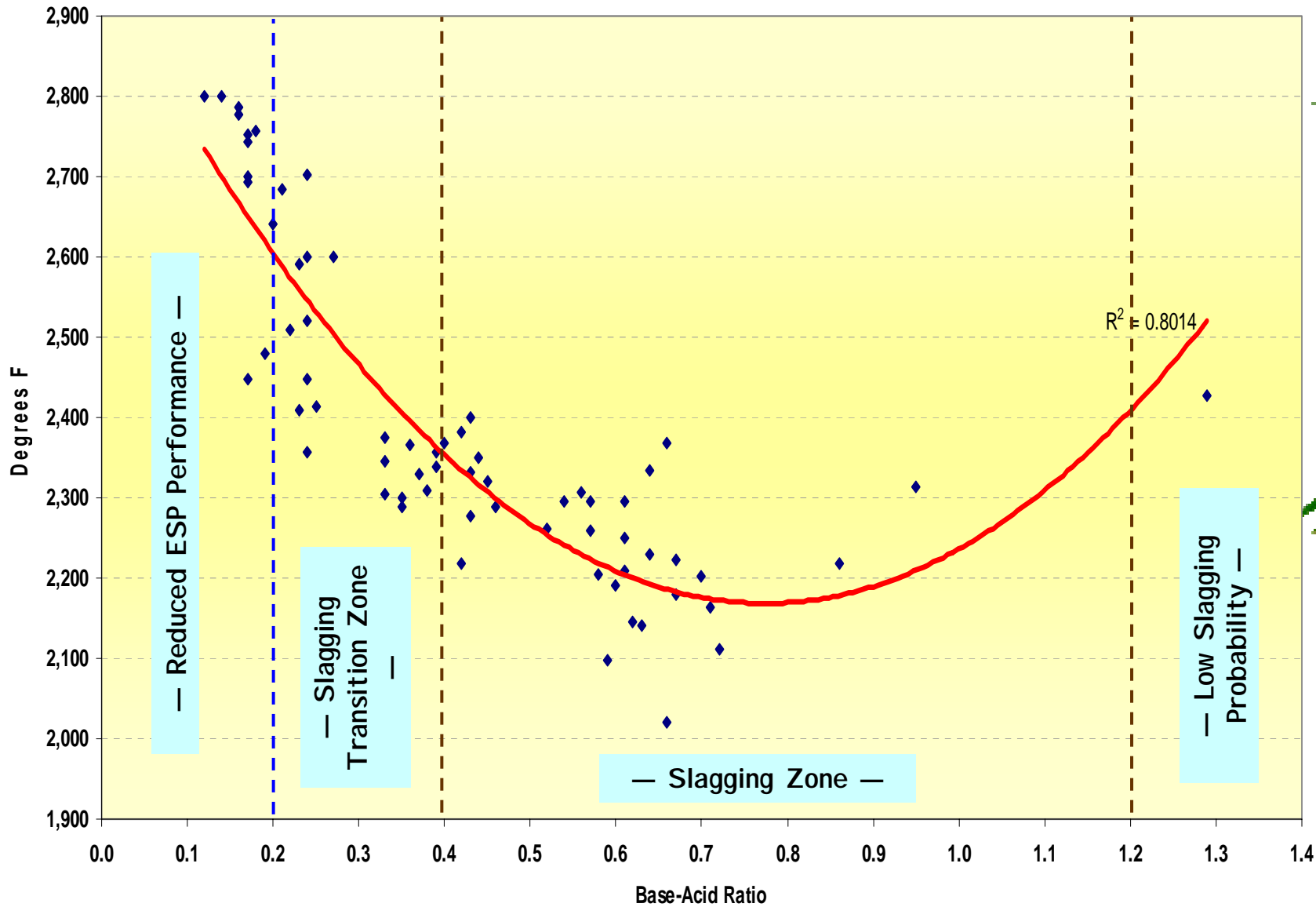
$y = -141.08x + 2771.2$



Provided by CONSOL Energy



### B:A vs Fusion-Hemispherical



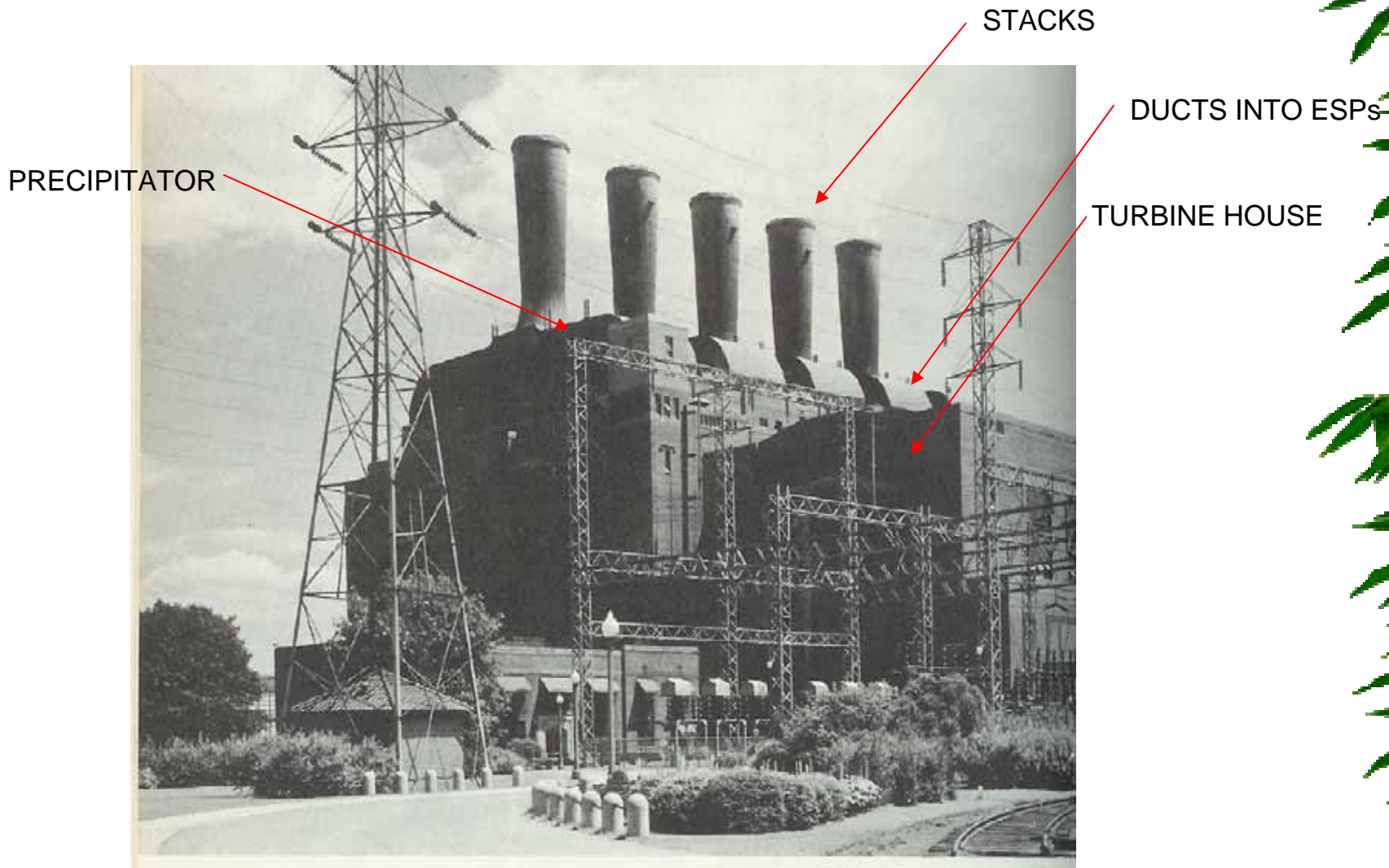
## Coal Blending

- ♦ Most characteristics can be averaged
- ♦ Critical exceptions
  - ♦ **Volatile release** — Coals with higher volatile release will reduce NO<sub>x</sub> formation
  - ♦ **Reactivity** — More reactive coals will reduce NO<sub>x</sub> formation
  - ♦ **Lower fuel N** — Coals with less fuel-N will reduce NO<sub>x</sub> formation
  - ♦ **Higher fuel O** — Trim excess air to compensate for the extra O in lower rank coals
  - ♦ **HGI** — Biased toward the harder coal
  - ♦ **Ash viscosity**
    - ♦ Usually non-Newtonian (*non-linear*)
    - ♦ Many interdependencies
      - ♦ Flue gas temperature & gas atmosphere (reducing, oxidizing)
      - ♦ Formation temperature
      - ♦ Heating and cooling rates for elements and compounds originally present
      - ♦ Reaction mechanism & reaction rates
  - ♦ **Ash fusion**
    - ♦ Indirect measure of viscosity
    - ♦ Not linear with temperature
    - ♦ Effected by combustion atmosphere (reducing vs. oxidizing)
    - ♦ Eutectics



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TRENTON CHANNEL POWER PLANT LOW PRESSURE  
FIRST UTILIY BOILER w/PRECIPITATOR — 1923



Electrostatic Precipitation  
Precipitator Operation

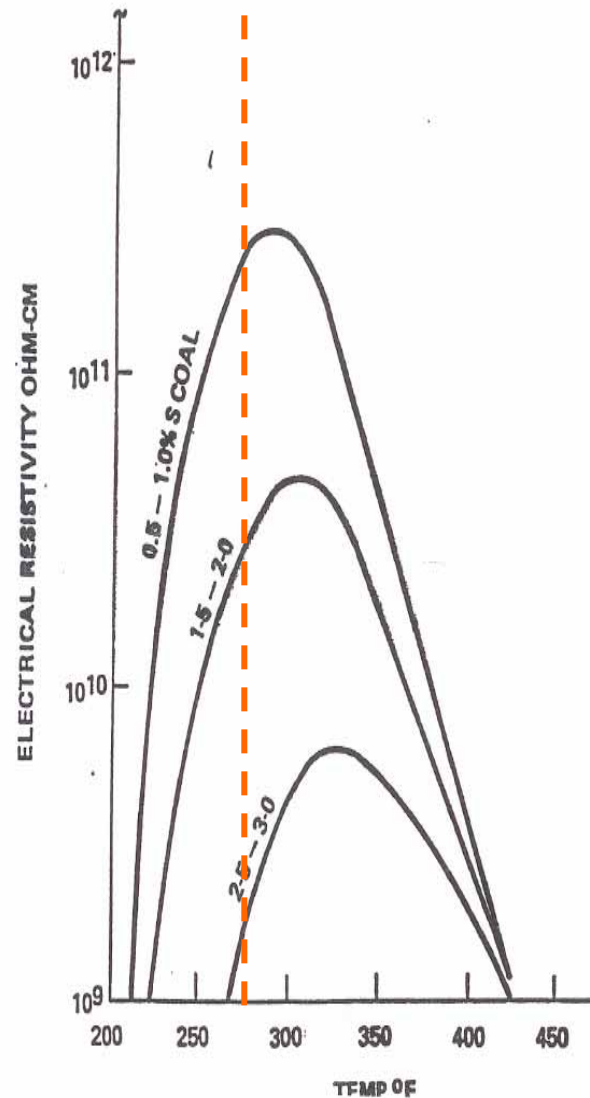
<u>PRECIPITATOR EFFICIENCY BY NUMBER OF FIELDS</u>			
<b>FIELD NUMBER</b>	<b>COLLECTION</b>	<b>BY PASSED</b>	<b>EFFICIENCY</b>
ENTERING ASH	100.00%		
1	80.00%	20.00%	
2	14.00%	6.00%	
3	4.20%	1.80%	
4	1.26%	0.54%	99.70%
5	0.38%	0.16%	
6	0.11%	0.05%	
			99.99%



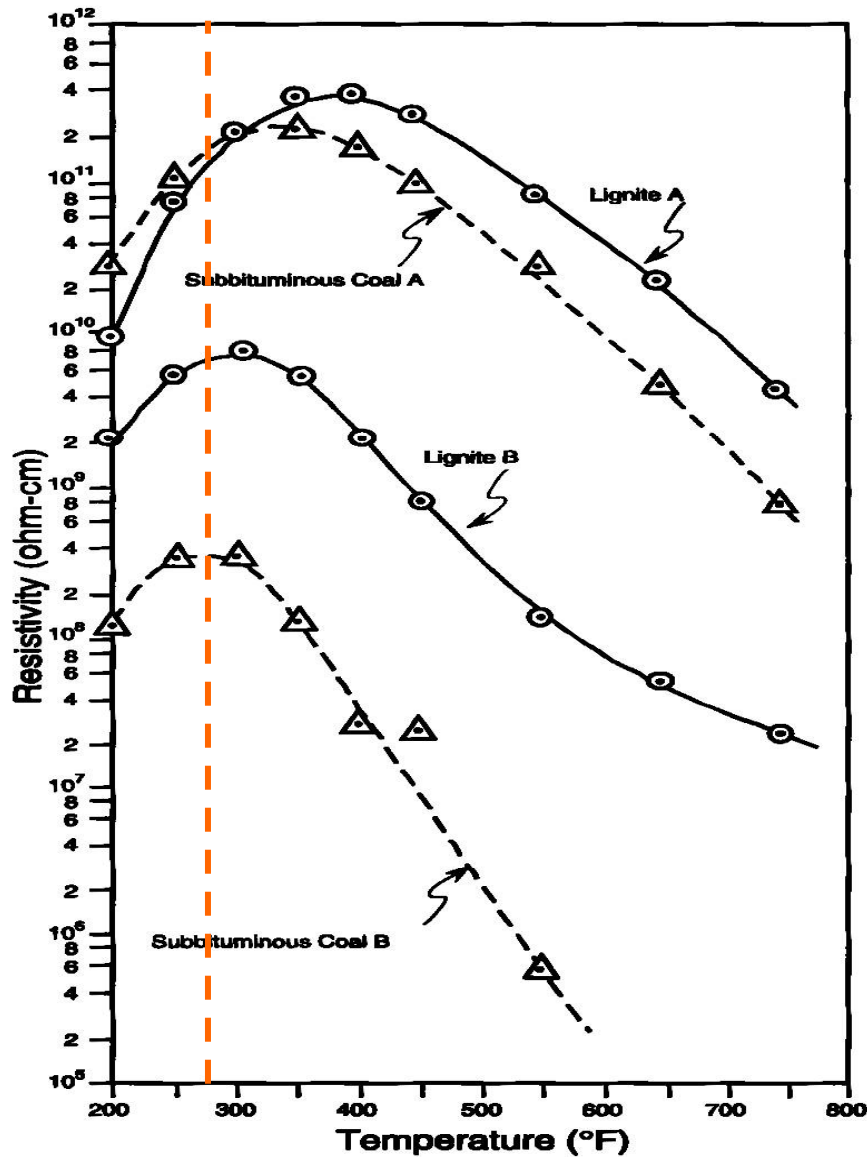
## Electrostatic Precipitation

### • Ash Resistivity ( $\Omega$ -cm)

- Highly dependent on flue gas temperature and relative humidity
- S [ $SO_3$ ], Na, Fe, Li (> improves collection efficiency)
  - Metals that act as conductors
  - High voltage field easily strips the metal of electrons
- $SiO_2 + Al_2O_3 < \sim 80\%$  (ESP Index)
  - Ash resistivity too high for efficient collection
  - "glass"
- $SiO_2 + Al_2O_3 + Fe_2O_3 < \sim 98\%$ ,
  - Ash resistivity too low
  - Difficult to remove from rappers, reentrainment

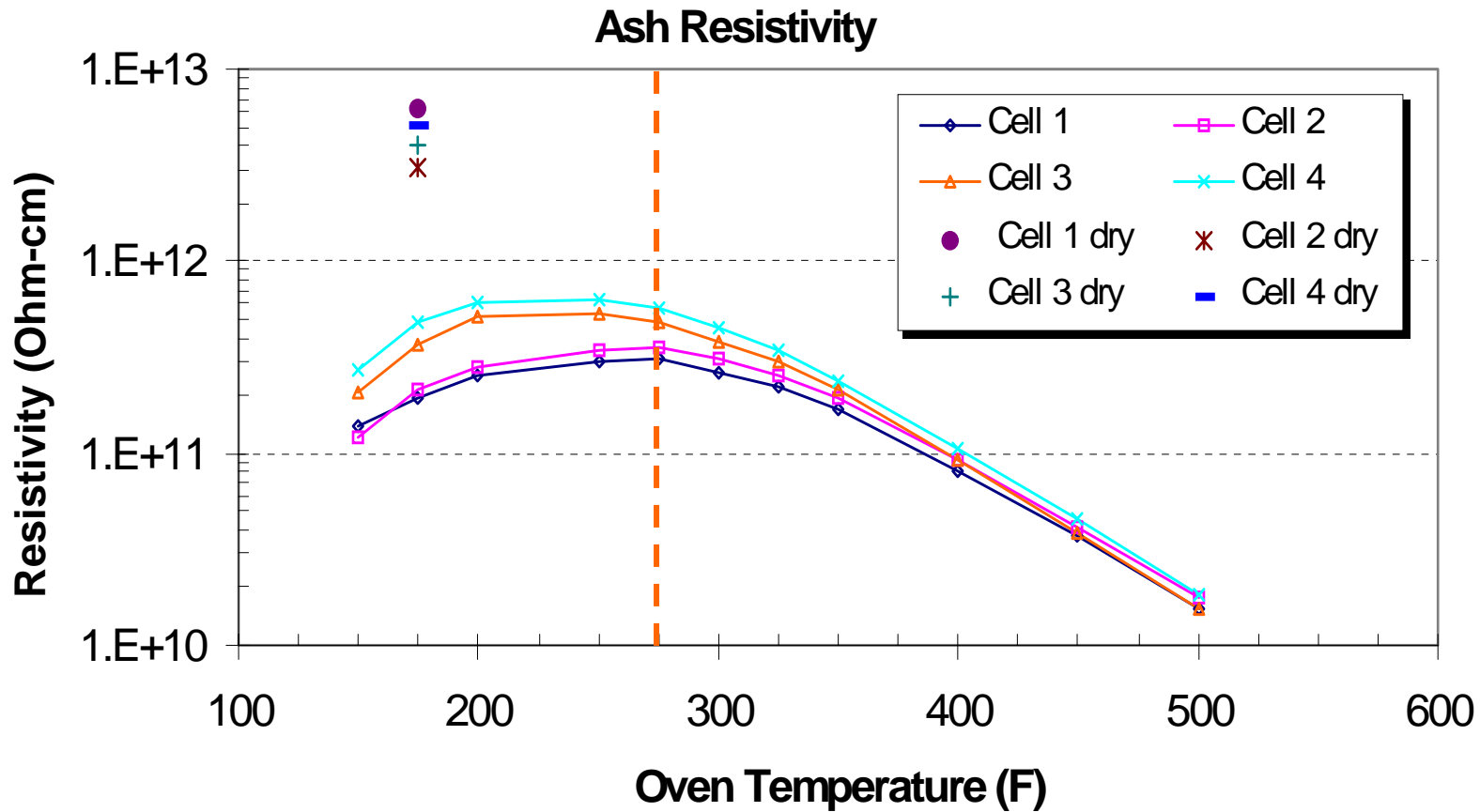


Electrostatic Precipitation



**Illustration of effect of ash composition on fly ash resistivity for coals from the same geographical location. (Miller, B. G., unpublished data, 1986.)**





One Lump or Two?

Coal Quality by  
Density or Particle Size

OR

What Number Do You Want?

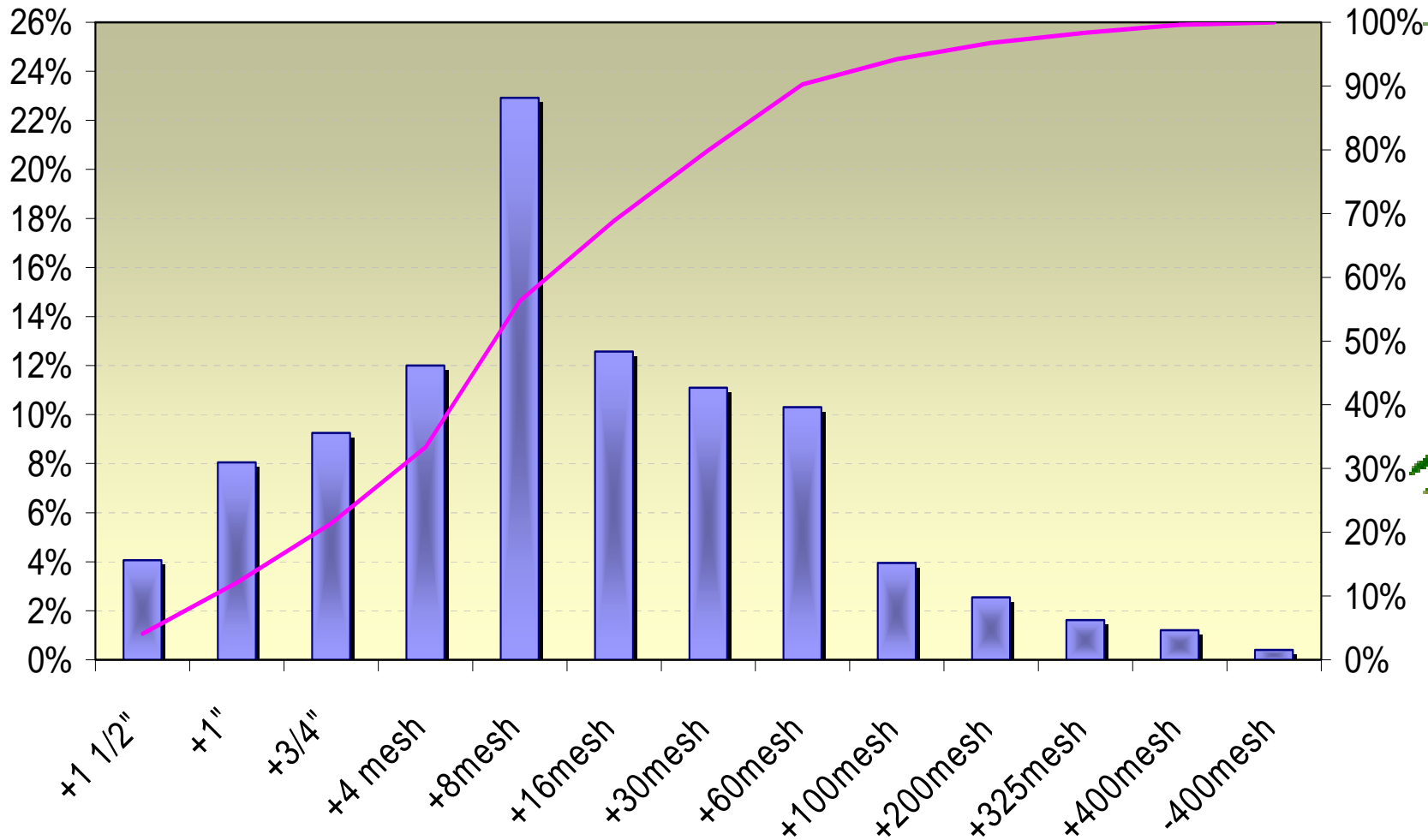


## Size Consist

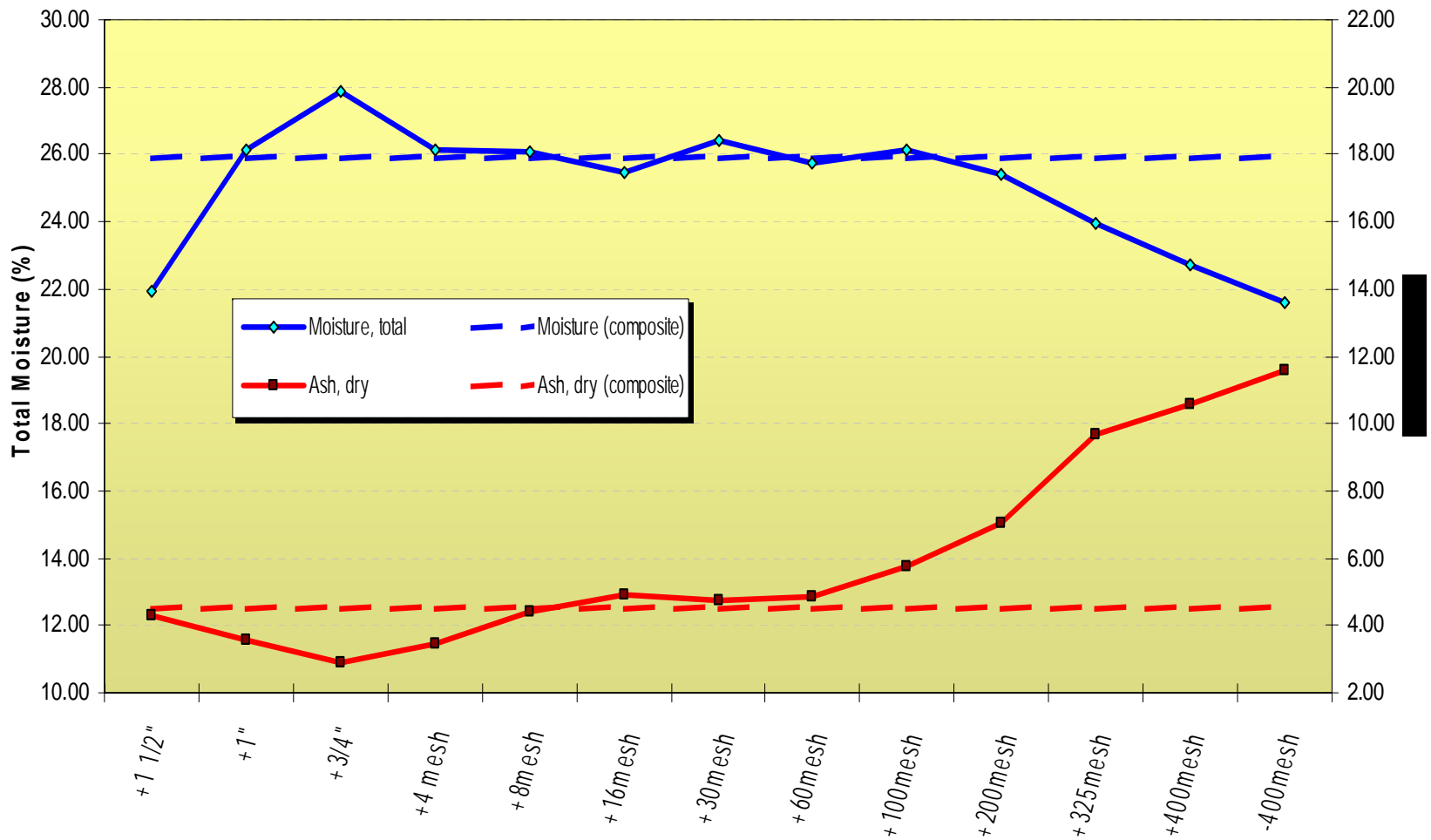
- ◆ Raw vs CROM vs washed (full vs. partial)
  - ◆ Raw (as-mined)
    - ◆ Roof, floor, slate, bone, sulfur balls, partings
  - ◆ CROM (Crushed Run-of-Mine)
    - ◆ Crushed raw coal with obvious impurities removed
  - ◆ Washed coal
    - ◆ Physical coal cleaning to remove ash
      - ◆ Pyritic sulfur removal is an artifact of ash removal
    - ◆ Blends coal & mineral matter to a blended specific gravity
      - ◆ Typically ~1.7
      - ◆ Coal ~1.3
      - ◆ Mineral matter ~2-5
    - ◆ Full washing typically 1.5" x 100 mesh
      - ◆ Newer wash plants will wash to 1.5" x 0
    - ◆ Partial washing
      - ◆ Typically includes 2"x¾" CROM + washed ¾"x100mesh
  - ◆ Washing improves coal quality by removing impurities
    - ◆ Yields tighter  $\sigma$  vs. mean



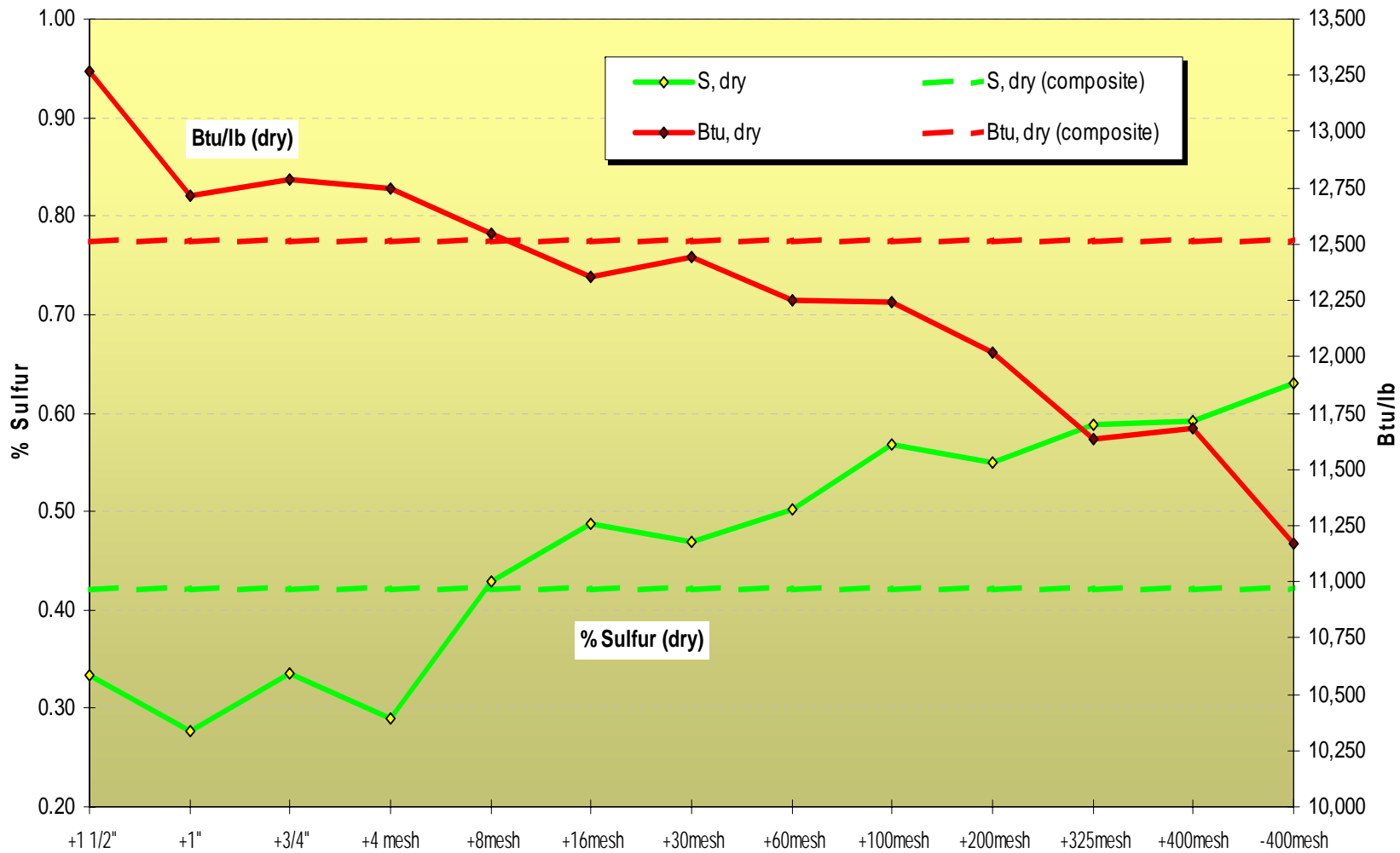
### PRB-MT CROM Size Distribution



### PRB-MT Coal Quality by Size (Moisture, Dry Ash)

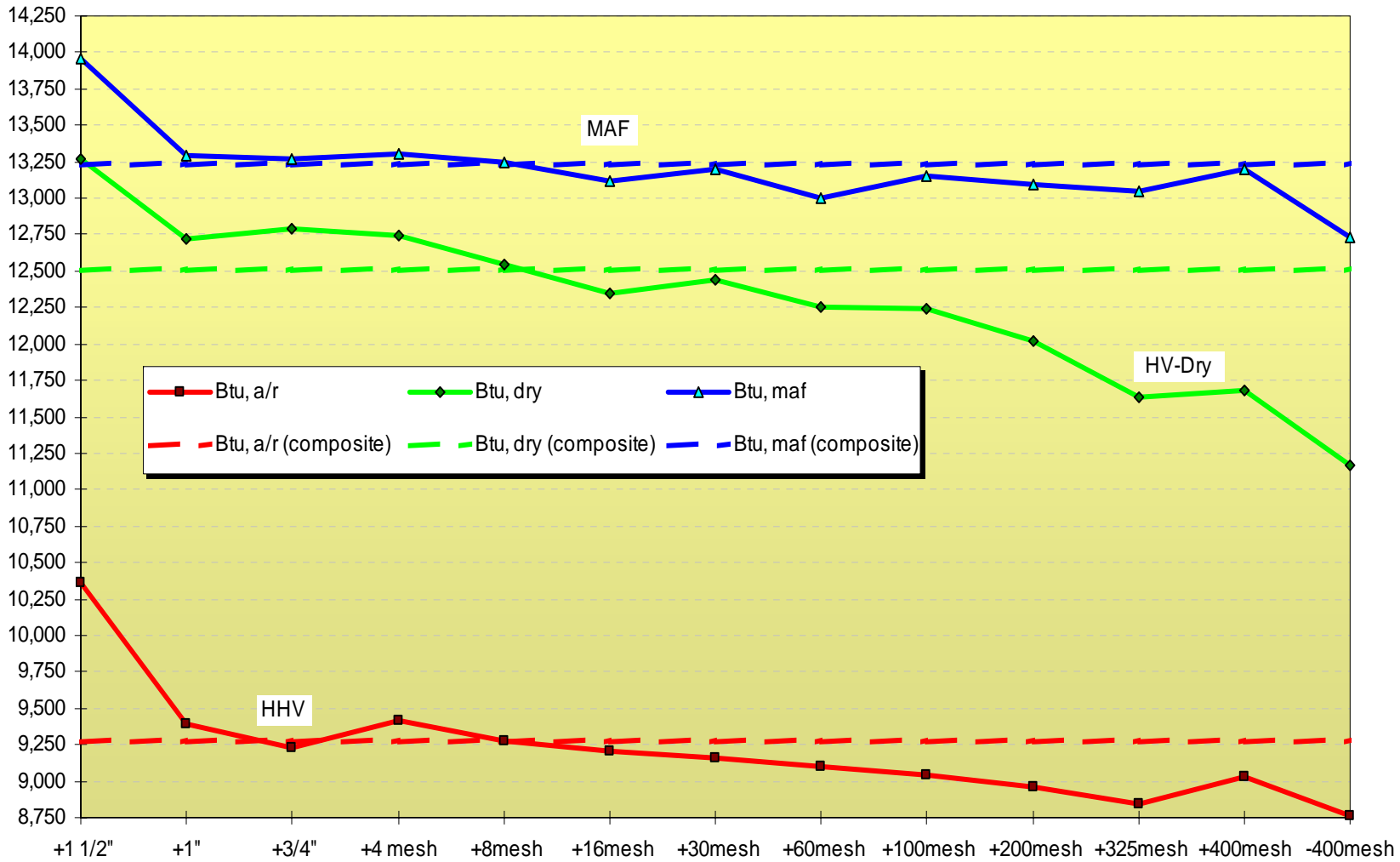


### PRB-MT Coal Quality by Size (Dry Sulfur, Dry Btu)

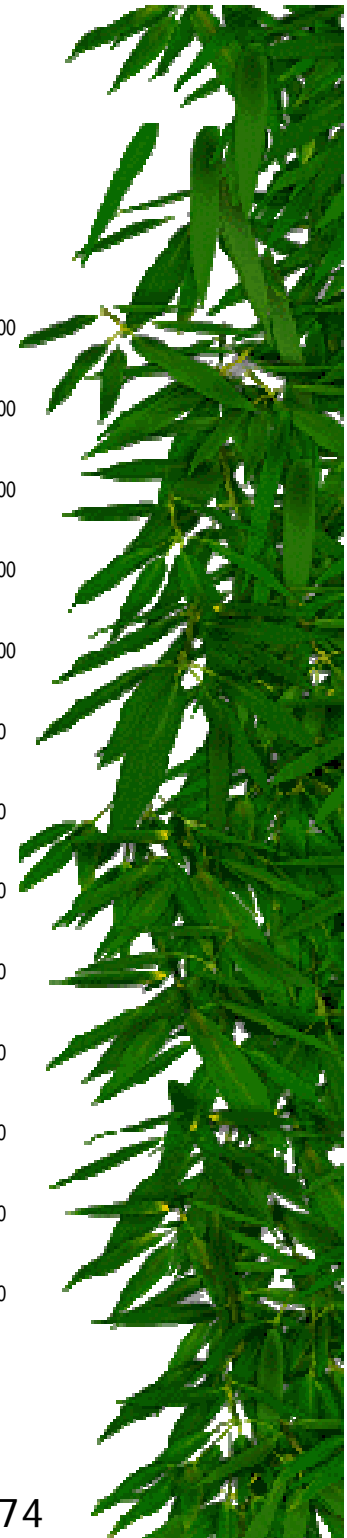


# "Coal and the Environment" — 2006 APC Round Table & Expo

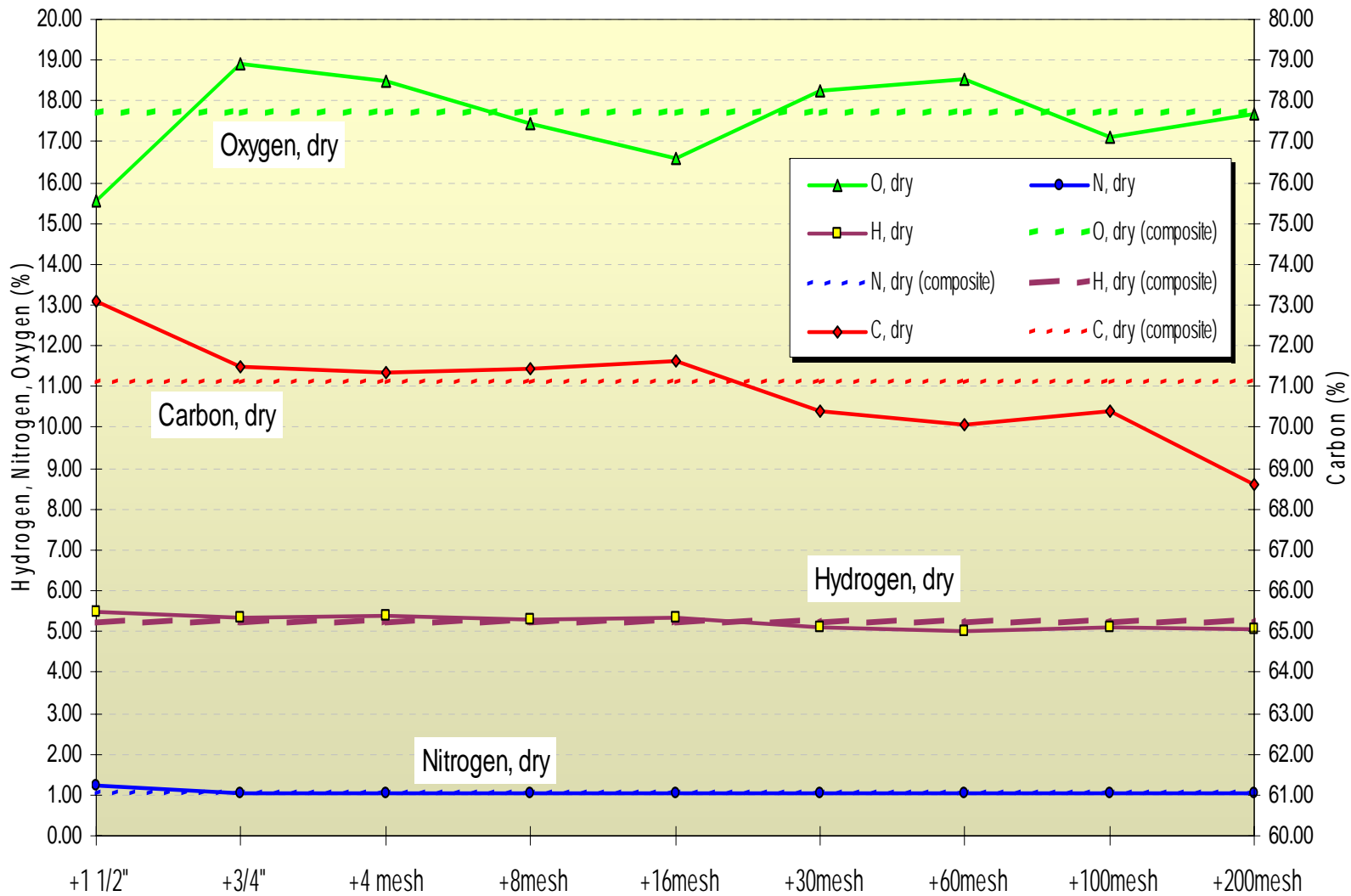
**PRB-MT Coal Quality by Size**  
(As-Received Btu, Dry Btu, MAF Btu)



### PRB-MT Coal Quality by Size (SO<sub>2</sub>, Ash Loading)



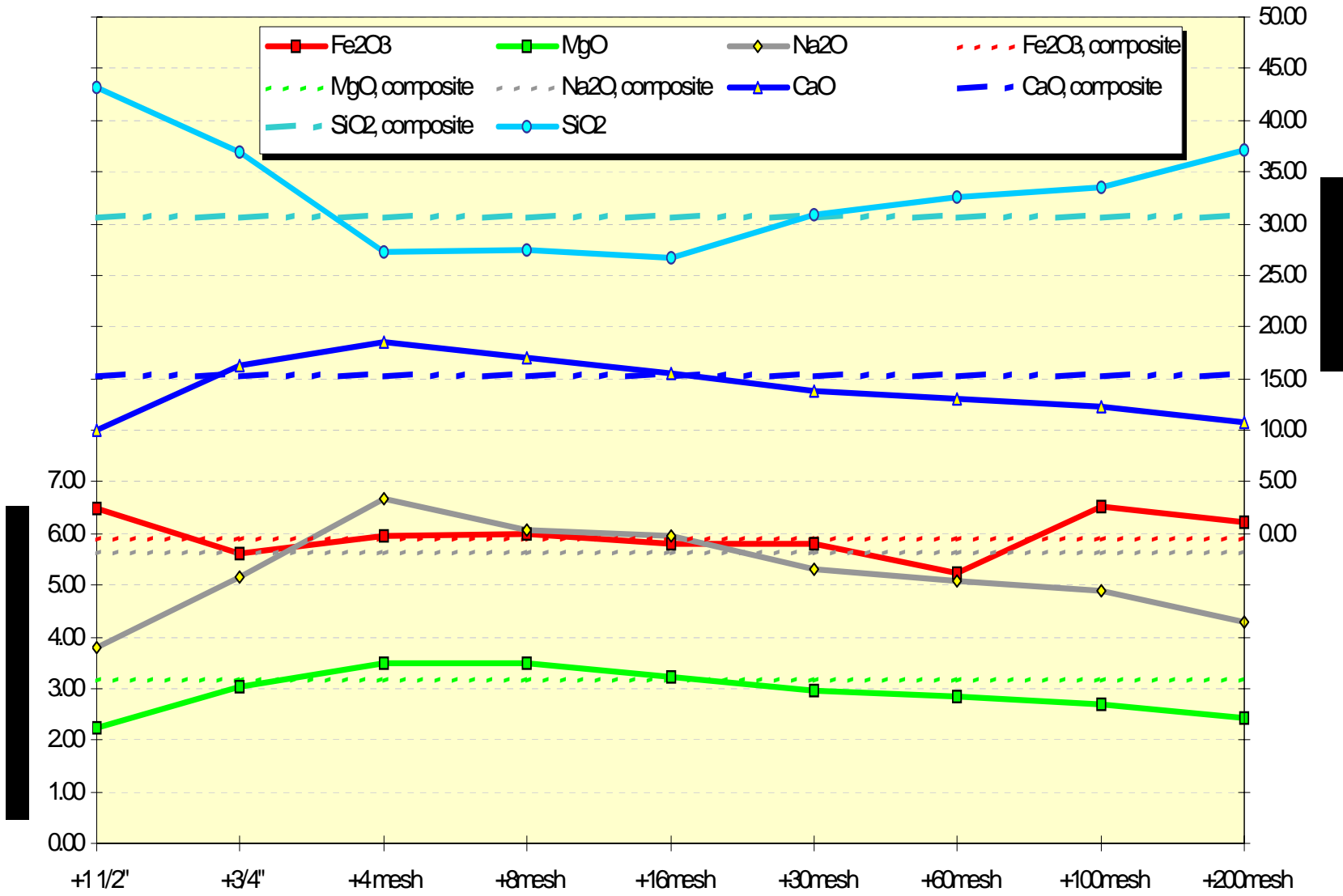
PRB-MT Coal Quality by Size (Ultimate, Dry Basis)



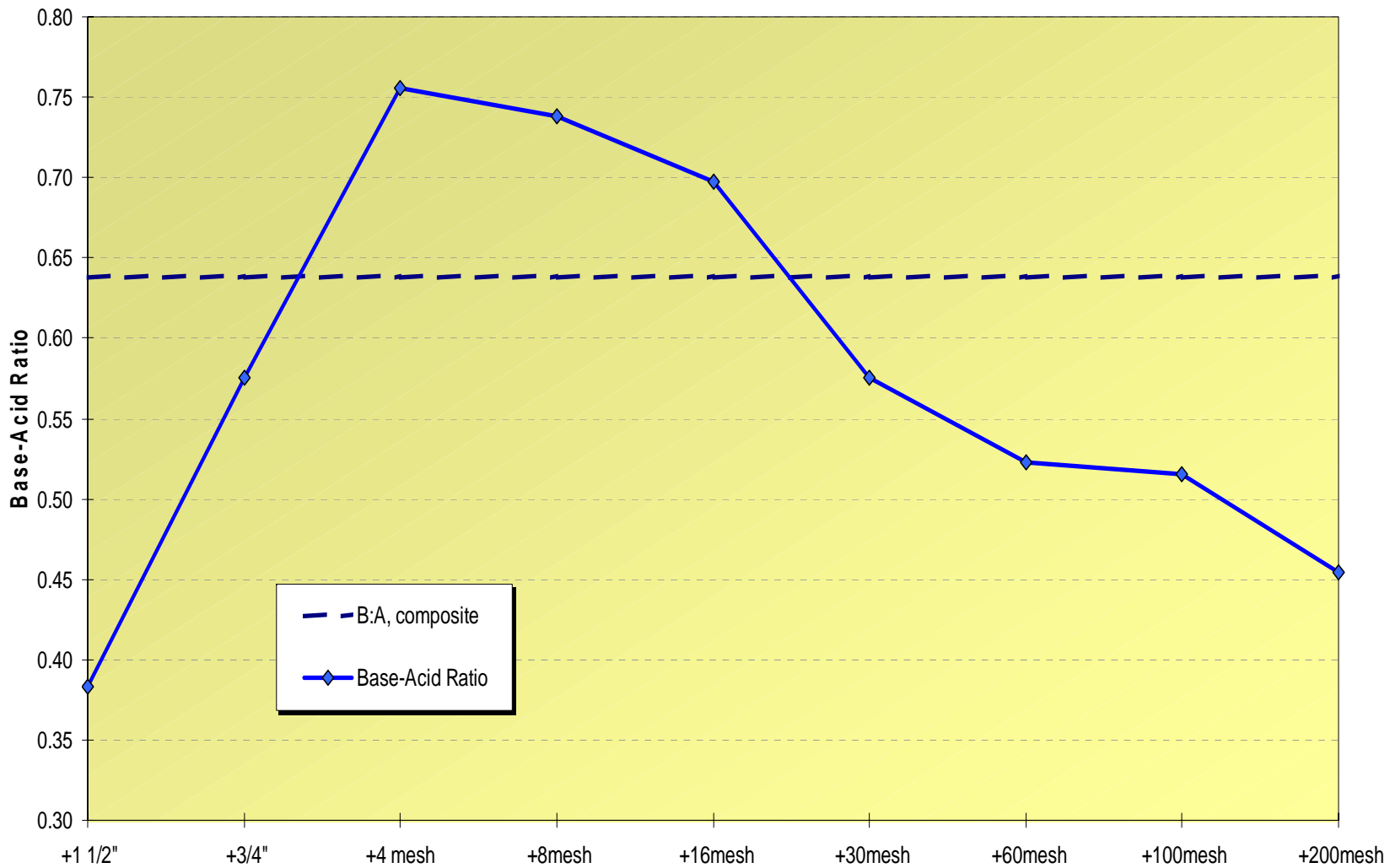
PRB-MT Coal Quality by Size  
(Na<sub>2</sub>O, Fe<sub>2</sub>O<sub>3</sub> Loading)



**PRB-MT Coal Quality by Particle Size**  
**Ash Mineral (Si, Fe, Ca, Mg, Na) as Oxides**



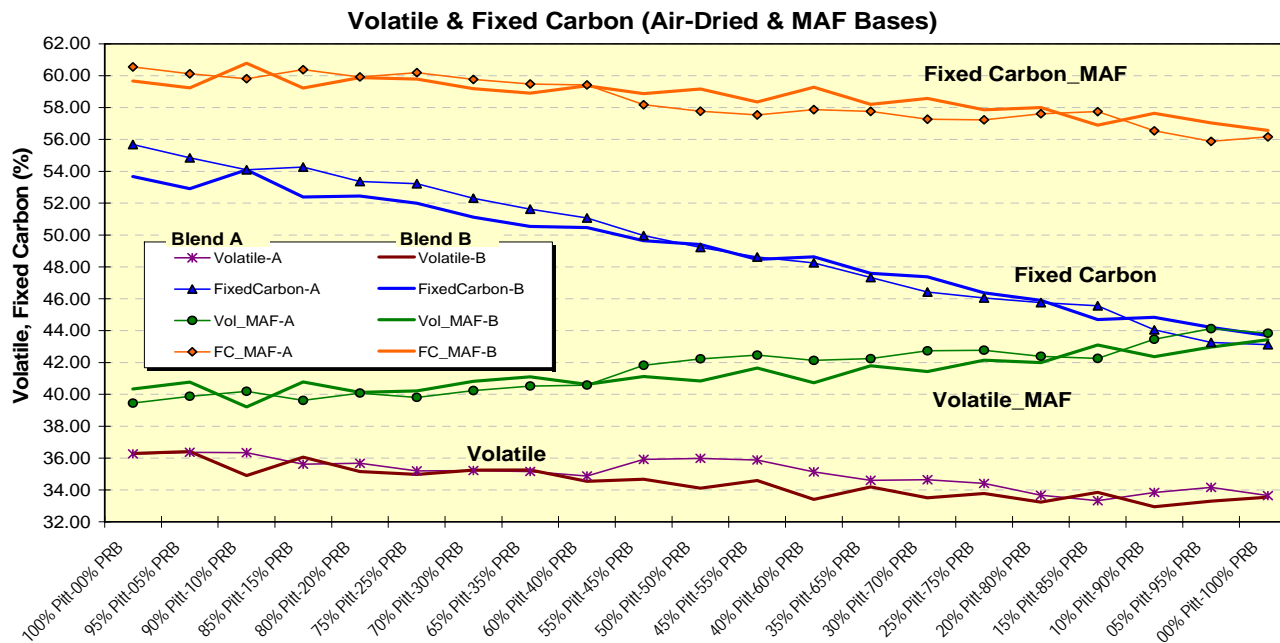
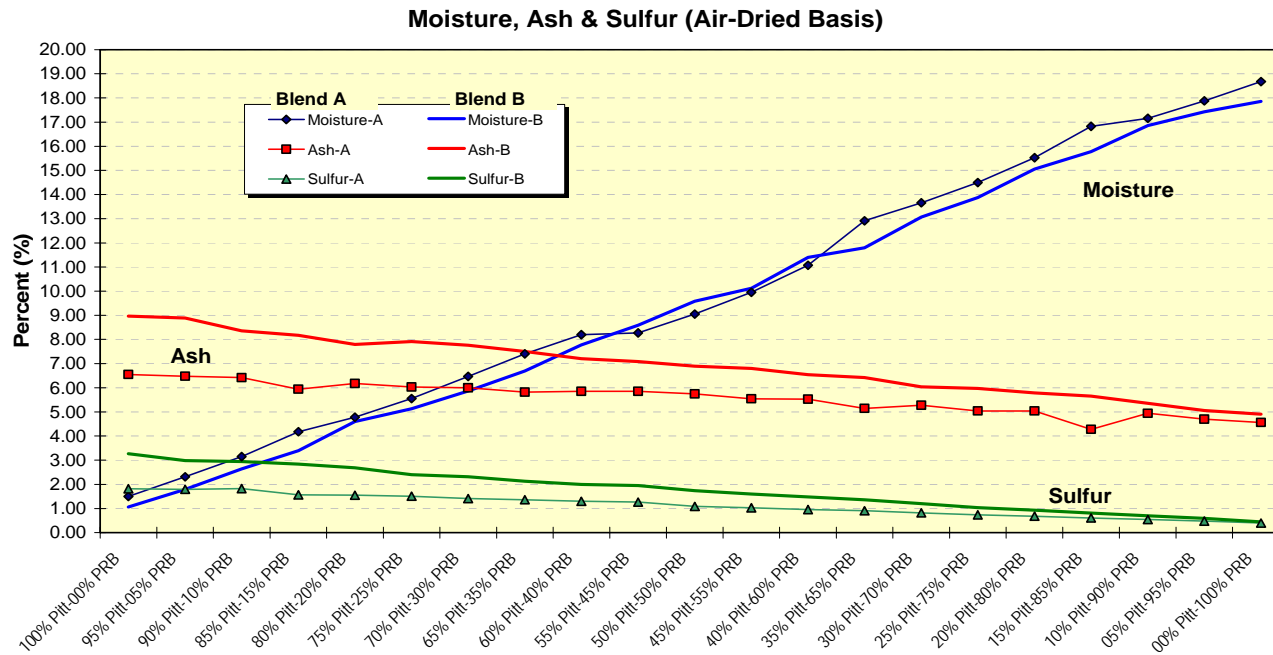
**PRB-MT Coal Quality by Size  
(Base-Acid Ratio)**



*Ash Fusions*  
&  
*Fusion Box*

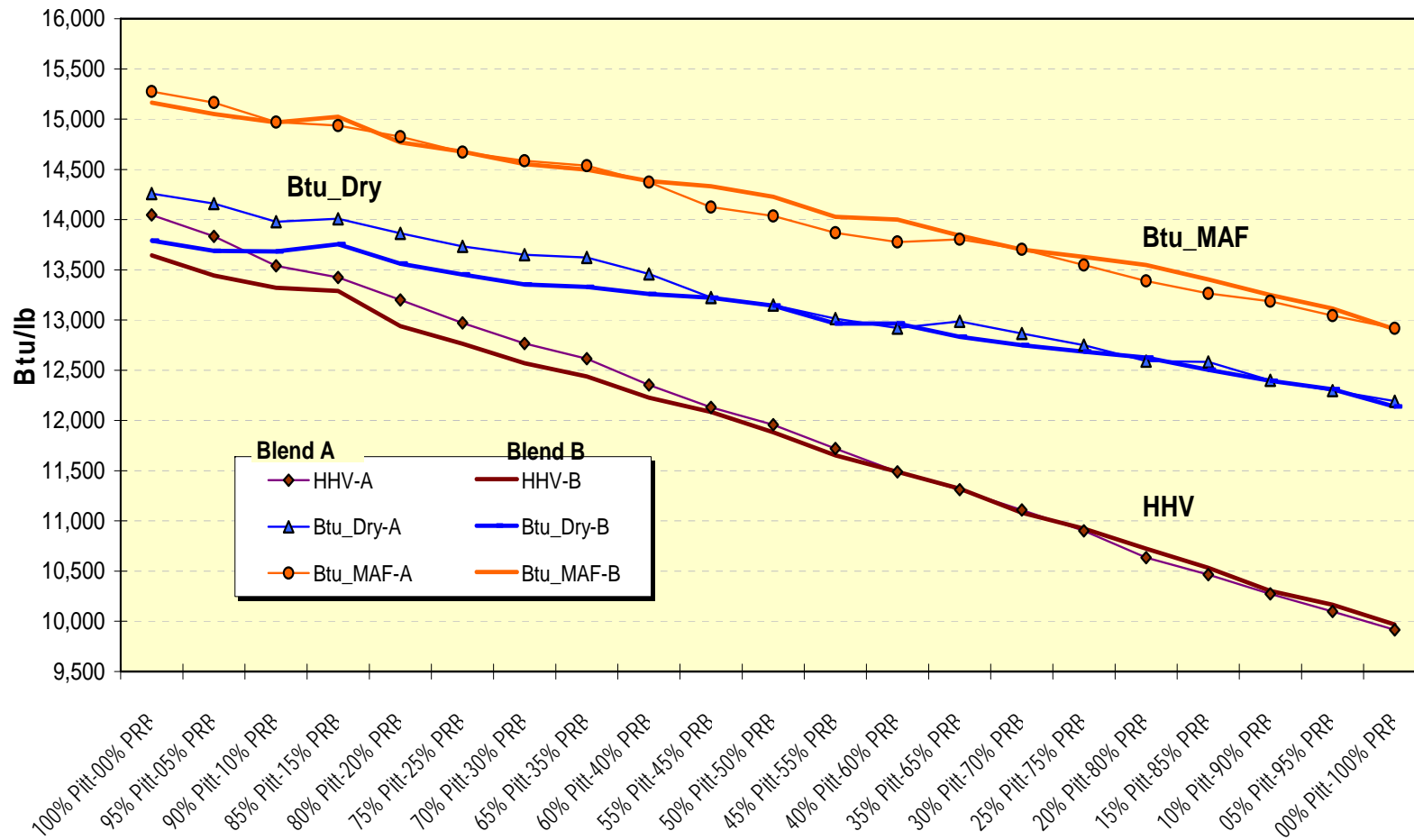


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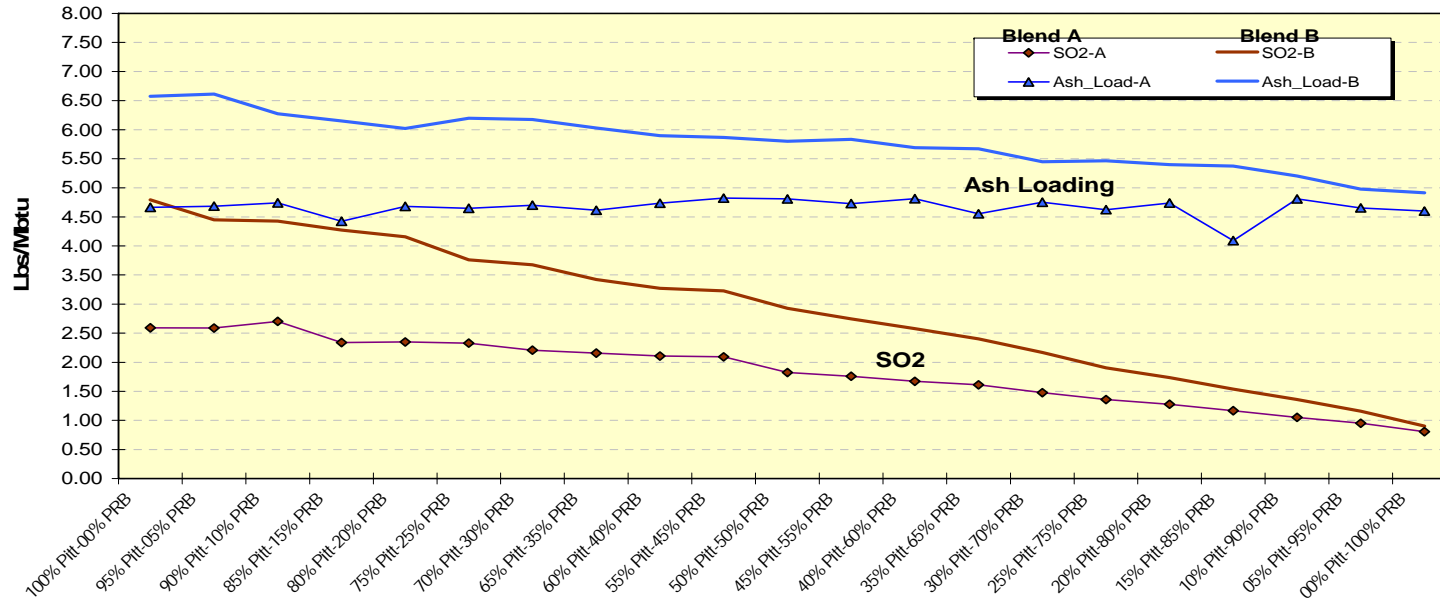
# "Coal and the Environment" — 2006 APC Round Table & Expo

## Heating Values (Air-Dried, Dry, MAF)

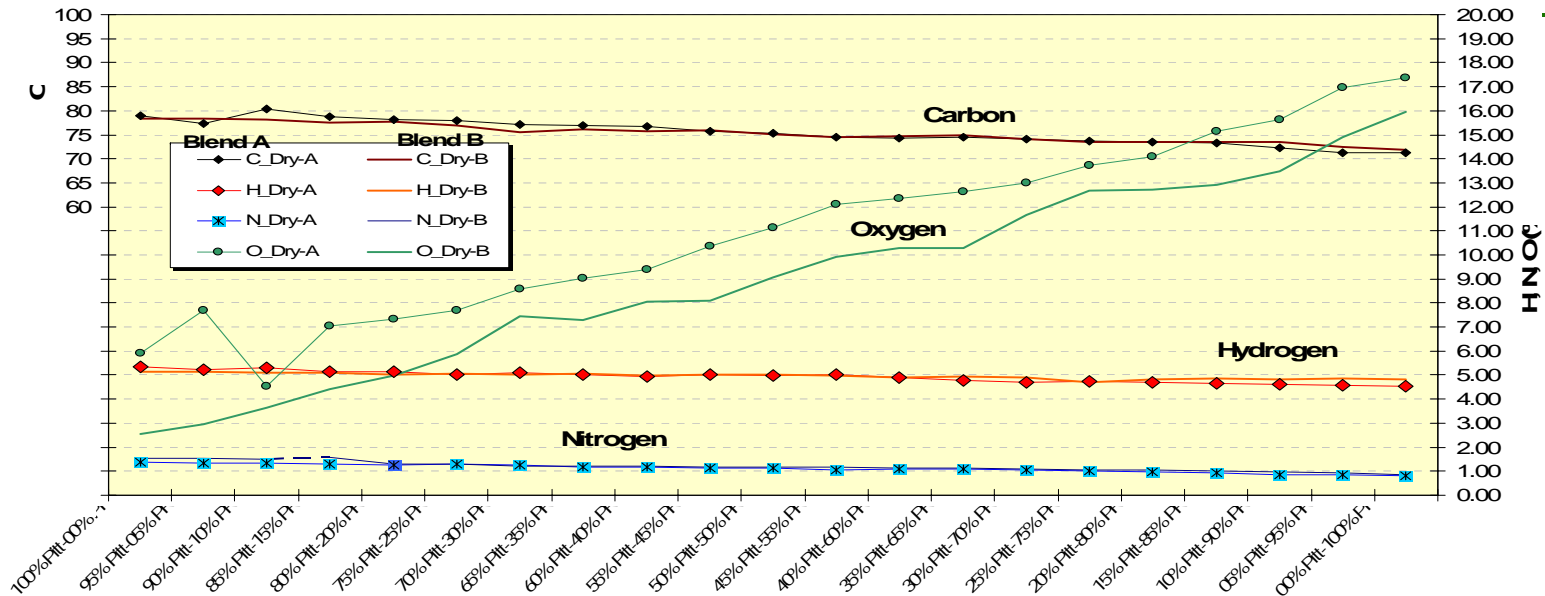


# "Coal and the Environment" – 2006 APC Round Table & Expo

### SO<sub>2</sub>, Ash Loading

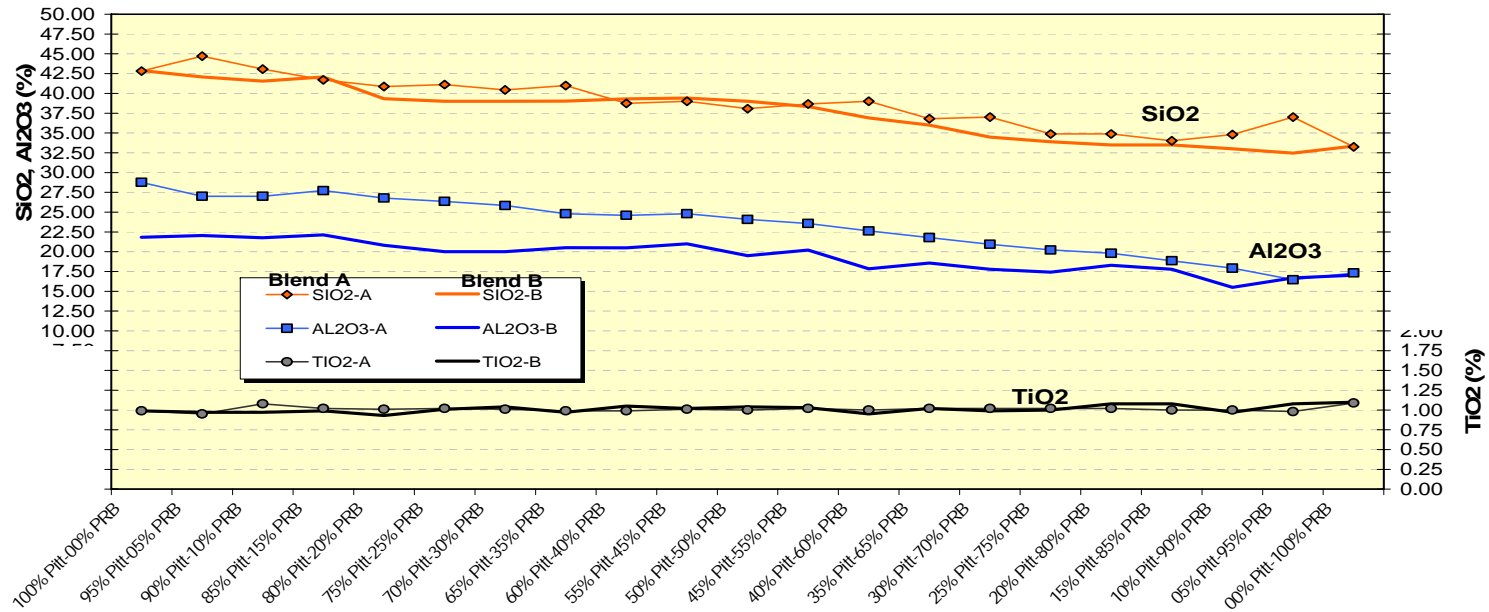


### Carbon, Hydrogen, Nitrogen, Oxygen (Dry Basis)

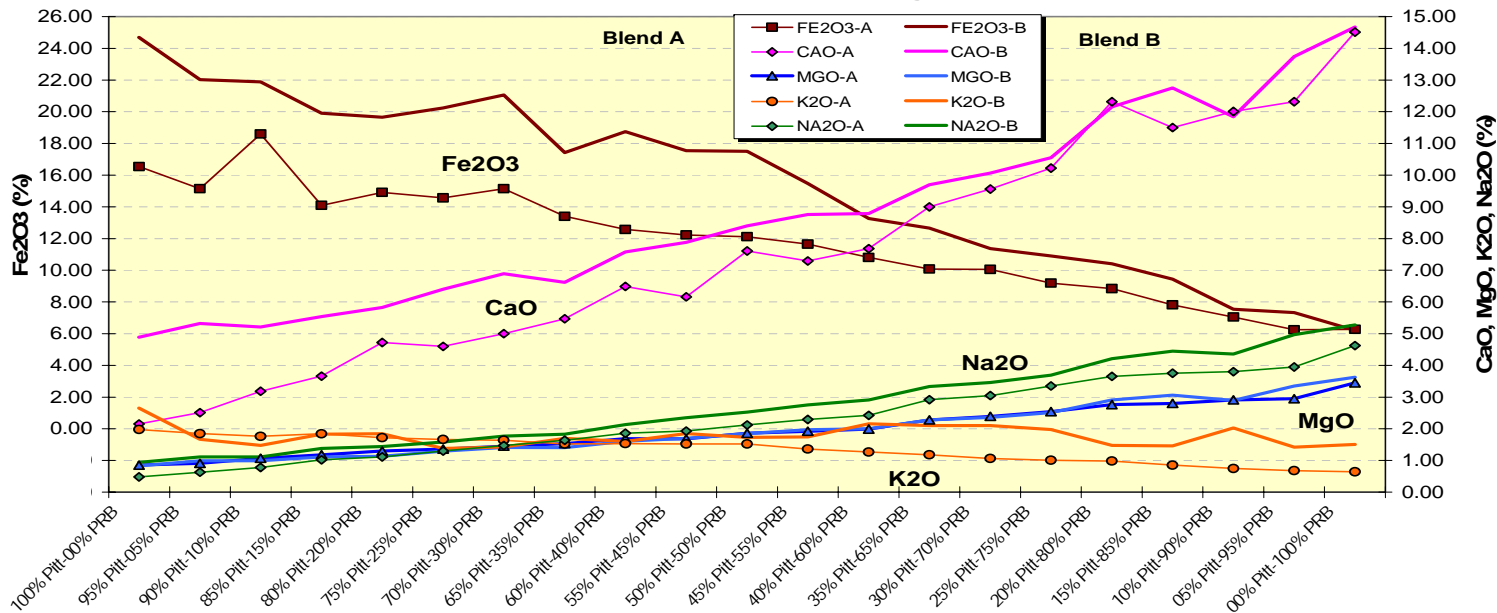


# "Coal and the Environment" — 2006 APC Round Table & Expo

## Ash Mineral — Acids (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>)

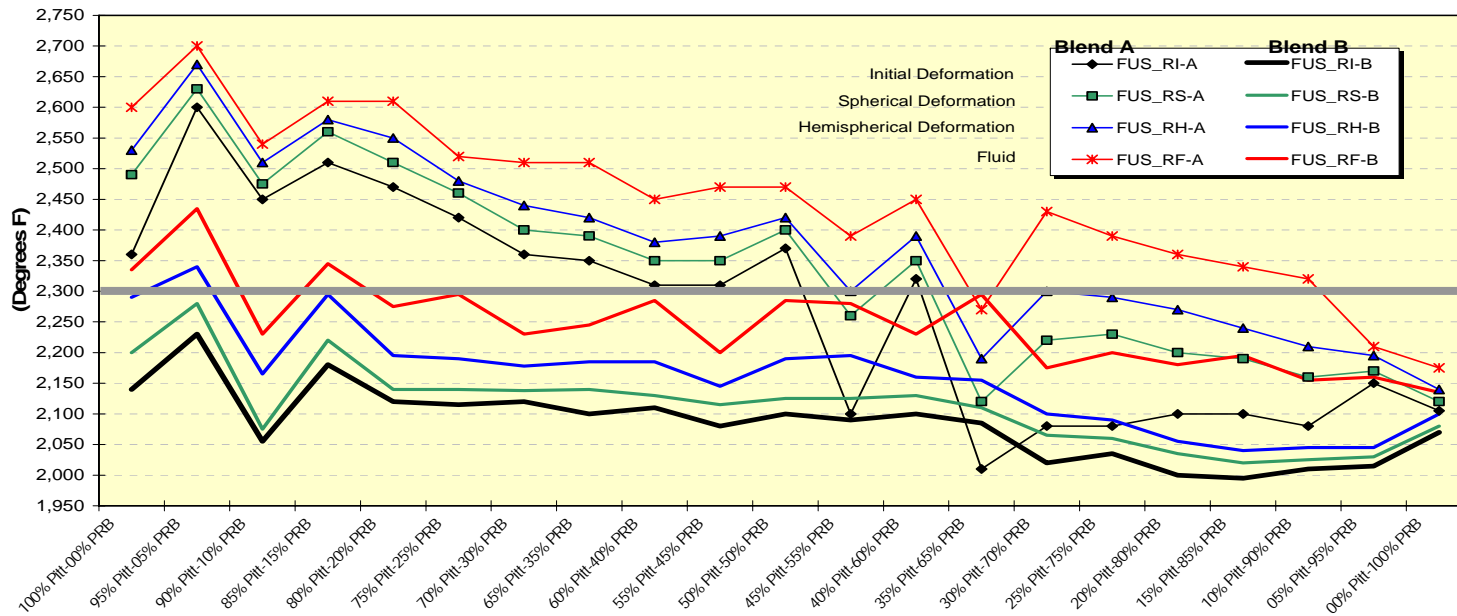


## Ash Mineral — Bases (Fe<sub>2</sub>O<sub>3</sub>, CaO, MgO, K<sub>2</sub>O, Na<sub>2</sub>O)

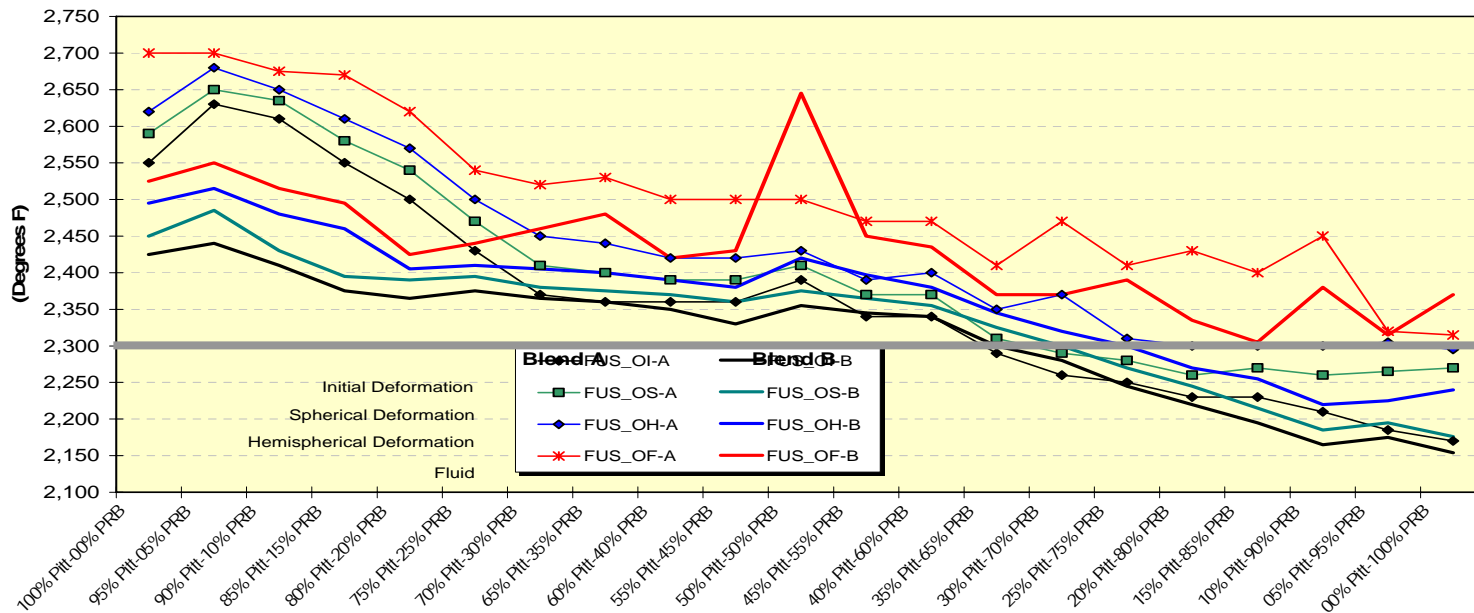


# "Coal and the Environment" — 2006 APC Round Table & Expo

## Ash Fusion — Reducing Atmosphere

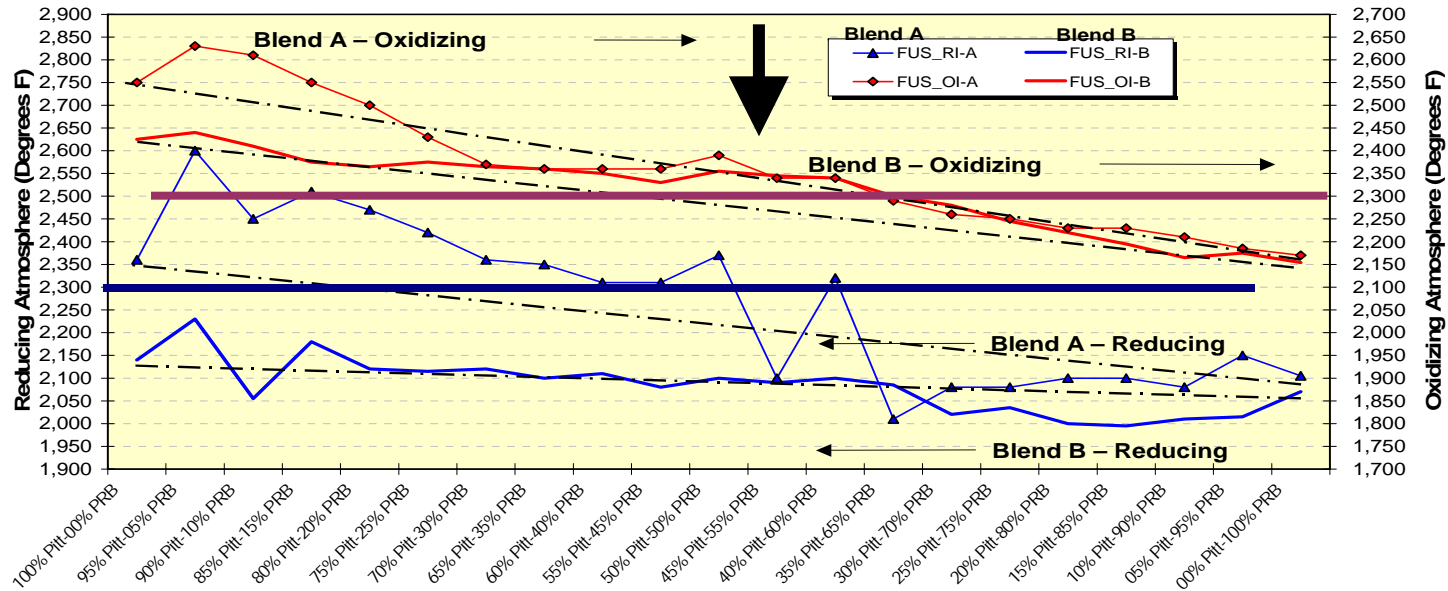


## Ash Fusion — Oxidizing Atmosphere

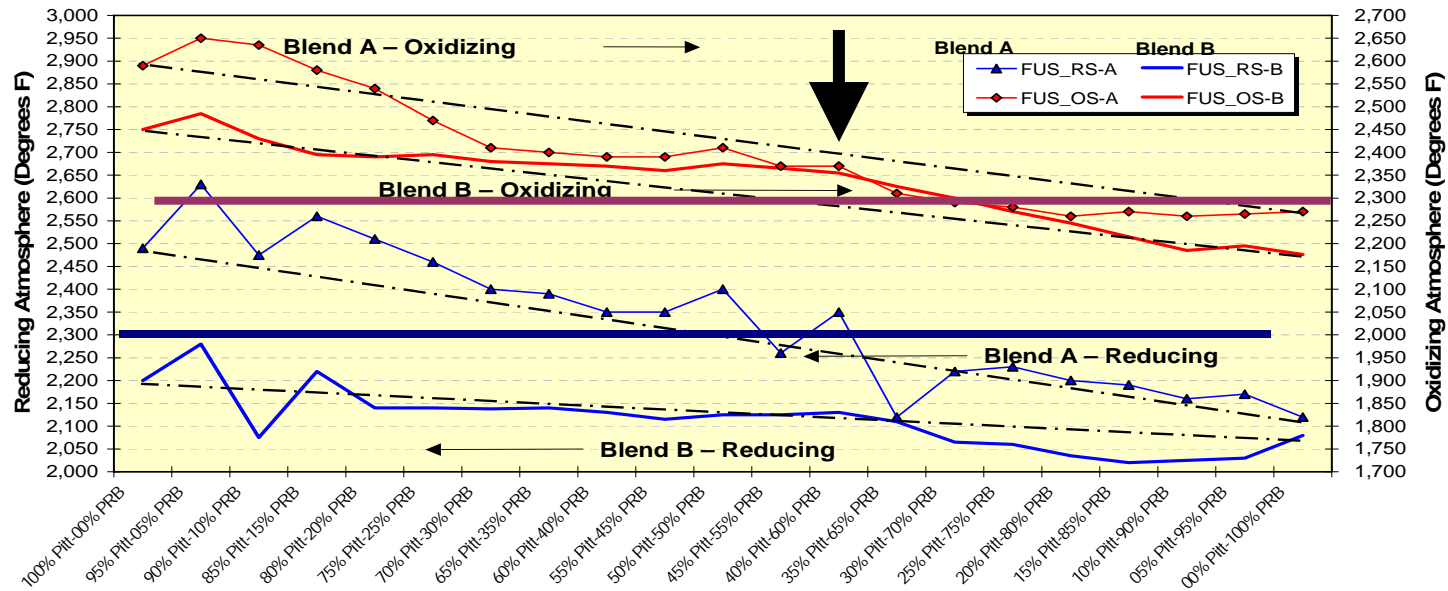


# "Coal and the Environment" – 2006 APC Round Table & Expo

## Ash Fusion, Initial Deformation Reducing & Oxidizing Atmospheres

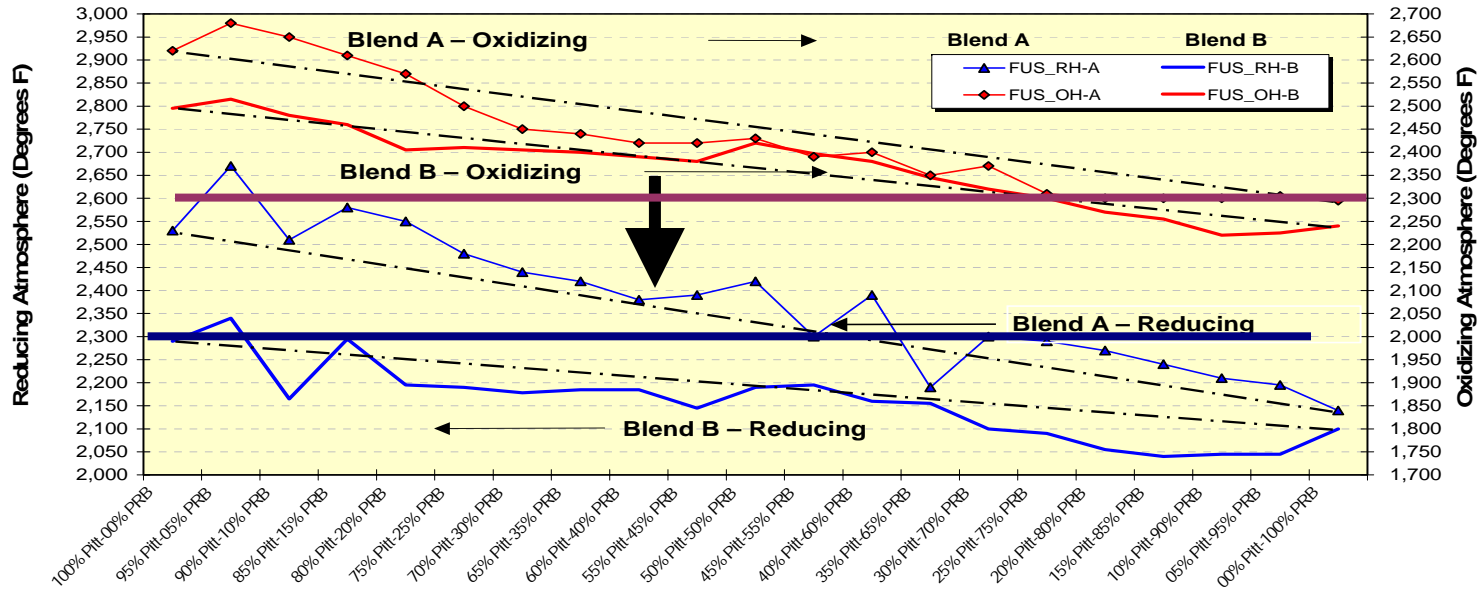


## Ash Fusion, Spherical Reducing & Oxidizing Atmospheres

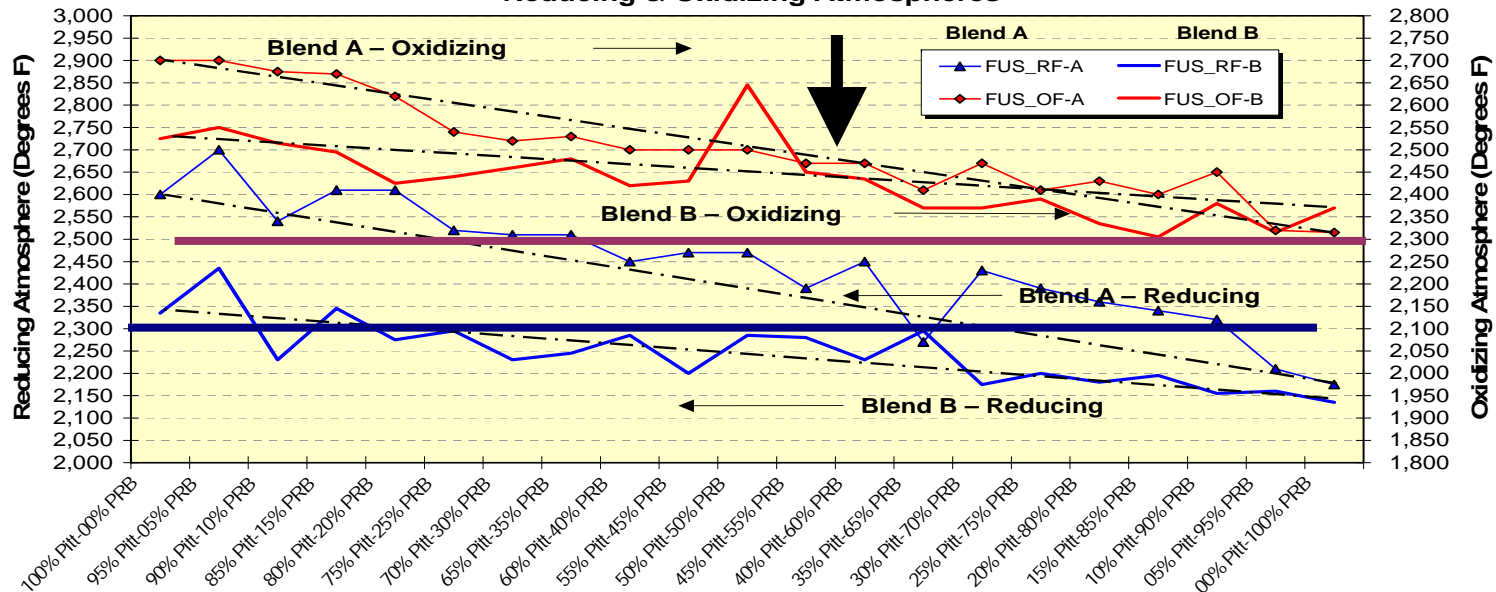


# "Coal and the Environment" – 2006 APC Round Table & Expo

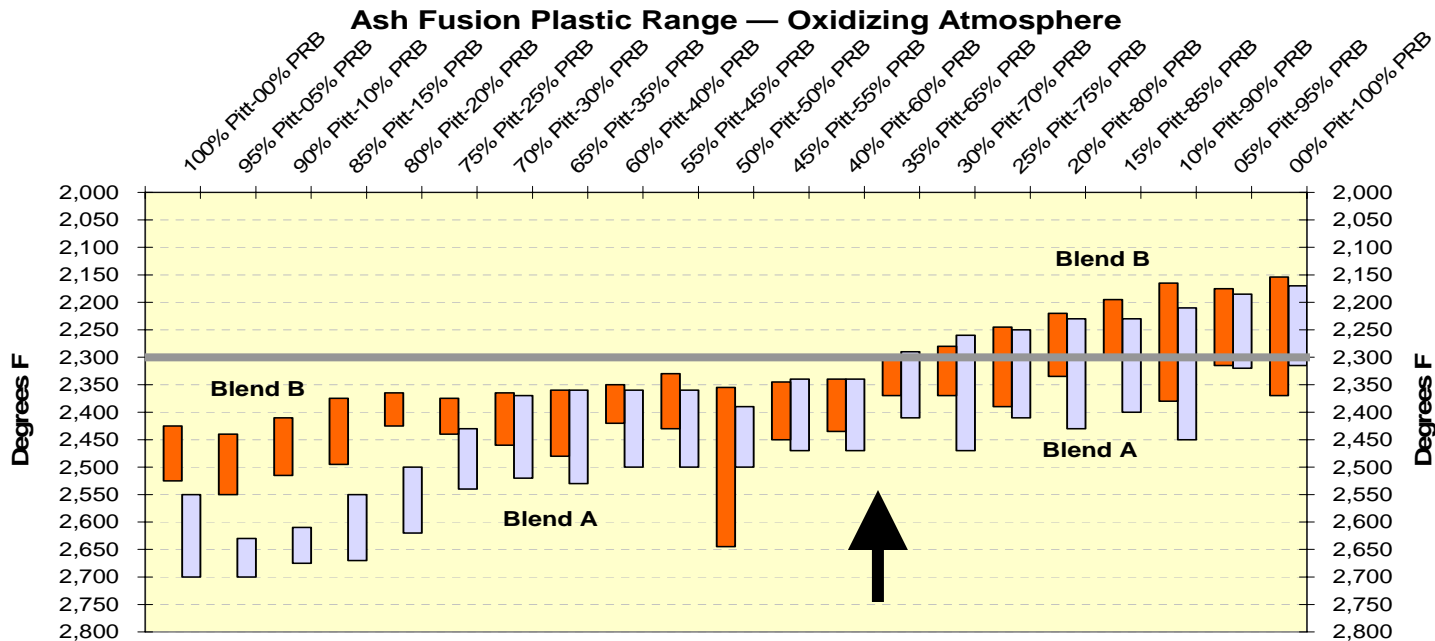
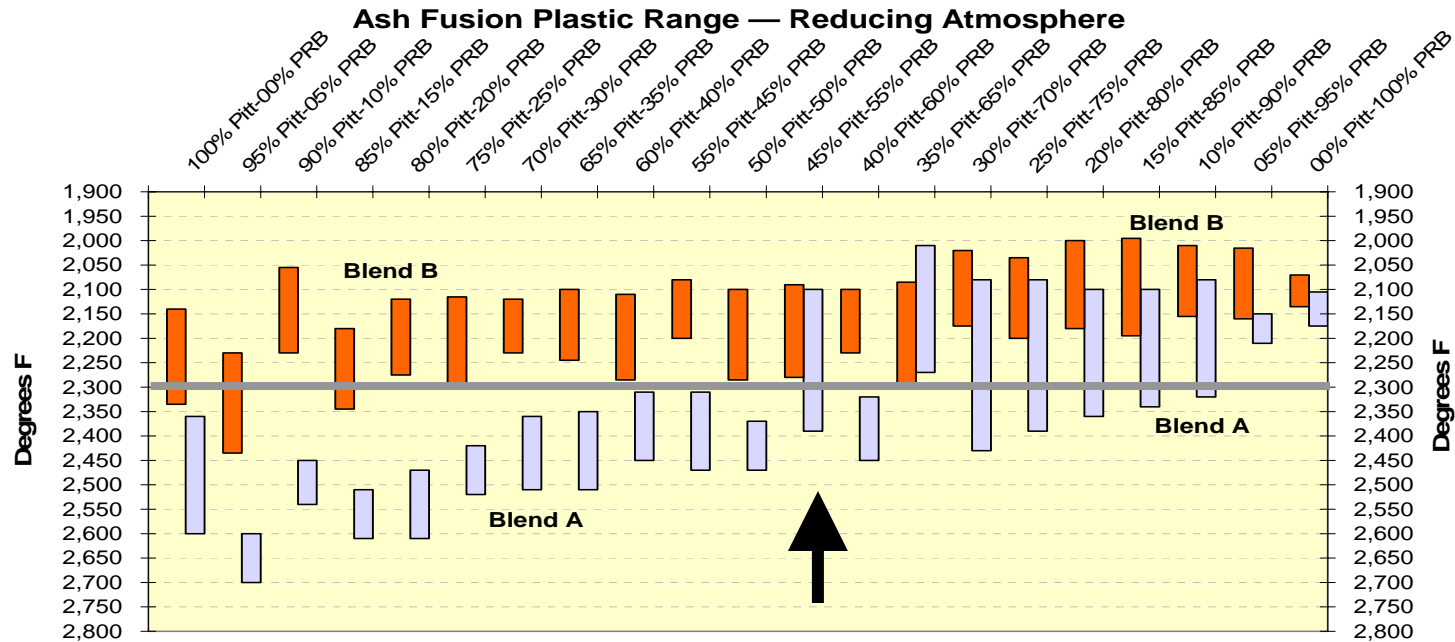
## Ash Fusion, Hemispherical Reducing & Oxidizing Atmospheres



## Ash Fusion, Fluid Reducing & Oxidizing Atmospheres



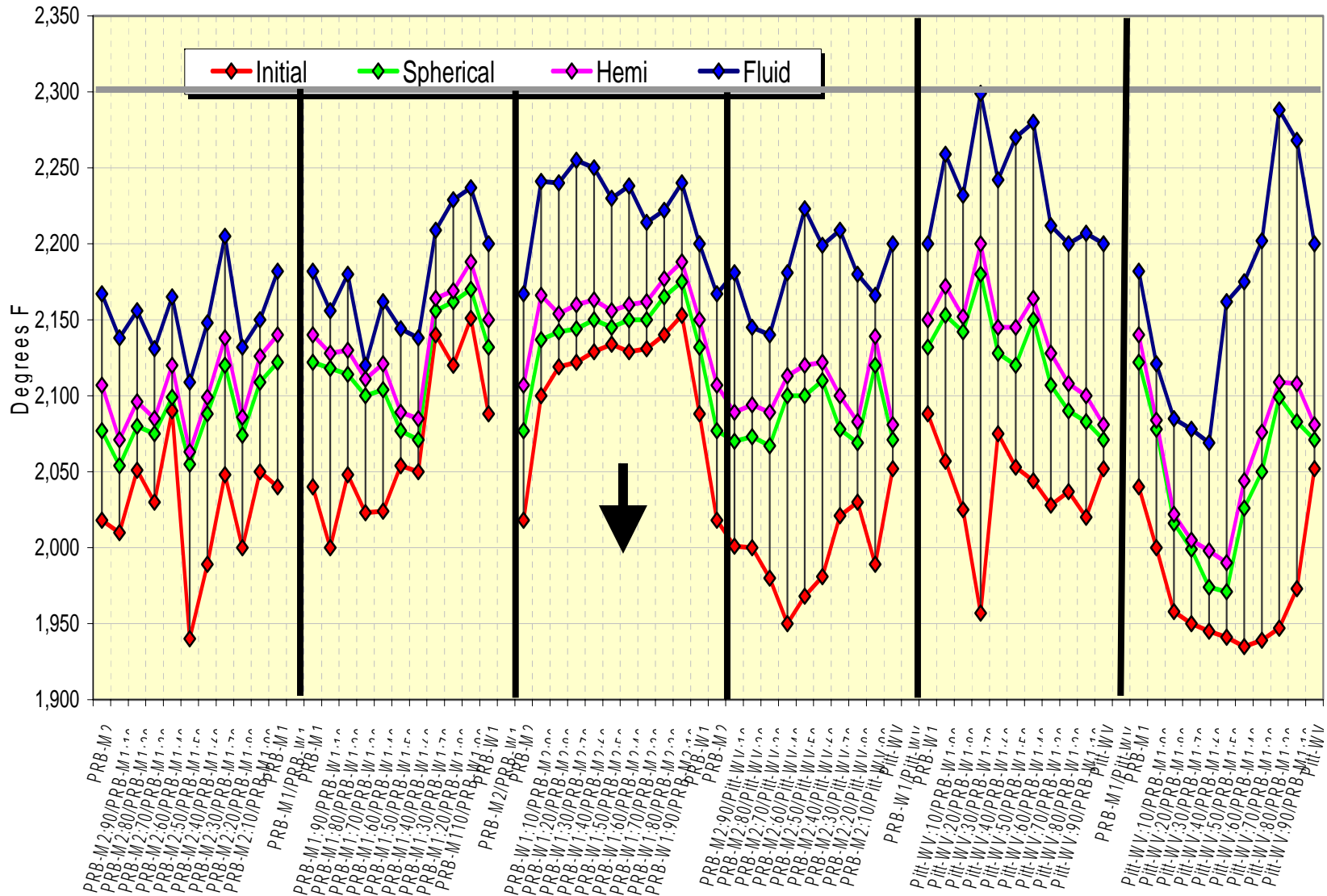
# "Coal and the Environment" — 2006 APC Round Table & Expo



# "Coal and the Environment" — 2006 APC Round Table & Expo

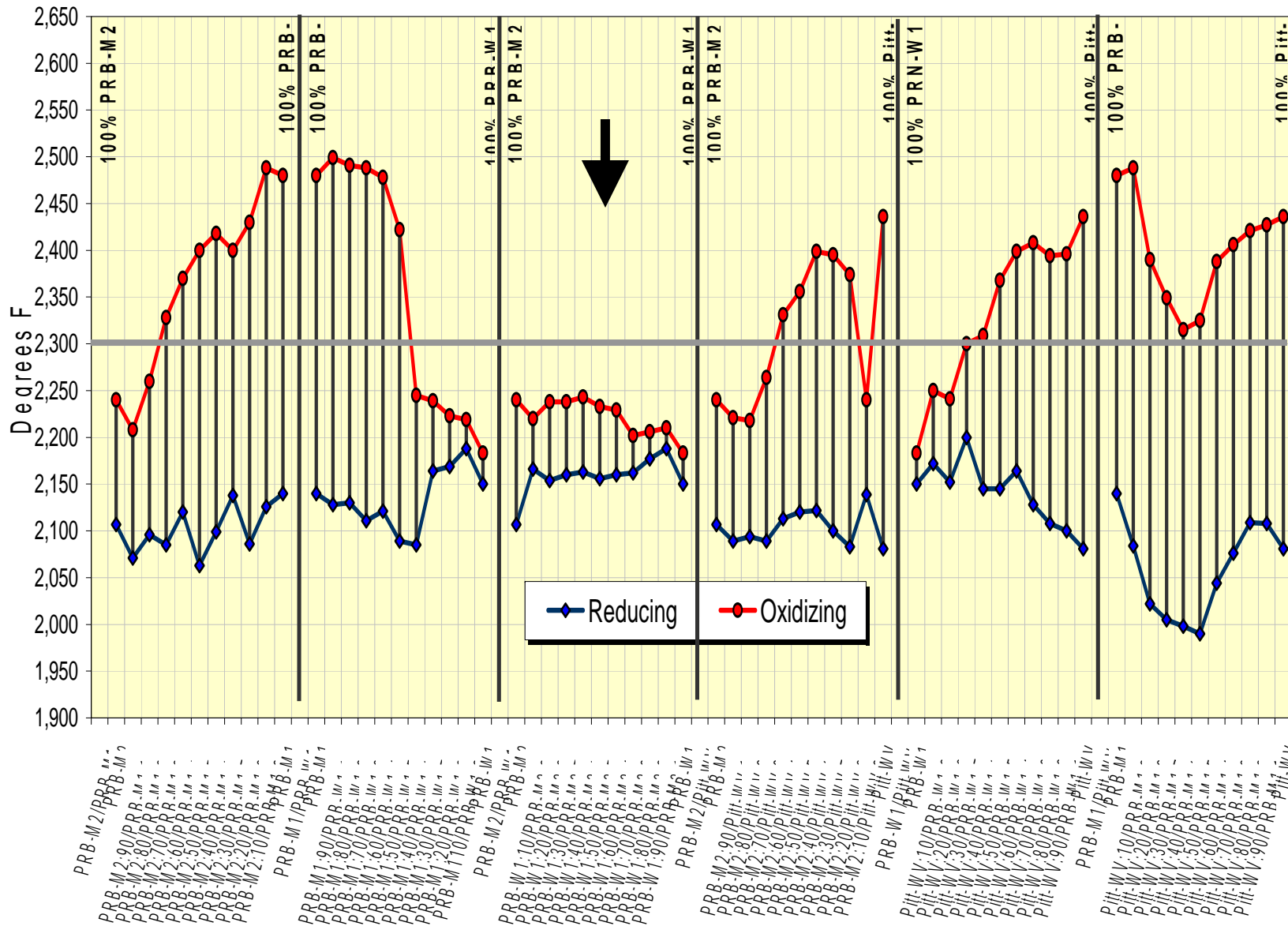
Coal Blends: PRB-M1, PRB-M2, PRB-W1, Pitt-WV

Reducing Fusions



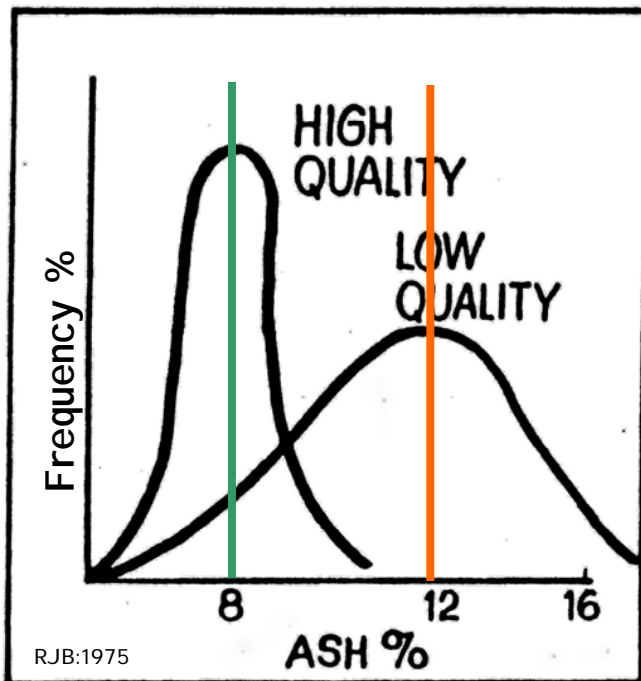
# "Coal and the Environment" — 2006 APC Round Table & Expo

PRB-M1, PRB-M2, PRB-W1, Pitt-WV Blends  
 Reducing & Oxidizing Hemispherical Fusions

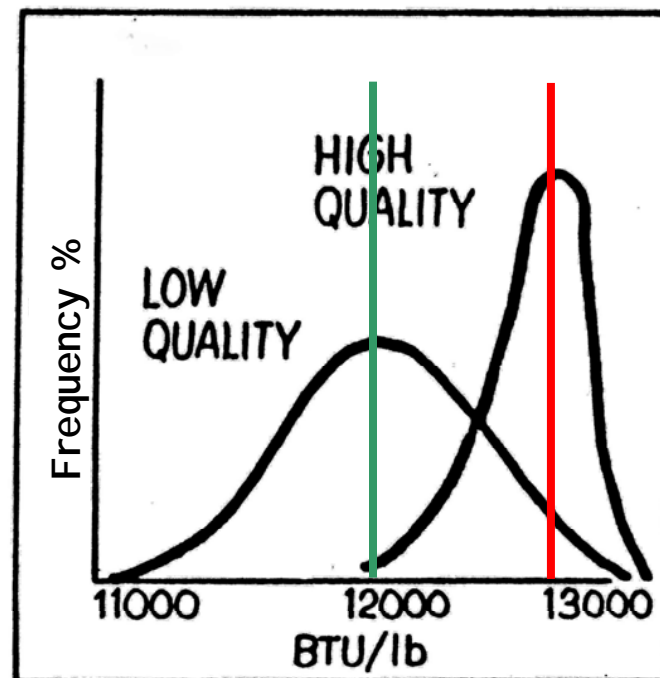


## Physical Coal Cleaning

### ASH CONTENT



### HEAT CONTENT



# "Coal and the Environment" — 2006 APC Round Table & Expo

## Float-Sink Coal Quality

06/11/84

RAW COAL - SAMPLED AFTER BREAKER FEEDER - 5/9-10/84



SIZE PLUS 4"

SIZE PCT: 5.70

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
SINK	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
0.00 - 1.60		24.00	9.80	2.76	13465	24.00	9.80	2.76	13465	100.00	69.32	1.34	-----
1.60 - OVER		76.00	88.12	0.89	-----	100.00	69.32	1.34	-----	76.00	88.12	0.89	-----



SIZE 4" X 3/8"

SIZE PCT: 56.28

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
SINK	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
0.00 - 1.30		43.62	3.65	0.97	14504	43.62	3.65	0.97	14504	100.00	34.81	1.50	9336
1.30 - 1.40		14.63	8.97	2.12	13639	58.25	4.99	1.26	14287	56.38	58.92	1.91	5339
1.40 - 1.50		4.01	18.93	3.49	12001	62.26	5.88	1.40	14140	41.75	76.42	1.83	2430
1.50 - 1.60		1.37	29.45	3.49	10313	63.63	6.39	1.45	14057	37.74	82.53	1.66	1413
1.60 - 1.80		2.13	40.60	3.94	8515	65.76	7.50	1.53	13878	36.37	84.53	1.59	1078
1.80 - OVER		34.24	87.26	1.44	615	100.00	34.81	1.50	9336	34.24	87.26	1.44	615



SIZE 3/8" X 28M

SIZE PCT: 27.84

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
SINK	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
0.00 - 1.30		54.23	3.07	0.88	14615	54.23	3.07	0.88	14615	100.00	22.50	1.65	11411
1.30 - 1.40		17.94	8.66	1.99	13665	72.17	4.46	1.18	14379	45.77	45.52	2.56	7615
1.40 - 1.50		3.96	18.11	4.06	12111	76.13	5.17	1.31	14261	27.83	69.27	2.93	3714
1.50 - 1.60		1.42	26.51	4.69	10728	77.55	5.56	1.37	14196	23.87	77.76	2.74	2321
1.60 - 1.80		1.95	37.42	4.31	8871	79.50	6.34	1.44	14066	22.45	81.00	2.62	1790
1.80 - OVER		20.50	85.15	2.46	1116	100.00	22.50	1.65	11411	20.50	85.15	2.46	1116



SIZE 28M X 100M

SIZE PCT: 4.40

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
SINK	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
0.00 - 1.30		53.40	2.06	0.83	14761	53.40	2.06	0.83	14761	100.00	19.47	1.99	11829
1.30 - 1.40		19.11	7.61	1.52	13841	72.51	3.52	1.01	14519	46.60	39.41	3.33	8469
1.40 - 1.50		4.35	15.81	2.90	12418	76.86	4.22	1.12	14400	27.49	61.52	4.59	4735
1.50 - 1.60		2.12	22.55	3.32	11307	78.98	4.71	1.18	14317	23.14	70.11	4.90	3292
1.60 - 1.80		2.32	32.21	3.87	9440	81.30	5.49	1.25	14177	21.02	74.91	5.06	2483
1.80 - OVER		18.70	80.21	5.21	1620	100.00	19.47	1.99	11829	18.70	80.21	5.21	1620



# "Coal and the Environment" — 2006 APC Round Table & Expo

06/11/84

RAW COAL - SAMPLED AFTER BREAKER FEEDER - 5/9-10/84



SIZE TOTAL W/O FROTH AND PLUS 4" SIZE PCT: 90.52

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
SINK	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
0.00 - 1.30		47.36	3.36	0.93	14557	47.36	3.36	0.93	14557	100.00	30.28	1.57	10096
1.30 - 1.40		15.87	8.78	2.04	13660	63.22	4.72	1.21	14332	52.64	54.49	2.14	6082
1.40 - 1.50		4.01	18.52	3.63	12056	67.24	5.54	1.35	14196	36.78	74.22	2.19	2813
1.50 - 1.60		1.42	28.05	3.85	10513	68.66	6.01	1.41	14120	32.76	81.03	2.01	1681
1.60 - 1.80		2.08	39.23	4.04	8668	70.74	6.99	1.48	13959	31.34	83.44	1.93	1280
1.80 - OVER		29.26	86.59	1.78	754	100.00	30.28	1.57	10096	29.26	86.59	1.78	754



SIZE 100M X 0 SIZE PCT: 3.78

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
FROTH	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
1ST MINUTE		76.00	11.15	1.91	13283	76.00	11.15	1.91	13283	100.00	29.51	1.82	10238
2ND MINUTE		0.0	0.0	0.0	0	76.00	11.15	1.91	13283	24.00	87.63	1.55	597
TAILINGS		24.00	87.63	1.55	597	100.00	29.51	1.82	10238	24.00	87.63	1.55	597



SIZE TOTAL SAMPLE MINUS PLUS 4" SIZE PCT: 94.30

SPEC GRAV		ELEMENTARY DATA				CUMULATIVE FLOAT				CUMULATIVE SINK			
SINK	FLOAT	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU	WT%	ASH	SUL	BTU
0.00 - 1.30		45.46	3.36	0.93	14557	45.46	3.36	0.93	14557	100.00	30.25	1.58	10101
1.30 - 1.40		15.23	8.78	2.04	13660	60.69	4.72	1.21	14332	54.54	52.66	2.12	6387
1.40 - 1.50		6.90	15.26	2.87	12598	67.59	5.80	1.38	14155	39.31	69.66	2.15	3570
1.50 - 1.60		1.36	28.05	3.85	10513	68.95	6.24	1.43	14083	32.41	81.23	2.00	1649
1.60 - 1.80		2.00	39.23	4.04	8668	70.95	7.17	1.50	13930	31.05	83.57	1.92	1259
1.80 - OVER		29.05	86.62	1.77	749	100.00	30.25	1.58	10101	29.05	86.62	1.77	749

NOTE: FROTH IS INCLUDED IN THE FOLLOWING FRACTIONS

FROTH	SPEC GRAV
SINK	FLOAT
1ST MINUTE	1.40 - 1.50
2ND MINUTE	*****
TAILINGS	1.80 - OVER



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Proximate

Type	Moisture	Ash, a/r	Volatile, a/r	FC, a/r	S, a/r	HHV, a/r	Btu, MAF	MoistureLoad	AshLoad	SO2	V/FC
PRB-MT-1a	24.95	3.94	30.72	40.39	0.35	9,340	13,134	26.71	4.22	0.75	0.76
PRB-MT-1b	24.67	3.90	32.62	38.81	0.35	9,476	13,135	26.03	4.12	0.74	0.84
PRB-MT-1c	22.45	4.59	31.83	41.14	0.33	9,569	13,136	23.46	4.80	0.69	0.77
PRB-MT-2	23.45	4.56	30.76	41.19	0.36	9,516	13,137	24.65	4.79	0.75	0.75
PRB-WY-1	26.55	5.01	32.10	36.35	0.25	8,855	13,139	29.98	5.66	0.56	0.88
PRB-WY-2	24.93	5.79	31.97	37.33	0.35	8,985	13,140	27.74	6.45	0.78	0.86
CApp-1	5.55	6.40	34.17	53.89	0.91	13,211	13,142	4.20	4.84	1.37	0.63
CApp-2	7.56	6.35	30.17	55.92	0.68	13,068	13,143	5.79	4.86	1.05	0.54
CApp-3	5.79	8.68	32.78	52.76	0.82	12,768	13,144	4.53	6.80	1.28	0.62
CApp-4	7.95	5.87	29.52	56.66	0.88	13,288	13,145	5.98	4.42	1.32	0.52
Pitt-1 <1.70S	6.24	6.70	31.89	54.75	1.42	13,061	13,147	4.78	5.13	2.17	0.58
Pitt-1 >1.70S	4.52	6.78	34.31	54.39	2.05	13,376	13,148	3.38	5.07	3.07	0.63
Pitt-2	5.28	6.99	34.11	53.61	1.58	13,268	13,149	3.98	5.27	2.38	0.64
Pitt-HSE-1	6.20	6.40	37.10	50.30	2.25	13,288	13,151	4.67	4.82	3.39	0.74
Pitt-HSE-2	5.50	7.59	36.31	50.60	2.43	13,215	13,152	4.16	5.74	3.68	0.72



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Ultimate, dry & HGI

Type	C, dry	H, dry	N, dry	O, dry	H:C	O:C	HGI
PRB-MT-1a	74.50	4.77	0.92	14.10	0.76	0.14	
PRB-MT-1b	72.04	5.42	1.08	15.80	0.90	0.16	47
PRB-MT-1c	70.80	5.34	0.86	16.66	0.90	0.18	46
PRB-MT-2	71.35	4.88	1.01	16.31	0.81	0.17	47
PRB-WY-1	68.58	5.24	1.08	17.92	0.91	0.20	46
PRB-WY-2	71.64	4.65	0.93	15.82	0.77	0.17	48
CApp-1	80.48	5.18	1.37	5.24	0.77	0.05	48
CApp-2	82.07	5.06	1.48	3.78	0.73	0.03	53
CApp-3	78.13	5.12	1.69	4.98	0.78	0.05	49
CApp-4	82.60	5.17	1.62	3.17	0.75	0.03	54
Pitt-1 <1.70S	79.36	5.14	1.57	5.27	0.77	0.05	52
Pitt-1 >1.70S	78.82	5.24	1.52	5.17	0.79	0.05	51
Pitt-2	77.77	5.22	1.54	6.42	0.80	0.06	54
Pitt-HSE-1	79.10	5.30	1.50	4.78	0.80	0.05	54
Pitt-HSE-2	78.00	5.08	1.52	4.71	0.78	0.05	55



*"Coal and the Environment" — 2006 APC Round Table & Expo*

**Ash Mineral**

Type	SiO2	Al2O3	TiO2	Fe2O3	CaO	MgO	K2O	Na2O	SO3	P2O5	BaO	MnO2	ba_ratio
PRB-MT-1a	29.29	16.53	1.20	3.88	15.36	4.28	0.43	7.43	16.50	0.27	0.95	0.04	0.67
PRB-MT-1b	28.90	16.20	1.24	5.37	16.70	3.63	1.20	10.40	14.30	0.10	0.92	0.04	0.80
PRB-MT-1c	38.40	18.40	0.93	6.24	14.00	6.14	0.50	3.42	15.00	0.12	0.77	0.04	0.52
PRB-MT-2	35.34	16.89	1.11	4.89	13.86	3.40	0.64	6.02	13.88	1.01	1.12	0.03	0.54
PRB-WY-1	29.90	14.90	0.88	4.55	23.10	6.47	1.60	1.30	11.70	3.24	0.74	0.01	0.81
PRB-WY-2	35.90	15.89	1.24	5.32	18.95	3.95	0.52	1.46	12.89	0.74	0.48	0.02	0.57
CApp-1	52.72	29.81	1.27	7.19	1.64	1.23	3.55	0.57	1.11	0.14	0.17	0.02	0.17
CApp-2	53.70	31.54	1.36	4.38	1.64	0.91	1.43	0.68	0.08	0.65	0.16	0.02	0.10
CApp-3	54.60	29.62	1.14	4.20	2.05	0.80	1.91	0.98	1.70	0.42	0.11	0.01	0.12
CApp-4	53.13	33.20	1.63	7.51	1.27	0.60	1.31	0.75	0.78	0.56	0.17	0.01	0.13
Pitt-1 <1.70S	52.22	24.47	1.02	11.60	3.01	0.84	1.97	0.60	1.45	0.48	0.28	0.02	0.23
Pitt-1 >1.70S	50.52	23.10	0.93	15.63	2.64	0.78	1.94	0.56	1.25	0.35	0.26	0.01	0.29
Pitt-2	50.94	23.93	0.86	12.26	2.99	0.70	2.05	0.60	2.01	0.26	0.08	0.02	0.25
Pitt-HSE-1	43.40	22.80	1.10	19.50	4.40	1.00	1.24	1.33	4.60	0.30	0.13	0.03	0.41
Pitt-HSE-2	44.06	22.28	0.93	18.17	5.47	0.95	1.54	0.95	4.67	0.51	0.19	0.04	0.40



*“Coal and the Environment” — 2006 APC Round Table & Expo*

**Ash Fusion**

Type	Red,Initial	Red,Soften	Red,Hemi	Red,Fluid	Red,Plastic	Ox,Initial	Ox,Soften	Ox,Hemi	Ox,Fluid	Ox,Plastic
PRB-MT-1a	2,095	2,150	2,185	2,225	130	2,260	2,375	2,445	2,490	230
PRB-MT-1b	2,083	2,151	2,155	2,170	87	2,233	2,415	2,448	2,468	235
PRB-MT-1c	2,018	2,077	2,107	2,167	149	2,140	2,227	2,240	2,285	145
PRB-MT-2	2,073	2,102	2,127	2,182	109	2,219	2,331	2,362	2,401	181
PRB-WY-1	2,042	2,098	2,123	2,165	123	2,094	2,184	2,200	2,249	155
PRB-WY-2	2,110	2,171	2,190	2,237	127	2,177	2,188	2,205	2,258	81
CApp-1	2,760	2,770	2,785	>2800	>40	>2800	>2800	>2800	>2800	>0
CApp-2	>2800	>2800	>2800	>2800	>0	>2800	>2800	>2800	>2800	>0
CApp-3	>2800	>2800	>2800	>2800	>0	>2800	>2800	>2800	>2800	>0
CApp-4	>2800	>2800	>2800	>2800	>0	>2800	>2800	>2800	>2800	>0
Pitt-1 <1.70S	2,472	2,499	2,530	2,585	113	2,550	2,590	2,625	2,670	120
Pitt-1 >1.70S	2,209	2,280	2,372	2,460	251	2,535	2,575	2,595	2,665	130
Pitt-2	2,145	2,195	2,355	2,435	290	2,350	2,385	2,415	2,490	140
Pitt-HSE-1	2,115	2,165	2,220	2,395	280	2,450	2,495	2,525	2,560	110
Pitt-HSE-2	2,118	2,181	2,249	2,329	211	2,406	2,449	2,497	2,540	134



Representative Sampling  
&  
Accurate Weighing

You Can't Control What You Can't Measure!

*not*

*What number do you want?*



## Sampling

### You Can't Control What You Can't Measure!

- ♦ **Representative sampling — MOST CRITICAL!**
  - ♦ Results based on sample received by laboratory
  - ♦ Critical for both gross and laboratory samples
  - ♦ Coal characteristics vary by particle size
  - ♦  $\Delta 1\%$  Moisture or Ash  $\sim 130\text{-}150$  Btu/lb  $\sim 100$  Btu/kWh
    - ♦ Want to lower your plant's reported heat rate and your coal sample is not collected by ASTM procedures?
      - ♦ Double the as-fired sample size
  - ♦ Most coal quality parameters follow normal distribution
- ♦ **Causes of errors**
  - ♦ Laboratory. . . . .5%
  - ♦ Sample Preparation. . . . .15%
  - ♦ **Sampling. . . . . 80%**
- ♦ **Sampling techniques**
  - ♦ Stop-belt (reference standard)
  - ♦ **Mechanical (best commercial method)**
  - ♦ Grab (continuous), auger, car-top, grab (one-time), stockpile core drill, stockpile auger, stockpile manual



## *"Coal and the Environment" — 2006 APC Round Table & Expo*

- ◆ **Operation**
  - ◆ Equipment is serial dependent
  - ◆ Improper or insufficient maintenance causes frequent sampler failure, low availability & biased results
  - ◆ Changing one setting, changes all downstream values
    - ◆ Primary cutter(s), primary-save conveyor, sample crusher, secondary-save conveyor, secondary sampler, reject system
      - ◆ On-line analyzer installed after sample crusher
      - ◆ On-line analyzer depends of sampler operation & sample bias
- ◆ **Sampler bias testing**
  - ◆ Stop-belt vs. other sampling methods
  - ◆ Statistical population (based on normal distribution)
  - ◆ Mechanical sampler "certification"
  - ◆ Samplers accepted bias at the 95% confidence level
- ◆ **Effects**
  - ◆ Corporate, regulatory, government
  - ◆ Industry statistics & records
  - ◆ Production cost, dispatch order, sales
  - ◆ Performance measurement & accurate costs (along with scales)
  - ◆ Problem solving
  - ◆ **Coal is purchased by the heat requirement, not tons**
    - ◆ **Tons are used for commercial exchange**
    - ◆ **Boilers require x-Btus to make y-MWhrs, not x-tons to make Y-MWhrs**



## Scales

### You Can't Control What You Can't Measure!

- ♦ Scale types:
  - ♦ Belt (electronic, mechanical), precision: 1%-0.25%
  - ♦ Bin, precision: 0.1%
  - ♦ Truck (static), precision: 0.1%
  - ♦ Rail (weigh-in-motion), precision: 0.25%
- ♦ Methods of calibration
  - ♦ Weighed material test (also certification)
  - ♦ Static weights (also certification)
  - ♦ Stacked weights (also certification)
  - ♦ Belt weights (approximate, but not certifiable)
  - ♦ Chains (approximate, 1-5%)
- ♦ All weights must be traceable to NIST reference weights
- ♦ Remember, coal is purchased by the heat requirement, not tons
  - ♦ Tons are just for commercial exchange
  - ♦ Boilers require  $x$ -Btus to make  $y$ -MWs, not  $x$ -tons to make  $Y$ -MWs



## Scales

- ♦ Methods of calibration
  - ♦ Weighed material test (also certification)
  - ♦ Static weights (also certification)
  - ♦ Stacked weights (also certification)
  - ♦ Belt weights (approximate, but not certifiable)
  - ♦ Chains (approximate, 1-5%)
- ♦ NIST Handbook 44
- ♦ All weights must be traceable to NIST reference weights



## Typical Coal Analyses

- ◆ **Proximate**
  - ◆ Moisture, ash, volatile, fixed carbon, sulfur, HHV
  - ◆ SO<sub>2</sub>, ash load, volatile/fixed carbon
- ◆ **Ultimate**
  - ◆ C, H, N, O in the coal maceral
- ◆ **Ash Mineral (oxides of major elements)**
  - ◆ Acids: Si, Al, Ti
  - ◆ Bases: Fe, Ca, Mg, K, Na
  - ◆ Minor: S, P, Ba, Sr, Mn
  - ◆ Base/Acid
  - ◆ ESP Index
- ◆ **Ash Fusion**
  - ◆ Oxidizing & reducing atmospheres
  - ◆ Initial deformation, spherical deformation, hemispherical deformation, fluid
  - ◆ Plastic range & fusion box
  - ◆ Eutectics
- ◆ **Trace Elements**



# "Coal and the Environment" — 2006 APC Round Table & Expo

## COMMERCIAL TESTING & ENGINEERING CO.

GENERAL OFFICES: 1919 SOUTH HIGHLAND AVE., SUITE 210-B, LOMBARD, ILLINOIS 60148 • (312) 953-8300

KEITH RISTINEN  
MANAGER  
NORTHWEST DIVISION



PLEASE ADDRESS ALL CORRESPONDENCE TO:  
609 CHARLES ST., BILLINGS, MT 59102  
OFFICE TEL. (406) 252-5818

July 30, 1985

PRB MT-CROM

AWS 29 AUG '85

NCE

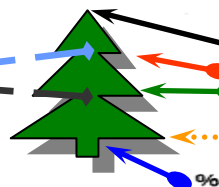
Kind of sample reported to us: Coal  
 Sample taken at:   
 Sample taken by: CT&E  
 Date sampled: 7/2/85  
 Date received: 7/11/85

### PROXIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	22.92	xxxxx
% Ash	5.14	6.67
% Volatile	32.84	42.61
% Fixed Carbon	39.10	50.72
	100.00	100.00
Btu/lb.	9590	12442
% Sulfur	0.38	0.49

### ULTIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	22.92	xxxxx
% Carbon	54.85	71.16
% Hydrogen	3.97	5.15
% Nitrogen	0.83	1.08
% Chlorine	0.05	0.06
% Sulfur	0.38	0.49
% Ash	5.14	6.67
% Oxygen (diff)	11.86	15.39
	100.00	100.00



Energy Sink -  
Energy Sink -  
Energy Source +  
Energy Source +

Moisture, Ash-free Btu = 13331

### SULFUR FORMS

	As Received	Dry Basis
% Pyritic Sulfur	0.12	0.15
% Sulfate Sulfur	0.00	0.00
% Organic Sulfur (Diff)	0.26	0.34
% Total Sulfur	0.38	0.49

### FUSION TEMPERATURE OF ASH

	Reducing	Oxidizing
Initial Deformation	1980 °F	2350 °F
Softening (H = W)	2020 °F	2380 °F
Softening (H = 1/2W)	2100 °F	2400 °F
Fluid	2160 °F	2430 °F

V/FC 0.84

% EQUILIBRIUM MOISTURE = 22.1

FREE SWEELING INDEX = xxxxx  
SJJ/lc

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Respectfully submitted,  
COMMERCIAL TESTING & ENGINEERING CO.

*Steve Judd*  
Manager, Billings Laboratory



Charter Member

OVER 40 BRANCH LABORATORIES STRATEGICALLY LOGATED IN PRINCIPAL COAL MINING AREAS, TIDEWATER AND GREAT LAKES PORTS, AND RIVER LOADING FACILITIES

# "Coal and the Environment" – 2006 APC Round Table & Expo

(313) 897-1354 or (313) 897-1296

## COAL ANALYSIS

Organization: Fuel Supply  
 Report for:  
 Project/Report No.:

Sampling Location: Mine Comparison  
 Sampling Area: As-Shipped  
 Sampling Method: Mechanical  
 Sampling Date:

Mine: Pittsburgh-Washed  
 Supplier:  
 Train ID/Vessel Name:

Sample Receipt Date: 02/26/1999

Sample Weight: 33,547.0 grams

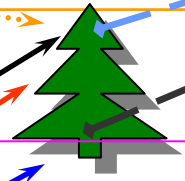
Sul. > 1.70

### Proximate

		AS-RECEIVED	DRY	MAF
Total Moisture	Energy Sink -	4.52		
Ash	Energy Sink -	6.78	7.10	
Volatile	Energy Source +	34.31	35.95	38.68
Fixed Carbon	Energy Source +	54.39	56.99	61.32
Sulfur		2.05	2.14	
Btu		13376	14010	15080
Air-Dry Loss		2.30		
Residual Moisture (1-gram)		2.27		
SO2 (fuel maximum)		3.06		
Ash Loading (fuel maximum)		5.07		
V/FC		0.63		

### Ultimate

	AS-RECEIVED	DRY
Carbon	75.23	78.82
Hydrogen	5.00	5.24
Nitrogen	1.45	1.52
Oxygen	4.97	5.21



# "Coal and the Environment" — 2006 APC Round Table & Expo

## PRB WY-CROM

Sample Date: 05-Oct-2003

Material Type Fuel: Coal

Sampling Method: Rotary Splitter

<u>Moisture</u>	<u>Procedure</u>	<u>Units</u>	<u>Value</u>
Total Sample Size	ASTM D2013	grams	99.30
Air-Dry Loss	ASTM D2013	%	6.98
Residual	ASTM D3173	%	12.88

<u>Short Proximate</u>			<u>As Received</u>		<u>Dry</u>	<u>MAF</u>
Total Moisture	ASTM D3302	%	18.96	Energy Sink -		
Ash	ASTM D3180	%	6.05	Energy Sink -	7.47	
Volatile	ASTM D3175	%	33.18	Energy Source +	40.94	44.25
Fixed Carbon-A/R	ASTM D3175	%	41.81	Energy Source +	51.59	55.75
Sulfur	ASTM D4239	%	0.40		0.49	
Calorific Value	ASTM D5865	Btu/lb	9,612		11,860	12,818
SO2 (fuel maximum)		lbs/MBtu	0.83			
Ash Load (fuel max)		lbs/MBtu	6.30			
V/FC Ratio			0.79			

<u>Ultimate</u>				
Carbon	ASTM D3176	%	56.01	69.11
Hydrogen	ASTM D3176	%	3.73	4.60
Nitrogen	ASTM D3176	%	0.89	1.10
Oxygen	ASTM D3176	%	13.96	17.22

Energy Sink -  
Energy Sink -  
Energy Source +  
Energy Source +



# "Coal and the Environment" – 2006 APC Round Table & Expo

CApp hvA-b

Sample Date:

06/12/2003

Material Type Fuel:

Sampling Method:

Manual

Sample Type:

As-Requested

Sampled By:

Unit:

<i>Moisture</i>	<i>Procedure</i>	<i>Units</i>	<i>Value</i>
Total Sample Size	ASTM D2013	grams	11230.0
Air-Dry Loss	ASTM D2013	%	6.25
Residual	ASTM D3173	%	1.47

<i>Short Proximate</i>	<i>As Received</i>		<i>Dry</i>	<i>MAF</i>
Total Moisture	ASTM D3302	%	7.63	
Ash	ASTM D3180	%	9.21	9.97
Volatile	ASTM D3175	%	29.23	31.65
Fixed Carbon-A/R	ASTM D3175	%	53.93	58.38
Sulfur	ASTM D4239	%	1.46	1.58
Calorific Value	ASTM D5865	Btu/lb	12,711	13,762
SO <sub>2</sub> (fuel maximum)		lbs/MBtu	2.30	
Ash Load (fuel max)		lbs/MBtu	7.24	
V/FC Ratio			0.54	

*Ultimate*

□

Carbon	ASTM D3176	%	70.66	76.49
Hydrogen	ASTM D3176	%	4.42	4.78
Nitrogen	ASTM D3176	%	1.21	1.31
Oxygen	ASTM D3176	%	5.41	5.86

*Ash Fusion*

*Reducing*

*Oxidizing*

Initial	ASTM D1857	°F	2,500	2,610
Spherical		°F	2,520	2,645
Hemispherical		°F	2,565	2,665
Fluid		°F	2,625	2,700



# "Coal and the Environment" — 2006 APC Round Table & Expo

CApp hvA-b

Sample Date: 06/12/2003

Material Type Fuel:

Sampling Method: Manual

Sample Type:

Sampled By:

Unit:

<u>Ash Mineral</u>	<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>
Silcon Dioxide, SiO2	%	50.33	Acid	%	81.17			
Alum Oxide, Al2O3	%	27.34	Base	%	18.83			
Titanm Dioxide, TiO2	%	1.25	Base Acid Ratio		0.23			
			Ash Ratio		0.17			
Iron Oxide, Fe2O3	%	12.91	Ash Type		Bituminous			
Calcium Oxide, CaO	%	1.24	Silica Ratio		0.77			
Magnesium Oxide, MgO	%	0.99	Silica Alumina Ratio		1.84			
Potassium Oxide, K2O	%	2.62	Iron Calcium Ratio		10.41			
Sodium Oxide, Na2O	%	0.55	Dolomite Percentage	%	11.84			
			ESP Index		77.67			
Mang Oxide, Mn3O4	%	0.03						
Sulfur Trioxide, SO3	%	1.16	Undetermined	%	0.32			
Phos Pentoxide, P2O5	%	0.97						
Barium Oxide, BaO	%	0.15						
Strontium Oxide, SrO	%	0.14						
<u>Trace Elements</u>			<u>Units</u>			<u>Value</u>		
Sb, Antimony	ppm	0.11	Pb, Lead	ppm	8.24	Ag, Silver	ppm	0.067
As, Arsenic	ppm	11.97	Mn, Manganese	ppm	18.9	Tl, Thallium	ppm	0.62
Ba, Barium	ppm	104	Hg, Mercury	ppm	0.082	V, Vanadium	ppm	30.1
Be, Beryllium	ppm	2.2	Mo, Molybdenum	ppm	1.12	Zn, Zinc	ppm	14.5
Cd, Cadmium	ppm	0.061	Ni, Nickel	ppm	13.61			
Cl, Chlorine	ppm	957.28	Se, Selenium	ppm	3.22			
Cr, Chromium	ppm	12.4						
Co, Cobalt	ppm	6.21						
Cu, Copper	ppm	15.8						
F, Fluorine	ppm	<10						



# "Coal and the Environment" — 2006 APC Round Table & Expo

## COMMERCIAL TESTING & ENGINEERING CO.

GENERAL OFFICES: 1919 SOUTH HIGHLAND AVE., SUITE 210-B, LOMBARD, ILLINOIS 60148 • (312) 953-8300

KEITH RISTINEN  
MANAGER  
NORTHWEST DIVISION



PLEASE ADDRESS ALL CORRESPONDENCE TO:  
609 CHARLES ST., BILLINGS, MT 59102  
OFFICE TEL. (406) 252-5818

PRB MT-CROM

July 30, 1985

AWS 29 AUG '85  
NCE

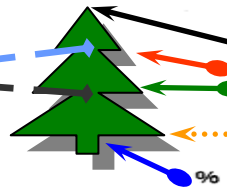
Kind of sample reported to us: **Coal**  
 Sample taken at:   
 Sample taken by: **CT&E**  
 Date sampled: **7/2/85**  
 Date received: **7/11/85**

### PROXIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	22.92	xxxxx
% Ash	5.14	6.67
% Volatile	32.84	42.61
% Fixed Carbon	39.10	50.72
	100.00	100.00
Btu/lb.	9590	12442
% Sulfur	0.38	0.49

### ULTIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	22.92	xxxxx
% Carbon	54.85	71.16
% Hydrogen	3.97	5.15
% Nitrogen	0.83	1.08
% Chlorine	0.05	0.06
% Sulfur	0.38	0.49
% Ash	5.14	6.67
% Oxygen (diff)	11.86	15.39
	100.00	100.00



Energy Sink -  
Energy Sink -  
Energy Source +  
Energy Source +

Moisture, Ash-free Btu = 13331

### SULFUR FORMS

	As Received	Dry Basis
% Pyritic Sulfur	0.12	0.15
% Sulfate Sulfur	0.00	0.00
% Organic Sulfur (Diff)	0.26	0.34
% Total Sulfur	0.38	0.49

### FUSION TEMPERATURE OF ASH

	Reducing	Oxidizing
Initial Deformation	1980 °F	2350 °F
Softening (H = W)	2020 °F	2380 °F
Softening (H = 1/2W)	2100 °F	2400 °F
Fluid	2160 °F	2430 °F

V/FC 0.84

% EQUILIBRIUM MOISTURE = 22.1

FREE SWEELING INDEX = xxxxx  
SJJ/lc

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Respectfully submitted,  
COMMERCIAL TESTING & ENGINEERING CO.

*Steve Judd*  
Manager, Billings Laboratory



Charter Member

OVER 40 BRANCH LABORATORIES STRATEGICALLY LOGATED IN PRINCIPAL COAL MINING AREAS,  
TIDEWATER AND GREAT LAKES PORTS, AND RIVER LOADING FACILITIES

# "Coal and the Environment" – 2006 APC Round Table & Expo

(313) 897-1354 or (313) 897-1296

## COAL ANALYSIS

Organization: Fuel Supply  
 Report for:  
 Project/Report No.:

Mine:  
 Supplier: **Pittsburgh Seam-Washed**  
 Train ID/Vessel Name:

Sampling Location: Mine Comparison  
 Sampling Area: As-Shipped  
 Sampling Method: Mechanical  
 Sampling Date:

Sample Receipt Date: **02/26/1999**

Sample Weight: 33,547.0 grams

Sul. > 1.70

### Proximate

	AS-RECEIVED	DRY	MAF
Total Moisture	4.52		
Ash	6.78	7.10	
Volatile	34.31	35.95	38.68
Fixed Carbon	54.39	56.99	61.32
Sulfur	2.05	2.14	
Btu	13376	14010	15080
Air-Dry Loss	2.30		
Residual Moisture (1-gram)	2.27		
SO <sub>2</sub> (fuel maximum)	3.06		
Ash Loading (fuel maximum)	5.07		
V/FC	0.63		

### Ultimate

	AS-RECEIVED	DRY
Carbon	75.23	78.82
Hydrogen	5.00	5.24
Nitrogen	1.45	1.52
Oxygen	4.97	5.21



# "Coal and the Environment" — 2006 APC Round Table & Expo

## PRB-WY CROM

Sample Date: 05-Oct-2003

Material Type Fuel: Coal

Sampling Method: Rotary Splitter

<u>Moisture</u>	<u>Procedure</u>	<u>Units</u>	<u>Value</u>
Total Sample Size	ASTM D2013	grams	99.30
Air-Dry Loss	ASTM D2013	%	6.98
Residual	ASTM D3173	%	12.88

<u>Short Proximate</u>			<u>As Received</u>		<u>Dry</u>	<u>MAF</u>
Total Moisture	ASTM D3302	%	18.96	Energy Sink -		
Ash	ASTM D3180	%	6.05	Energy Sink -	7.47	
Volatile	ASTM D3175	%	33.18	Energy Source +	40.94	44.25
Fixed Carbon-A/R	ASTM D3175	%	41.81	Energy Source +	51.59	55.75
Sulfur	ASTM D4239	%	0.40		0.49	
Calorific Value	ASTM D5865	Btu/lb	9,612		11,860	12,818
SO2 (fuel maximum)		lbs/MBtu	0.83			
Ash Load (fuel max)		lbs/MBtu	6.30			
V/FC Ratio			0.79			

<u>Ultimate</u>				
Carbon	ASTM D3176	%	56.01	69.11
Hydrogen	ASTM D3176	%	3.73	4.60
Nitrogen	ASTM D3176	%	0.89	1.10
Oxygen	ASTM D3176	%	13.96	17.22

Energy Sink -  
Energy Sink -  
Energy Source +  
Energy Source +



# "Coal and the Environment" – 2006 APC Round Table & Expo

**CApp hvAb**

Sample Date: 06/12/2003

Material Type Fuel: Sampling Method: Manual

Sample Type: As-Requested Sampled By:

Unit:

<i>Moisture</i>	<i>Procedure</i>	<i>Units</i>	<i>Value</i>
Total Sample Size	ASTM D2013	grams	11230.0
Air-Dry Loss	ASTM D2013	%	6.25
Residual	ASTM D3173	%	1.47

<i>Short Proximate</i>	<i>As Received</i>		<i>Dry</i>	<i>MAF</i>
Total Moisture	ASTM D3302	%	7.63	
Ash	ASTM D3180	%	9.21	9.97
Volatile	ASTM D3175	%	29.23	31.65
Fixed Carbon-A/R	ASTM D3175	%	53.93	58.38
Sulfur	ASTM D4239	%	1.46	1.58
Calorific Value	ASTM D5865	Btu/lb	12,711	13,762
SO <sub>2</sub> (fuel maximum)		lbs/MBtu	2.30	
Ash Load (fuel max)		lbs/MBtu	7.24	
V/FC Ratio			0.54	

<i>Ultimate</i>				
Carbon	ASTM D3176	%	70.66	76.49
Hydrogen	ASTM D3176	%	4.42	4.78
Nitrogen	ASTM D3176	%	1.21	1.31
Oxygen	ASTM D3176	%	5.41	5.86

<i>Ash Fusion</i>			<i>Reducing</i>	<i>Oxidizing</i>
Initial	ASTM D1857	°F	2,500	2,610
Spherical		°F	2,520	2,645
Hemispherical		°F	2,565	2,665
Fluid		°F	2,625	2,700



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Sample Date: 06/12/2003

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Material Type Fuel:

Sampling Method:

Sample Type: As-Requested

Sampled By:

Unit:

<u>Ash Mineral</u>	<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>
Silcon Dioxide, SiO2	%	50.33	Acid	%	81.17			
Alum Oxide, Al2O3	%	27.34	Base	%	18.83			
Titanm Dioxide, TiO2	%	1.25	Base Acid Ratio		0.23			
			Ash Ratio		0.17			
Iron Oxide, Fe2O3	%	12.91	Ash Type		Bituminous			
Calcium Oxide, CaO	%	1.24	Silica Ratio		0.77			
Magnesium Oxide, MgO	%	0.99	Silica Alumina Ratio		1.84			
Potassium Oxide, K2O	%	2.62	Iron Calcium Ratio		10.41			
Sodium Oxide, Na2O	%	0.55	Dolomite Percentage	%	11.84			
			ESP Index		77.67			
Mang Oxide, Mn3O4	%	0.03						
Sulfur Trioxide, SO3	%	1.16	Undetermined	%	0.32			
Phos Pentoxide, P2O5	%	0.97						
Barium Oxide, BaO	%	0.15						
Strontium Oxide, SrO	%	0.14						
<u>Trace Elements</u>	<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>		<u>Units</u>	<u>Value</u>
Sb, Antimony	ppm	0.11	Pb, Lead	ppm	8.24	Ag, Silver	ppm	0.067
As, Arsenic	ppm	11.97	Mn, Manganese	ppm	18.9	Tl, Thallium	ppm	0.62
Ba, Barium	ppm	104	Hg, Mercury	ppm	0.082	V, Vanadium	ppm	30.1
Be, Beryllium	ppm	2.2	Mo, Molybdenum	ppm	1.12	Zn, Zinc	ppm	14.5
Cd, Cadmium	ppm	0.061	Ni, Nickel	ppm	13.61			
Cl, Chlorine	ppm	957.28	Se, Selenium	ppm	3.22			
Cr, Chromium	ppm	12.4						
Co, Cobalt	ppm	6.21						
Cu, Copper	ppm	15.8						
F, Fluorine	ppm	<10						



## New Technology Issues

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Greenhouse Gases

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NO<sub>x</sub>



## New Technology Brings New Issues

- ♦ Low NO<sub>x</sub> burners (LNB)
  - ♦ Increased UBC, LOI
  - ♦ Accelerated waterwall tube wastage
- ♦ SCR, SNCR
  - ♦ NH<sub>3</sub> or urea storage
  - ♦ ID fans
- ♦ Wet ESP
- ♦ Combustion tuning
- ♦ Sorbents, activated carbon injection (ACI)
- ♦ Advanced coal cleaning & trace element concentration
- ♦ On-line analyzers (various technologies)
- ♦ Low emissive fuels require smaller furnaces or reduced output from furnaces designed for coal
- ♦ Carbon sequestration



## Greenhouse Gases

- ◆ Carbon sequestration
  - ◆ H<sub>2</sub> combustion (C removal)
  - ◆ CO<sub>2</sub> capture
  - ◆ Amine scrubbers
  - ◆ Mineral sequestration
- ◆ NO<sub>x</sub> Reduction
  - ◆ SCR, SNCR
  - ◆ NO<sub>x</sub> scrubbers
  - ◆ Oxygen Enhanced Combustion (OEC)
  - ◆ Zero N<sub>2</sub> combustion
- ◆ CH<sub>4</sub> hydrates
  - ◆ Frozen tundra (above Arctic Circle)
- ◆ CH<sub>4</sub> ice (on ocean floor)



## Greenhouse Gases

- ♦ CO<sub>2</sub> (carbon dioxide)
- ♦ CH<sub>4</sub> (methane)
- ♦ H<sub>2</sub>O (water vapor)
- ♦ N<sub>2</sub>O (nitrous oxide)
- ♦ Halocarbons (e.g. hydrochlorofluorocarbons, perfluorocarbons, SF<sub>6</sub>)

### **~1% of the atmosphere**

- ♦ >97% H<sub>2</sub>O vapor
- ♦ Balance, <3%
  - ♦ Energy-related CO<sub>2</sub>, 81%
  - ♦ Methane, CH<sub>4</sub>, 9%
  - ♦ Nitrous oxide, N<sub>2</sub>O, 6%
  - ♦ Other CO<sub>2</sub>, 2%
  - ♦ Other gases, 2%



## Greenhouse Gases

### Global Warming Potential (GWP)

Greenhouse Gas	GWP
<b>CO2 (base)</b>	1
<b>CH4</b>	21
<b>N2O</b>	310
HFC-23	11,700
HFC-125	2800
HFC-134a	1300
HFC-143a	3800
HFC-152a	140
HFC-227	2900
HFC-236fa	6300
HFC-431mee	1300
CF4	6500
C2F6	9200
C4F10	7000
C6F14	7400
SF6	23,900



## NO<sub>x</sub>

- ♦ NO<sub>x</sub> emissions from coal combustion produced from 3 sources
  - ♦ **Thermal NO<sub>x</sub>**
    - ♦ Fixation of atmospheric N @ ↑T
    - ♦  $f(\text{combustion } T (>2370^\circ\text{F}), \text{ air/fuel})$
    - ♦ NO(T) ↓ by ↓T, ↓t, ↓[N<sub>2</sub>], ↓[O<sub>2</sub>]
  - ♦ **Fuel NO<sub>x</sub>**
    - ♦ Oxidation of coal N compounds
    - ♦ Primary source of NO<sub>x</sub>
    - ♦ T < 2650°F, NO(F) ~ 75-95% of total NO
    - ♦ NO(F) more readily produced than NO(T)
    - ♦ Unlike NO(T), NO(F)
      - ♦ < sensitive to T over the range in coal flames
      - ♦ > sensitive to air/fuel
  - ♦ **Prompt NO<sub>x</sub>**
    - ♦ [H-C] in flame zone + N<sub>2</sub> ⇒ N ⇒ NO
    - ♦ Fixation of atmospheric N<sub>2</sub> by H-C fragments in the reducing atmosphere of the flame zone
    - ♦ Total NO(P) ↓↓↓ compared to NO(T) & NO(F)
  - ♦ Majority of NO<sub>x</sub> species produced is NO
    - ♦ NO<sub>2</sub> < 5% of total NO<sub>x</sub>
    - ♦ « N<sub>2</sub>O



## NO<sub>x</sub> Control in Pulverized Coal Combustion

Classified in 2 categories

- ♦ Combustion modifications where NO<sub>x</sub> production is reduced during the combustion process
- ♦ Flue gas treatment which removes NO<sub>x</sub> from flue gas following its formation

Emission control methods include:

- ♦ Reducing peak flame T
- ♦ Reducing residence time at peak flame T
- ♦ Chemically reducing NO<sub>x</sub>
- ♦ Oxidizing NO<sub>x</sub> followed by absorption
- ♦ Removing N
- ♦ Sorbents
- ♦ Combinations of above



**Tee-Time...  
Travel Safely  
&  
Thank You!**

