REINHOLD ENVIRONMENTAL Ltd.

2012 NOx-Combustion Round Table
& Expo Presentation

February 13-14, 2012, in Columbus, OH / Hosted by AEP

Good Morning!

&

Thank You for the Invitation to Speak

Please take a moment to give your pagers and cell phones a rest; please turn them off or switch to vibrate mode

Now grab a coffee, a pen/pencil and a buddy to keep you awake

“How Does the Choice of Fuel Effect Emissions & NO_x Formation”

2012 NO_x–Combustion Round Table & Expo

13 February 2012

Renaissance Columbus Downtown Hotel
Columbus, Ohio

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Objective

To understand
coal characteristics,
coal sampling & weighing,
&
how they effect
emissions & NO_X formation

How Does the Choice of Fuel Effect Emissions & NOx

Coal Analysis

Mine/Supplier:	Pittsburgh Seam	Sampling Method:	Mechanical
Sample #:	99F-00852	Sample Date:	2/25/1999
Sample Description:	S> 1.7%	Sample Receipt:	2/26/1999

Proximate	As=Received	Dry	MAF
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	
Heating Value	13,376	14,010	15,080

ADL	2.30
Residual Moisure	2.27

Moisture Load	3.38
Ash Load	5.07
SO2	3.07
V/FC	0.63

Ultimate	As=Received	Dry	MAF
Carbon	75.23	78.82	84.84
Hydrogen	5.00	5.24	5.64
Nitrogen	1.45	1.52	1.64
Oxygen	4.97	5.21	5.61

Hardgrove Grindability Index

HGI	**50.8 @2.89% Moisture**

How Does the Choice of Fuel Effect Emissions & NOx

Coal Analysis

Mine/Supplier:	Pittsburgh Seam	Sampling Method:	Mechanical
Sample #:	99F-00852	Sample Date:	2/25/1999
Sample Description:	S> 1.7%	Sample Receipt:	2/26/1999

Ash Fusion - 8 point	Reducing	Oxidizing
Initial	2,209	2,535
Spherical	2,280	2,575
Hemispherical	2,372	2,595
Fluid	2,460	2,665
Plastic Range	251	130

Ash Mineral

SiO_2	50.52
Al_2O_3	23.10
TiO_2	0.93
Fe_2O_3	15.63
CaO	2.64
MgO	0.78
K_2O	1.94
Na_2O	0.56
SO_3	1.25
P_2O_5	0.35
BaO	0.26
SrO	0.81
MnO_2	0.01
Undetermined	1.22

B/A	0.29
Ash Ratio	0.22
Ash Type	Bituminous
Slagging Index	1
Slagging Type	Medium
Fouling Index	0.16
Fouling Type	Low
Silica Ratio	0.73
Si/Al	2.19
Fe/Ca	5.92
Dolomite %	15.87

Trace Elements	*Units*	*Value*		*Units*	*Value*		*Units*	*Value*
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, Thalium	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						

What is coal?

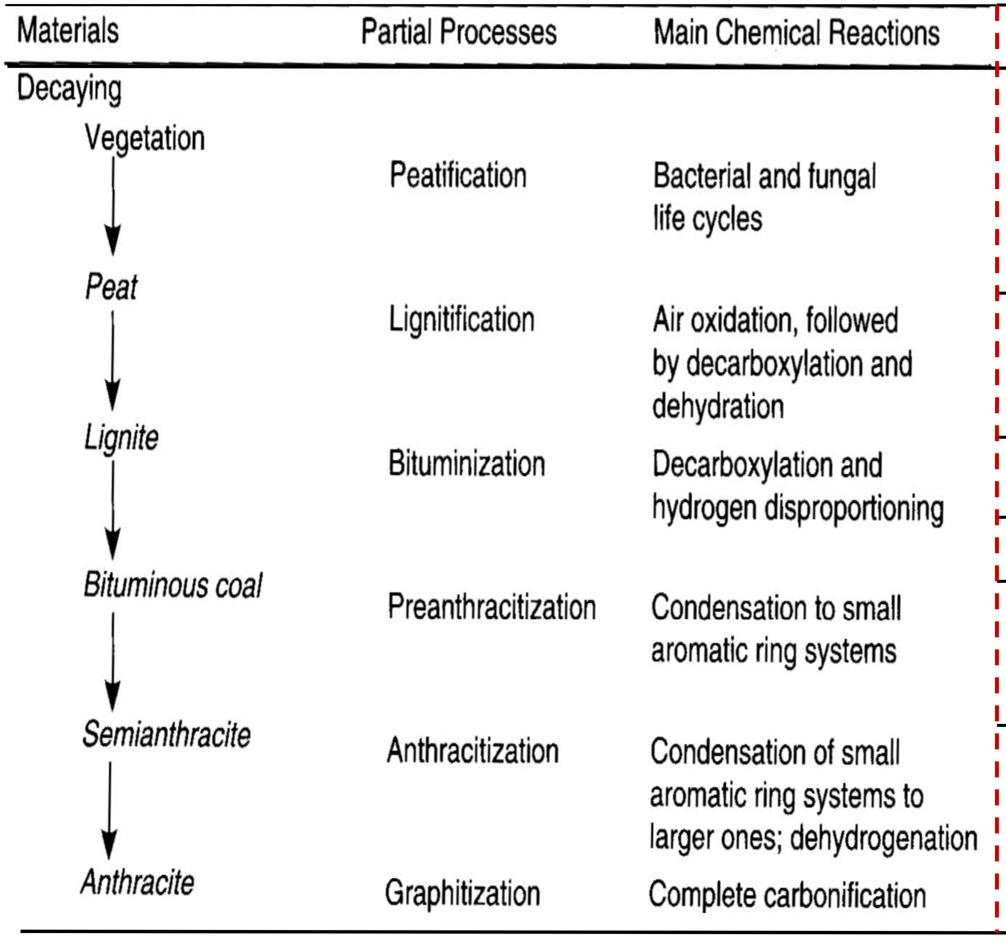
It's definitely not just black and burns

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)

How Does the Choice of Fuel Effect Emissions & NOx

Coalification Process



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

	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

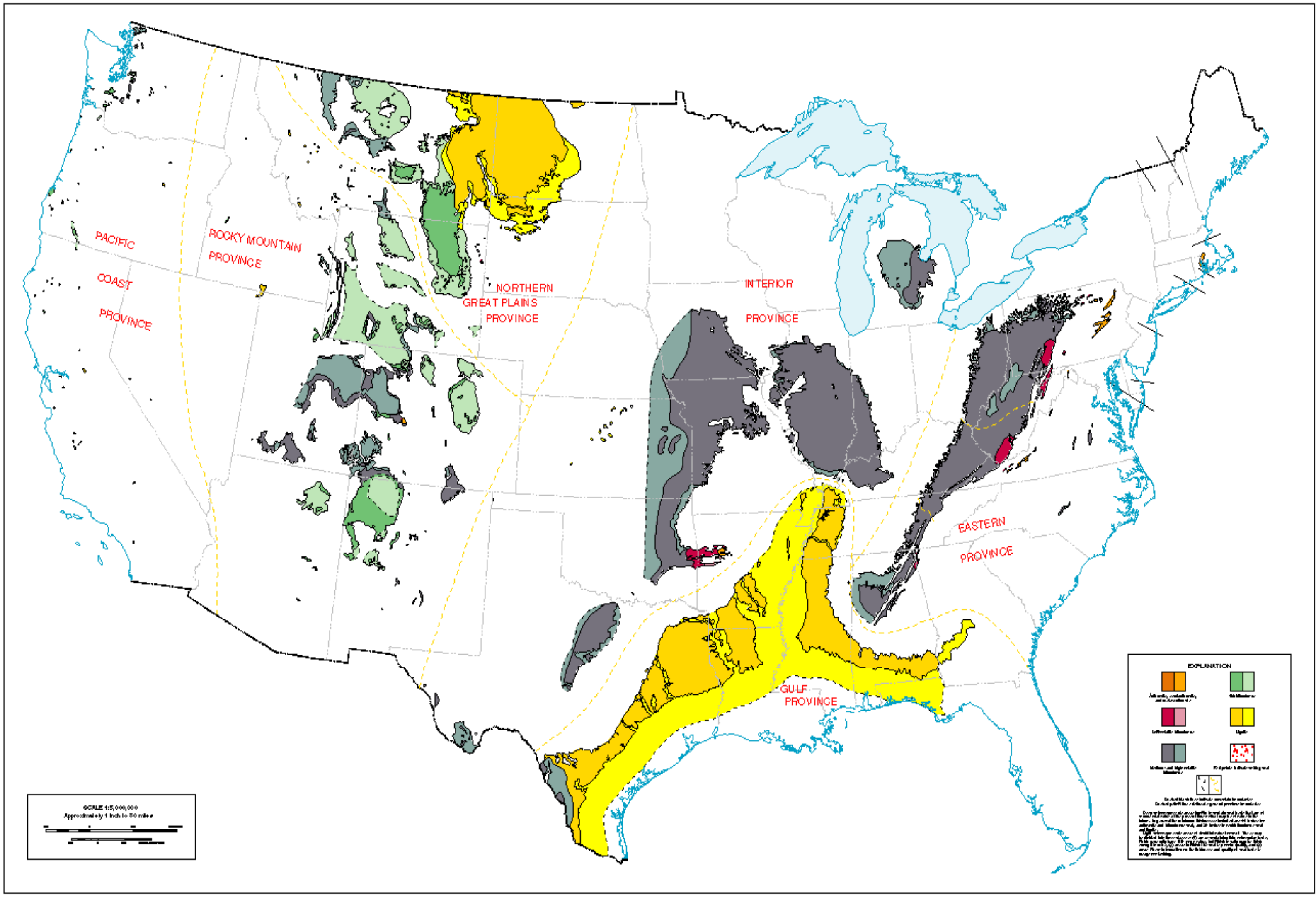
Increasing Aromatization & Loss of Oxygen with Time

Wt%, dry mmf basis

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

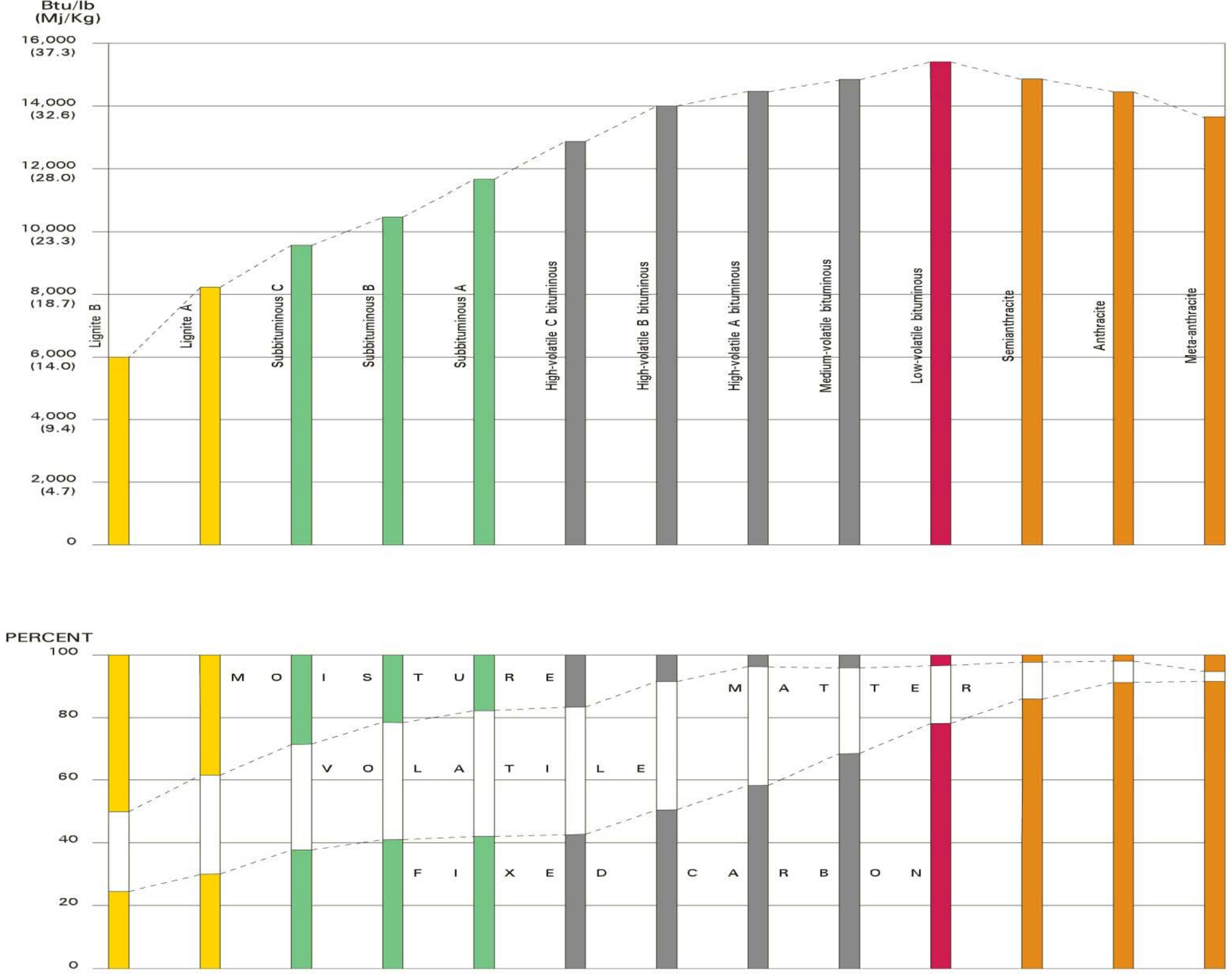
How Does the Choice of Fuel Effect Emissions & NOx

Coal Deposits in the USA



How Does the Choice of Fuel Effect Emissions & NOx

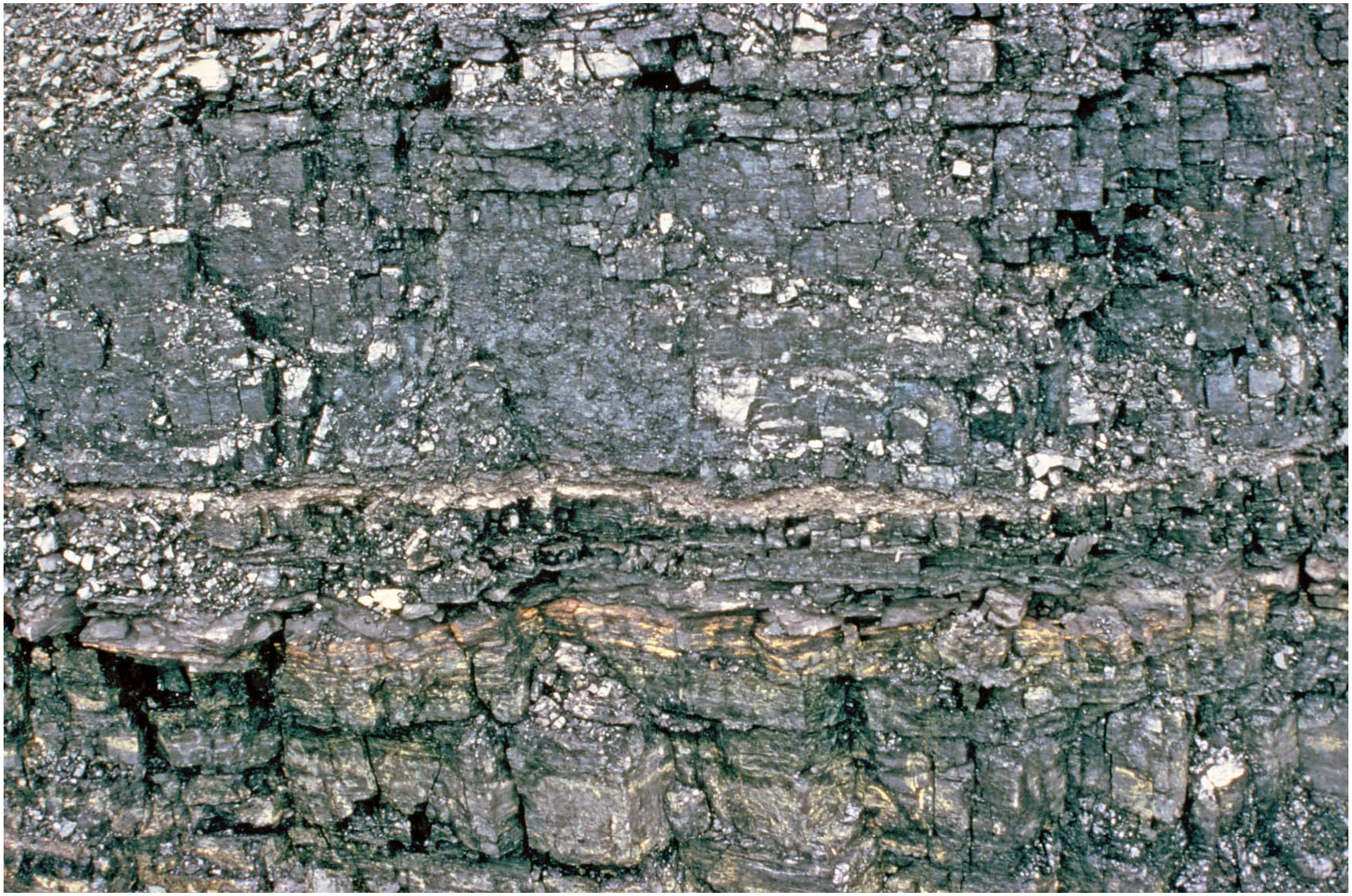
Coal Quality by Rank



MAXIMUM CALORIFIC VALUES OF COALS OF DIFFERENT RANKS
COMPARED TO PROXIMATE ANALYSIS DATA

How Does the Choice of Fuel Effect Emissions & NOx

Coal Seam — Pittsburgh (Northern Appalachia)



How Does the Choice of Fuel Effect Emissions & NOx

Unfortunately, no fossil fuel (or for that matter, renewables) can be fully evaluated unless basic coal science is understood. Without this understanding:

- Operators make decisions without adequate training
- 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

How Does the Choice of Fuel Effect Emissions & NOx

Knowing just a coal’s
short prox
is no longer sufficient

Does not contain enough
information to make
informed decisions

Coal

Mechanical combination of coal + mineral matter

Coal Maceral (bark, sap, leaves)

- Sorry, no dinosaurs
- Complex aromatic hydrocarbon
  - C, H, N, O, S, (Cl, Na, ...)
- Volatile & Fixed Carbon — **energy source**
- Hydrophobic (rejects water)

Mineral Matter (ash)

- Combustible & non-combustible minerals — **energy sink**
- Mostly minerals of the following oxides
  - Si, Al, Ti, Fe, Ca, Mg, K, Na, S, P, Ba, Sr, Mn, Cl, + ...
  - 60^+ of the first 92 elements
- Hydrophilic (accepts water)

Moisture

- Inherent (Equilibrium, Bed) & Surface — **energy sink**

How Does the Choice of Fuel Effect Emissions & NOx

Hypothesized Coal Structures

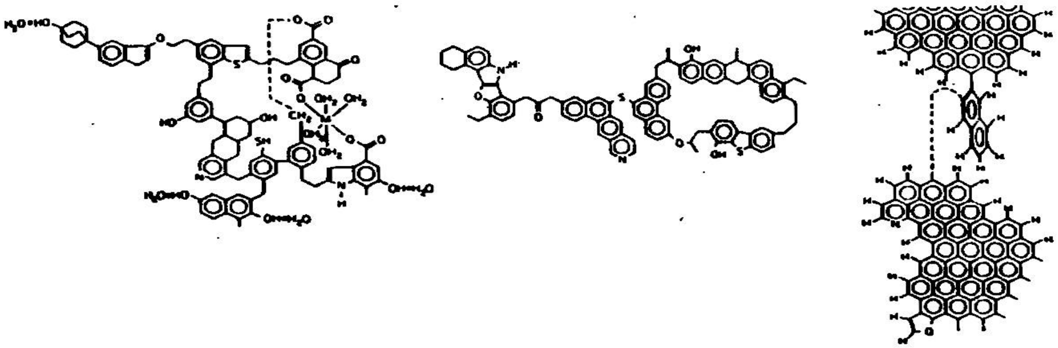


Figure 13. Spiro and Kosky (1982) models for a low-, intermediate-, and high-rank coal.

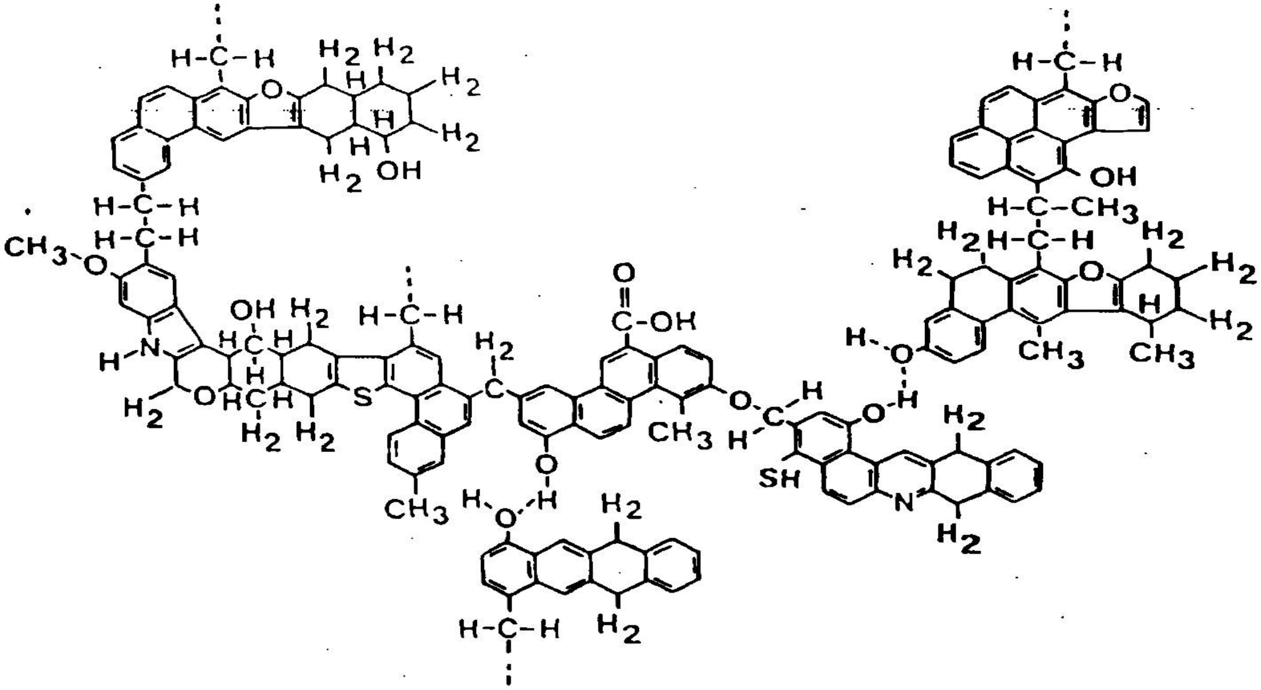
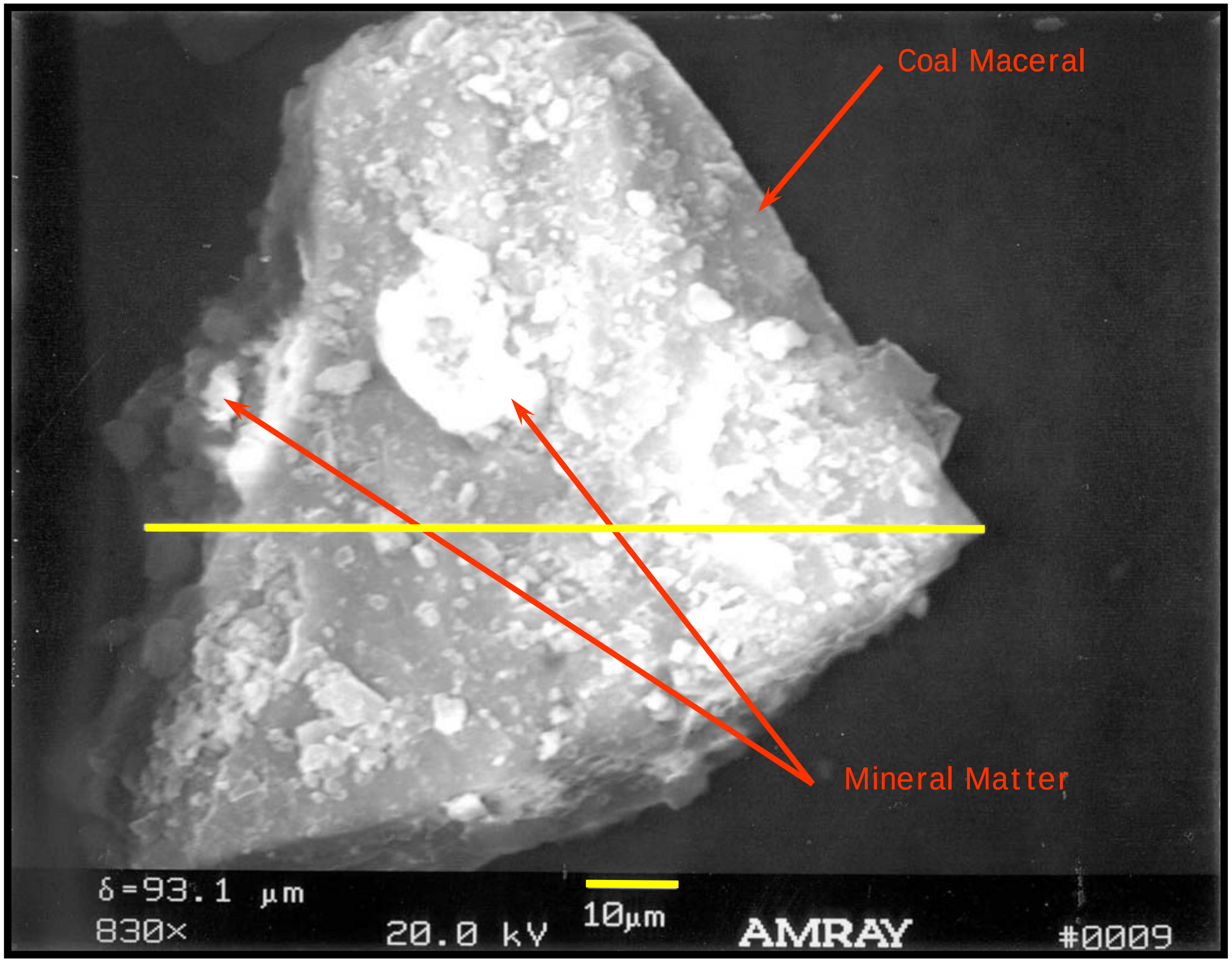


Figure 12. The Solomon (1981) model of a Pittsburgh high-volatile bituminous coal.

How Does the Choice of Fuel Effect Emissions & NOx

SEM Photomicrograph of Coal Particle



Sub-bituminous coal particle, about 93-µm across.

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

How Does the Choice of Fuel Effect Emissions & NOx

Let's Start with a Proximate Instead of a Short Proximate

- Moisture
- Ash
- **Volatile**
- **Fixed Carbon**
- Sulfur
- Heating Value

- **MAF Heating Value**
- **Moisture Load**
- **Ash Load**
- **SO2**
- **Volatile/Fixed Carbon**

How Does the Choice of Fuel Effect Emissions & NOx

Proximate

- [-] Moisture
- [-] Ash (really Mineral Matter)
- [+] Volatile
- [+] Fixed Carbon
- Btu (HHV)
- Sulfur
- SO_2 (lbs SO_2/MBtu)
- Ash loading (lbs ash/MBtu)

Ultimate

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

Ash Mineral

- (Si, Al, Ti), (Fe, Ca, Mg, K, Na)
- Base-Acid Ratio
- Fe_2O_3 (%), Fe loading (lbs Fe_2O_3/MBtu)
- CaO (%), Ca loading (lbs CaO/MBtu)
- Na_2O (%), Na loading (lbs Na_2O/MBtu)

How Does the Choice of Fuel Effect Emissions & NOx

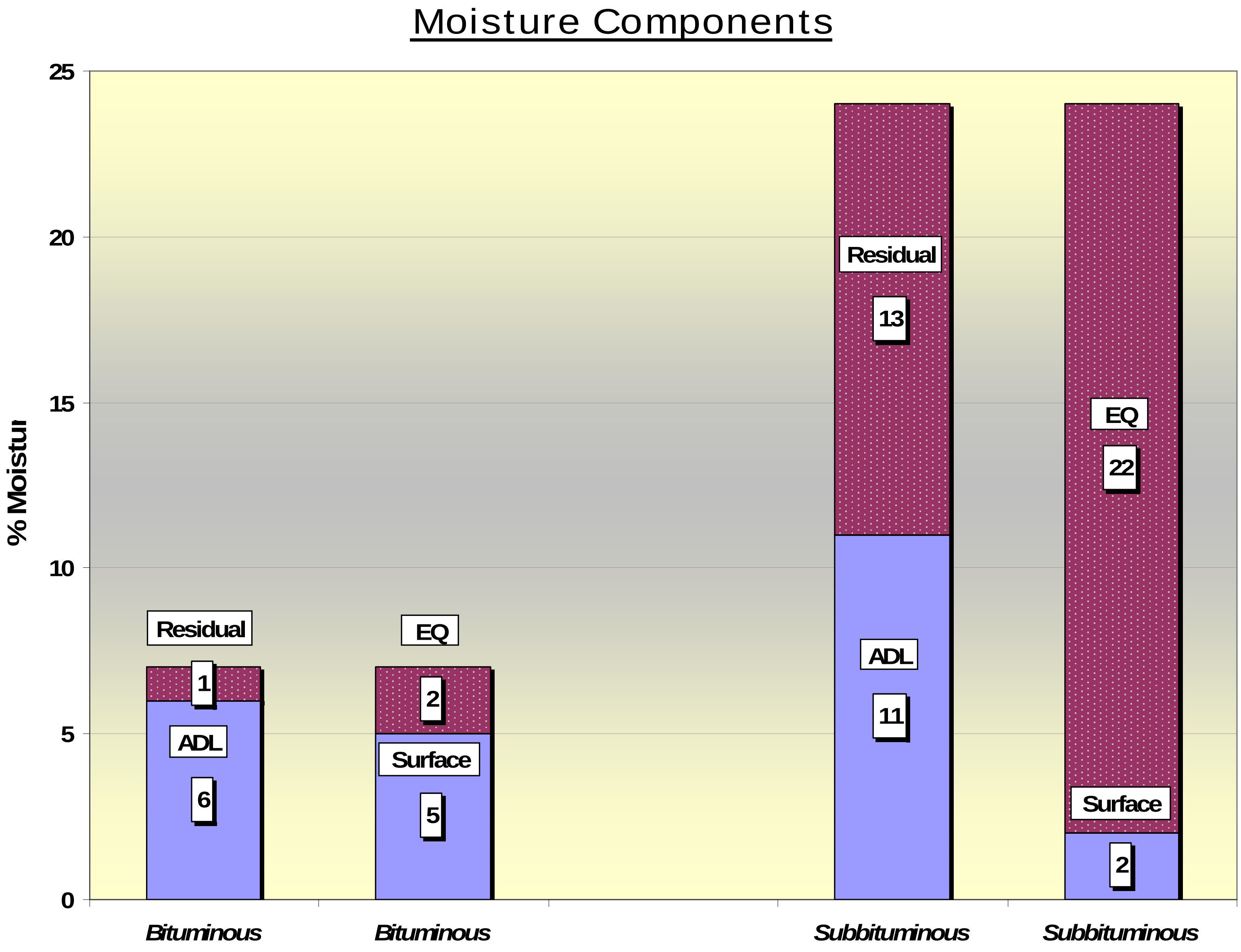
Coal & Coke Comparisons

	High Volatile Bituminous (steam & met)			Pet Coke	Sub-Bituminous (steam)	
Proximate	Pitt (S<1.7)	Pitt (S>1.7)	CApp Mid-Sulfur	Pet Coke	PRB (Na<4)	PRB (Na>4)
Moisture (%) (-)	6.24	4.52	6.91	6.51	23.13	24.60
Ash (%) (-)	6.70	6.78	8.28	0.45	4.22	3.60
Volatile (%) (+)	31.89	34.31	34.23	9.16	32.97	31.57
Fixed Carbon (%) (+)	54.75	54.39	50.28	83.89	39.68	40.23
Sulfur (%)	1.42	2.05	1.37	5.39	0.29	0.25
HHV (Btu/lb)	13,061	13,376	12,730	13.802	9,554	9,507
MAF (Btu/lb)	15,002	15,080	15,010	14,848	13,152	13,241
Moisture Load (lbs/MBtu)	4.78	3.38	5.43	4.71	24.21	25.88
Ash Load (lbs/MBtu)	5.13	5.04	6.51	0.32	4.41	3.79
SO2 (lbs/MBtu)	2.17	3.07	2.15	7.81	0.62	0.53
V/FC (%/%)	0.58	0.63	0.68	0.11	0.83	0.78

Moisture, %

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

How Does the Choice of Fuel Effect Emissions & NOx


Moisture Components

How Does the Choice of Fuel Effect Emissions & NOx

Ash With Your Coal? — No Thank You

Volatility & Fixed Carbon

- Volatile is the gaseous material that evolves ~300-500°F
    - Provides heat for char oxidation
- Fixed Carbon (by difference)
    - Carbon char burns by oxidation ($C \Rightarrow CO \Rightarrow CO_2$)
- Volatile/FC ["fireball" location driver]
- Coal Volatility
    - High Vol (>28%) [steam coal]
        - if 2<FSI<8, could be met coal
    - Mid Vol (20%-28%) [met coals, sometimes steam coal]
    - Low Vol (<20%) [met coals]

How Does the Choice of Fuel Effect Emissions & NOx

Sulfur

- **SO_2**
  - **Lbs SO_2/MBtu ≡ S% * 20,000 / Heating Value (Btu/lb)**
    - 1.0% S @12,000 Btu/lb = 1.67 lbs SO_2/MBtu
    - 1.1% S @13,200 Btu/lb = 1.67 lbs SO_2/MBtu
    - 0.9% S @10,800 Btu/lb = 1.67 lbs SO_2/MBtu

- **Sulfur Forms**
  - **Organic S**
    - Part of coal matrix
    - Not economically removable (today)
    - Released in flame zone, converts to SO_2 & SO_3, sulfate deposition
  - **Pyritic S**
    - Component of ash, mostly FeS_2, 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%

How Does the Choice of Fuel Effect Emissions & NOx

Btu (Heating Value, Calorific Value), Btu/lb

- **As-Received**
    - Contractual, regulatory
    - HHV (higher heating value)
    - Performance
- **As-Determined**
    - Laboratory basis
    - Seldom reported
    - Air-dried only
- **Dry**
    - Lab comparison
    - Quality comparison
    - Corrects for moisture bias
- **MAF**
    - Fingerprint
    - Theoretical total energy (volatile + fixed carbon)

Ultimate (dry basis)

- Carbon
- Hydrogen
- Nitrogen
- *Chlorine*
- Oxygen

Reactivity
Atomic Ratios

- H:C
- O:C

Ultimate (C, H, N, O)

- Performance calculations (as-fired basis)
- Fuel rank & comparison (dry basis)
  - C (50-98%)
  - H (3-5.5%)
  - N (0.5-2%)
  - O (2-25% by difference)
    - O difference = 100 – (Moisture + Ash + S + C + H + N + Cl)
  - C, H, N & O exists in the coal maceral
- Function of coal rank
  - Reported on Moisture & Mineral-Matter Free Basis
    - Based on Parr equations
- Reactivity
  - H:C – indicator of coal reactivity
  - O:C – indicator of coal reactivity
  - N:C – indicator of fuel N reactivity

How Does the Choice of Fuel Effect Emissions & NOx

Coal & Coke Comparisons

Ultimate (dry)	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
Carbon	79.36	78.82	75.64	86.05	68.65	71.47
Hydrogen	5.14	5.24	5.22	2.36	4.48	5.03
Nitrogen	1.57	1.52	1.60	1.59	0.93	1.14
Chlorine	0.095	0.103	0.180	0.009	0.013	0.010
Oxygen	5.27	5.17	7.00	3.90	20.06	17.25

Atomic Ratios

H:C	0.77	0.79	0.69	0.33	0.82	0.84
O:C	0.050	0.049	0.071	0.034	0.219	0.181

How Does the Choice of Fuel Effect Emissions & NOx

Ash Mineral

- Acids (SiO_2, Al_2O_3, TiO_2)
- Bases (Fe_2O_3, CaO, MgO, K_2O, Na_2O)
- Minor Elements (SO_3, P_2O_5, BaO, MnO_2)

Calculated Values

- Base/Acid
- Slagging & Fouling Indexes
  - High Rank Coals
  - Low Rank Coals
- Fe, Ca, Na, Alkali Loads, “Sticky Alkali” Loads
- Fe/Ca, Si/Al, Si/Ca, Si/Na
- Si + Al (ESP index)

Ash (Mineral Matter)

- **Slagging / Fouling Parameters**
  - **Fe, Na, Ca, Mg, K** (plastic-phase deposition)
  - **Na** (vapor deposition, especially PRB-MT)
  - **Fe** & **Ca** act as fluxes to depress ash's melting temperature
    - **S** generally trends with **Fe**
  - **Base-Acid Ratio**
  - $(Fe_2O_3 + CaO + MgO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2)$
  - Minimum fusion temperature, **B:A** ~0.6-0.8
  - High slagging potential, **B:A** ~0.4-1.2
  - High temperature fouling is primarily silicates
  - Low temperature fouling is primarily sulfates
- **Silica vs. Silicates**
  - "Glass" vs. clay
  - Material handling & combustion considerations
- **Na**, organic vs. inorganic compounds

How Does the Choice of Fuel Effect Emissions & NOx

Coal & Coke Comparisons

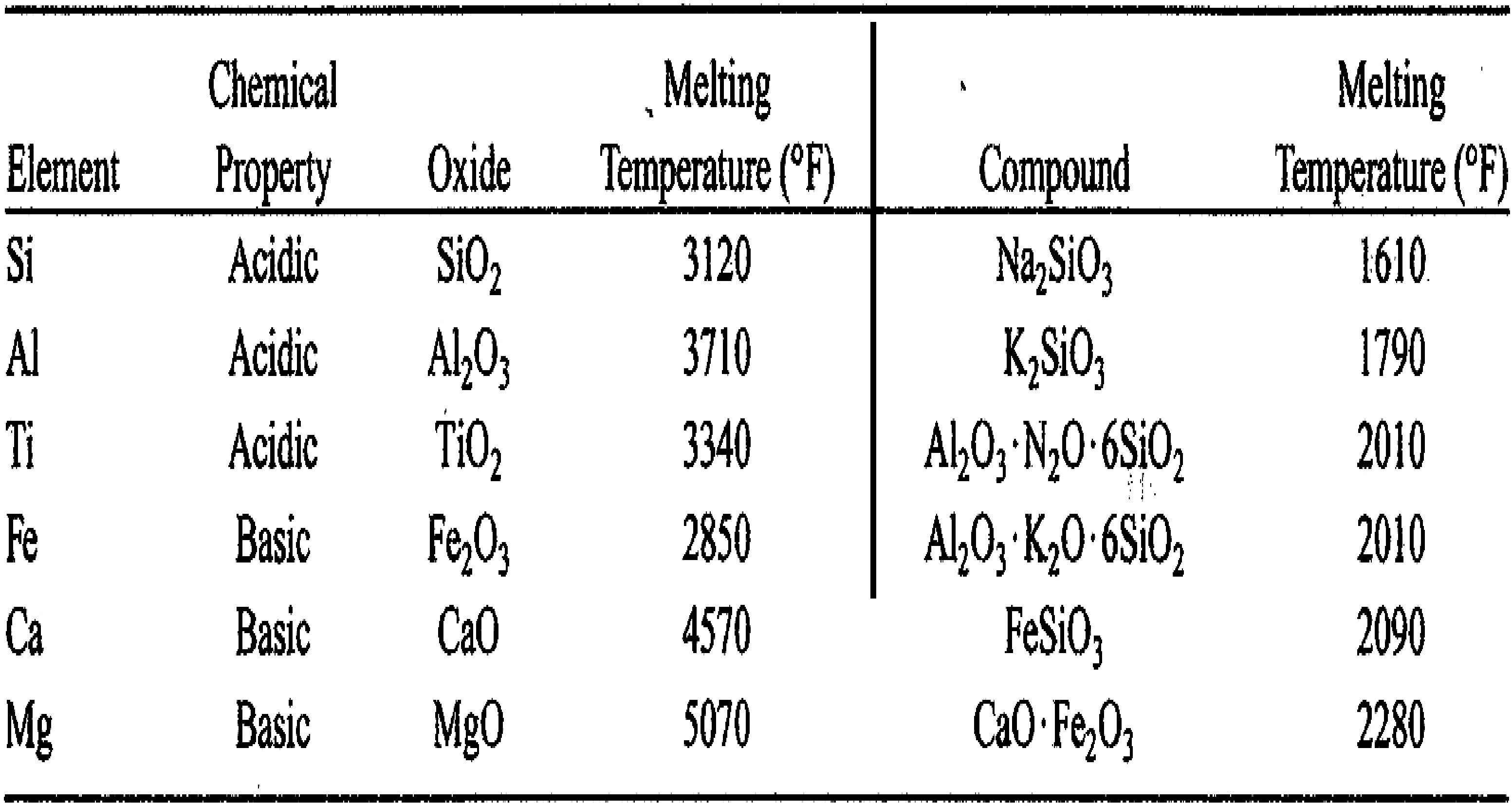
Ash Mineral	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
SiO_2	53.31	51.57	48.47	41.32	38.34	35.96
Al_2O_3	24.98	23.58	27.05	4.99	17.83	20.08
TiO_2	1.04	0.95	1.07	0.38	1.29	1.67
Fe_2O_3	11.84	15.95	11.98	2.26	5.03	5.20
CaO	3.07	2.69	1.93	2.79	14.23	20.19
MgO	0.86	0.80	1.09	0.58	4.63	4.89
K_2O	2.01	1.98	2.54	1.26	0.82	0.42
Na_2O	0.61	0.57	0.63	2.47	2.58	**11.58**
% Acid	81.18	77.58	80.83	69.95	67.80	57.71
% Base	18.82	22.42	19.17	30.05	32.20	42.29
Base / Acid	0.23	0.29	0.24	0.52	0.47	0.73
Slagging Type	Low	Severe	Low	Severe	High	High

How Does the Choice of Fuel Effect Emissions & NOx

Coal & Coke Comparisons

Ash Mineral	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
Si Ratio	73	77	76	58	62	54
Si + Al	75	78	85	46	54	56
Si/Al	2.19	2.13	1.79	9.28	2.15	1.79
Fe/Ca	5.92	3.85	6.21	1.66	0.35	0.26
Dolomite %	16	21	16	32	69	59
Fe + Ca	18.65	14.91	13.91	5.05	19.26	25.40
Fe Load	0.81	0.61	0.78	0.01	0.22	0.20
Ca Load	0.14	0.16	0.12	0.01	0.63	0.76

Fusion Characteristics of Ash Components



Element	Chemical Property	Oxide	Melting Temperature (°F)	Compound	Melting Temperature (°F)
Si	Acidic	SiO_2	3120	Na_2SiO_3	1610
Al	Acidic	Al_2O_3	3710	K_2SiO_3	1790
Ti	Acidic	TiO_2	3340	$Al_2O_3 \cdot N_2O \cdot 6SiO_2$	2010
Fe	Basic	Fe_2O_3	2850	$Al_2O_3 \cdot K_2O \cdot 6SiO_2$	2010
Ca	Basic	CaO	4570	$FeSiO_3$	2090
Mg	Basic	MgO	5070	$CaO \cdot Fe_2O_3$	2280

Source: *Routine Coal & Coke Analysis,* Dr John Riley, *pg 74, ASTM, 2007*

How Does the Choice of Fuel Effect Emissions & NOx

Coal Mineral Types

Mineral Class	Mineral type	Chemical Formula	Melting Temperature
Silicates	Kaolinite (Al-silicate)	$Al_2Si_2O_5(OH)_4$	3,200
	Fe-aluminosilicate	$Fe_xAl_ySi_z$	
	Illite (K-aluminosilicate)	~$K(Al,Fe)_4(Si,Al)_8O_{20}($	
	Chlorite	$(MgFeAl)_6(SiAl)_4O_{10}($	
	Calcium silicate	$CaSiO_3$	3,416
	Ca-aluminosilicate	$Ca_xAl_ySi_z$	
	Quartz	SiO_2	Trans to beta quartz at 1,063
Carbonates	Calcite	$CaCO_3$	2,426
	Dolomite	$CaMg(CO_3)_2$	1,704
	Siderite	$FeCO_3$	
	Ankerite	$Ca(FeMgMn)(CO_3)_2$	
Disulfides	Pyrite	FeS_2 (cubic)	1,112 dec
	Marcasite	FeS_2 (orthorhombic)	
Sulfates	Coquimbite	$Fe(SO_4)\cdot 9H_2O$	752 dec
	Barite	$BaSO_4$	2,876
	Szmolnokite	$FeSO_4\cdot H_2O$	572 dec
	Gypsum	$CaSO_4\cdot 2H_2O$	302 dec
	Bassanite	$CaSO_4\cdot \frac{1}{2}H_2O$	
	Anhydrite	$CaSO_4$	2,660
	Jarosite	$KFe_3(SO_4)_2(OH)_6$	
Feldspars	Plagioclase	$(NaCa)Al(AlSi)Si_2O_8$	
	Orthoclase	$KAlSi_3O_8$	
	Sphalerite	ZnS	3,092
Sulfides	Galena	PbS	2,035
	Pyrrhotite/iron sulfate	FeS	2,170
Mineral oxides	Iron oxide	Fe_2O_3	2,849
	Rutile	TiO_2	3,349
	Calcium aluminate	$Ca_3Al_2O_6$	2,795
	Spinel	$(Fe,Al,Mg)O_4$	3,704
	Apatite	$Ca_5F(PO_4)_3$	2,000
	Crandallite	$CaAl_3(PO_4)_2(OH)_5\cdot H_2O$	

dec = decompose

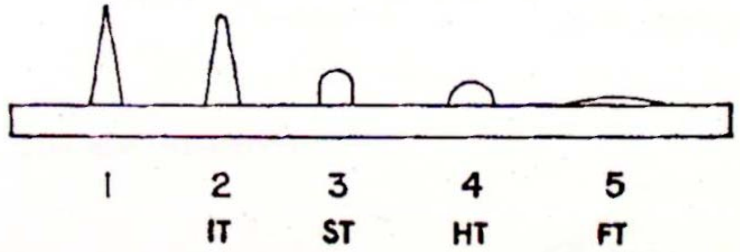
Sources: *Routine Coal & Coke Analysis, Dr John Riley, pg 11, ASTM, 2007; Zygaricke, 1990*

Ash Fusion Temperatures

- Reducing & oxidizing atmospheres (CO/CO_2 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

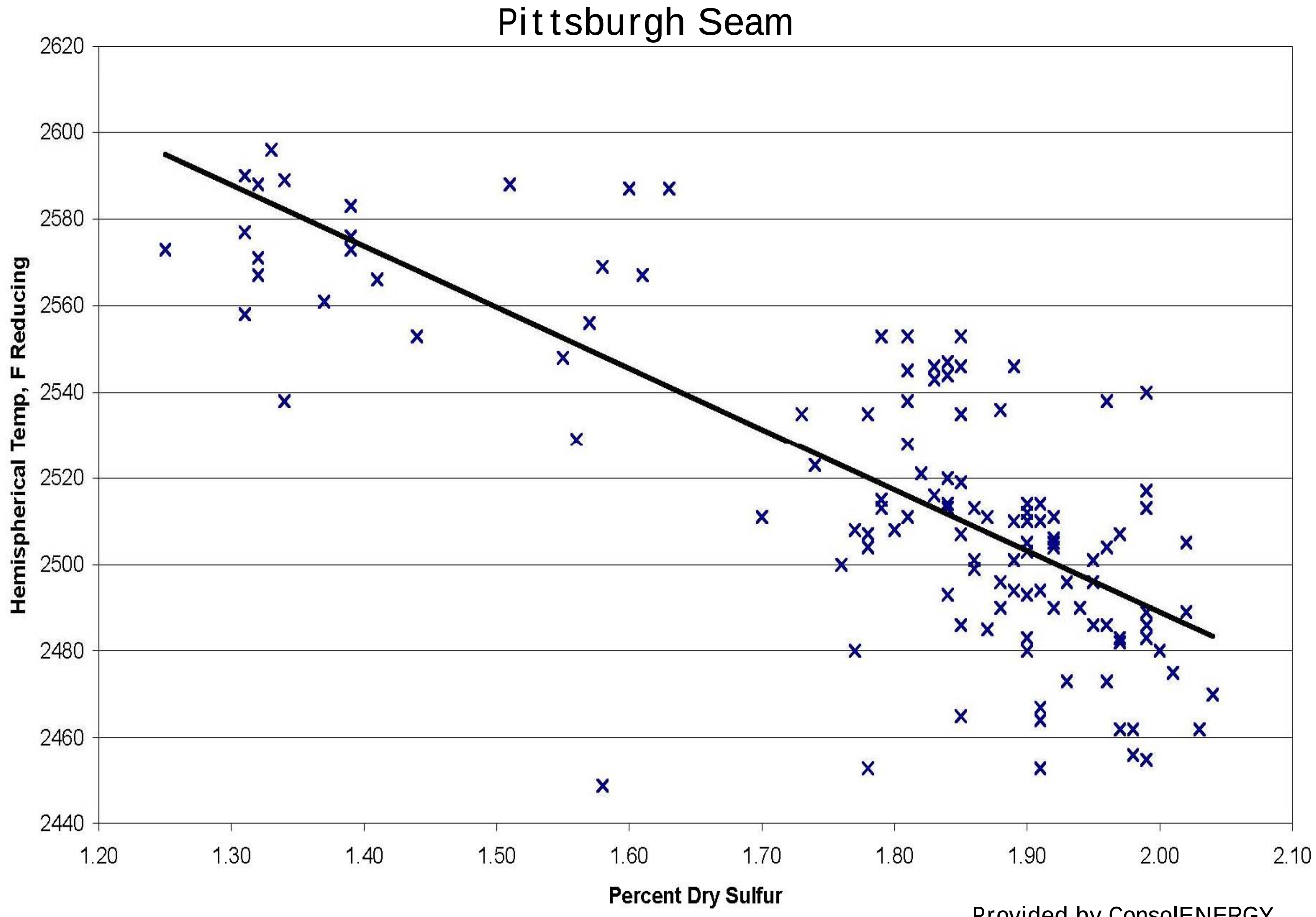
- Slagging Predictors
- Eutectic Predictor
- Oxidizing & Reducing Atmospheres
- Initial Deformation, Spherical Softening, Hemispherical Softening, Fluid
- Plastic Range



Critical Temperature Points

How Does the Choice of Fuel Effect Emissions & NOx

Sulfur vs. Ash Fusion Temperature



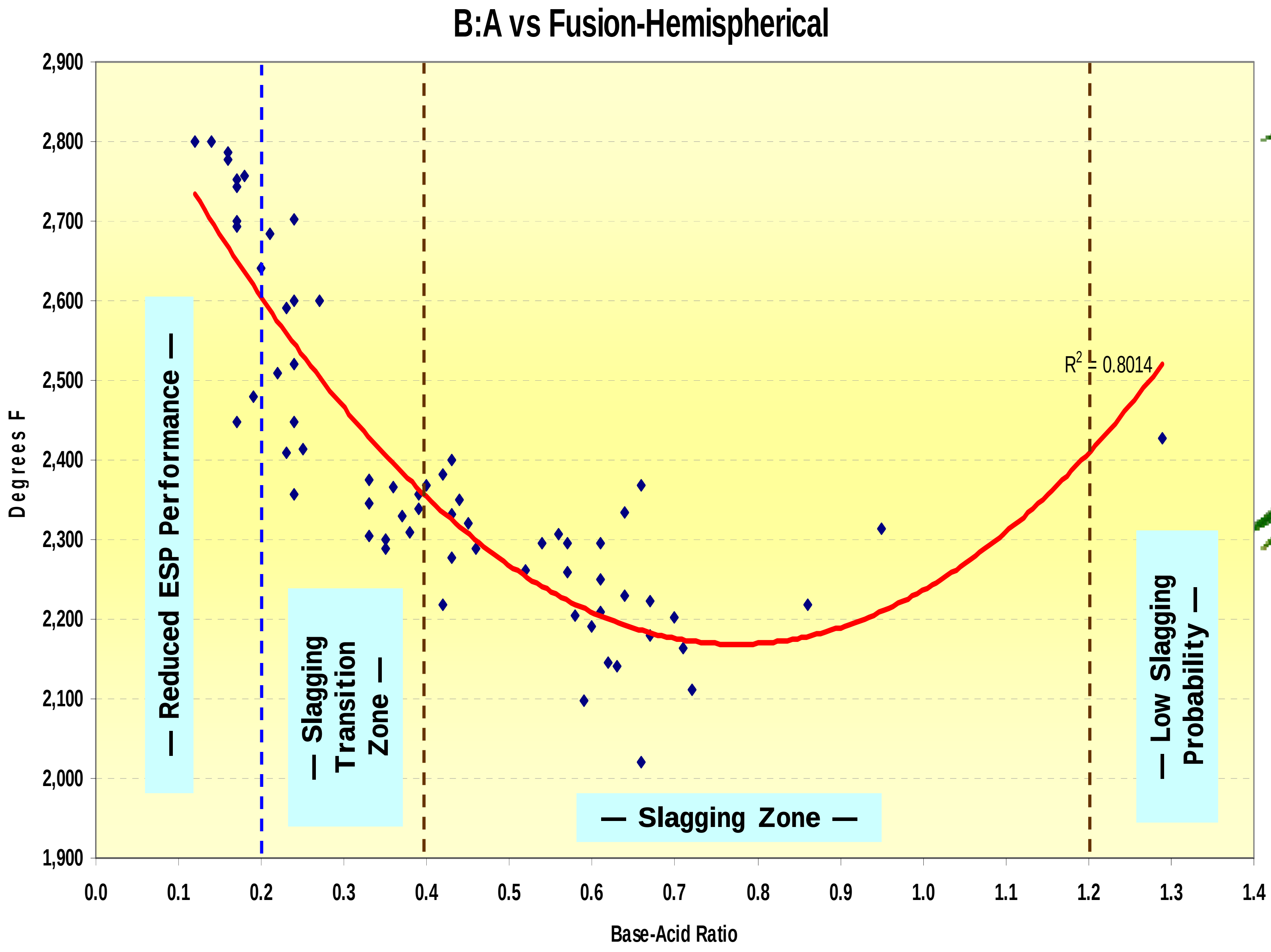
Provided by ConsolENERGY

How Does the Choice of Fuel Effect Emissions & NOx

Coal & Coke Comparisons

Ash Fusion	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
Reducing Atmosphere (°F)						
Initial Deformation	2,472	2,209	2,465	>2,800	2,135	2,066
Spherical Softening	2,499	2,280	2,540	>2,800	2,150	2,150
Hemispherical Softening	2,530	2,372	2,565	>2,800	2,160	2,161
Fluid	2,585	2,460	2,615	>2,800	2,249	2,177
Plastic	113	251	150	>0	105	111
Oxidizing Atmosphere (°F)						
Initial Deformation	2,550	2,535	2,615	>2,800	2,225	2,348
Spherical Softening	2,590	2,575	2,660	>2,800	2,390	2,412
Hemispherical Softening	2,625	2,595	2,670	>2,800	2,428	2,422
Fluid	2,670	2,665	2,705	>2,800	2,450	2,438
Plastic	120	130	90	>0	225	90

How Does the Choice of Fuel Effect Emissions & NOx



21 February 2012

How Does the Choice of Fuel Effect Emissions & NOx

Coal & Coke Comparisons

	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)

Sulfur Forms

	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
Organic S	0.80	1.10	0.84	--	0.27	0.29
Pyritic S	0.70	1.02	0.50	--	0.08	0.05
Sulfate	0.01	0.03	0.03	--	0.01	0.01

Equilibrium Moisture

	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
EQ Moisture	4.0	3.7	5.3	--	23.5	23.1

Hardgrove Grindability Index

	Pitt (S<1.7)	Pitt (S>1.7)	CApp	Pet Coke	PRB (Na<4)	PRB (Na>4)
HGI	51	53	46	52	47	51

Fly Ash Collection

ESPs

&

Ash Resistivity

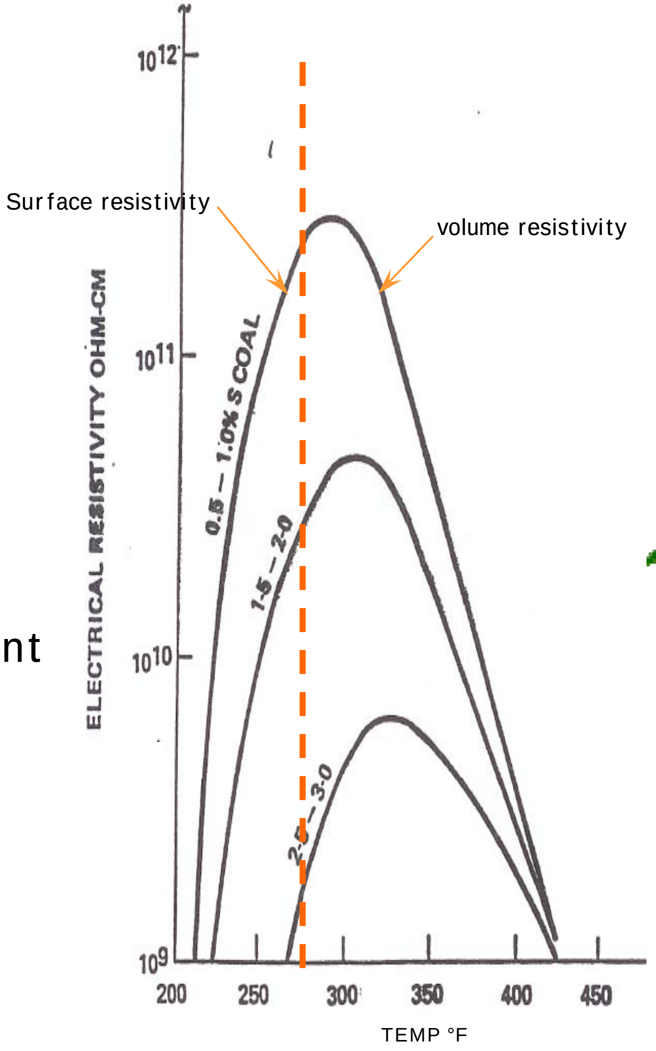
Ash ESP Parameters

- **Ash Load (Grain Loading)**
  - Lbs Ash/MBtu ≡
    Ash% * 10,000 / Heating Value (Btu/lb)
  - Not all ash travels to ESP
    - *f*(ash viscosity, ash fusion temperatures, furnace atmosphere)
    - High fusion temperature moves more ash to back pass and ESPs as economizer ash & fly ash
    - Low fusion temperature holds more ash in furnace and pendants in the form of slag & fouling deposits

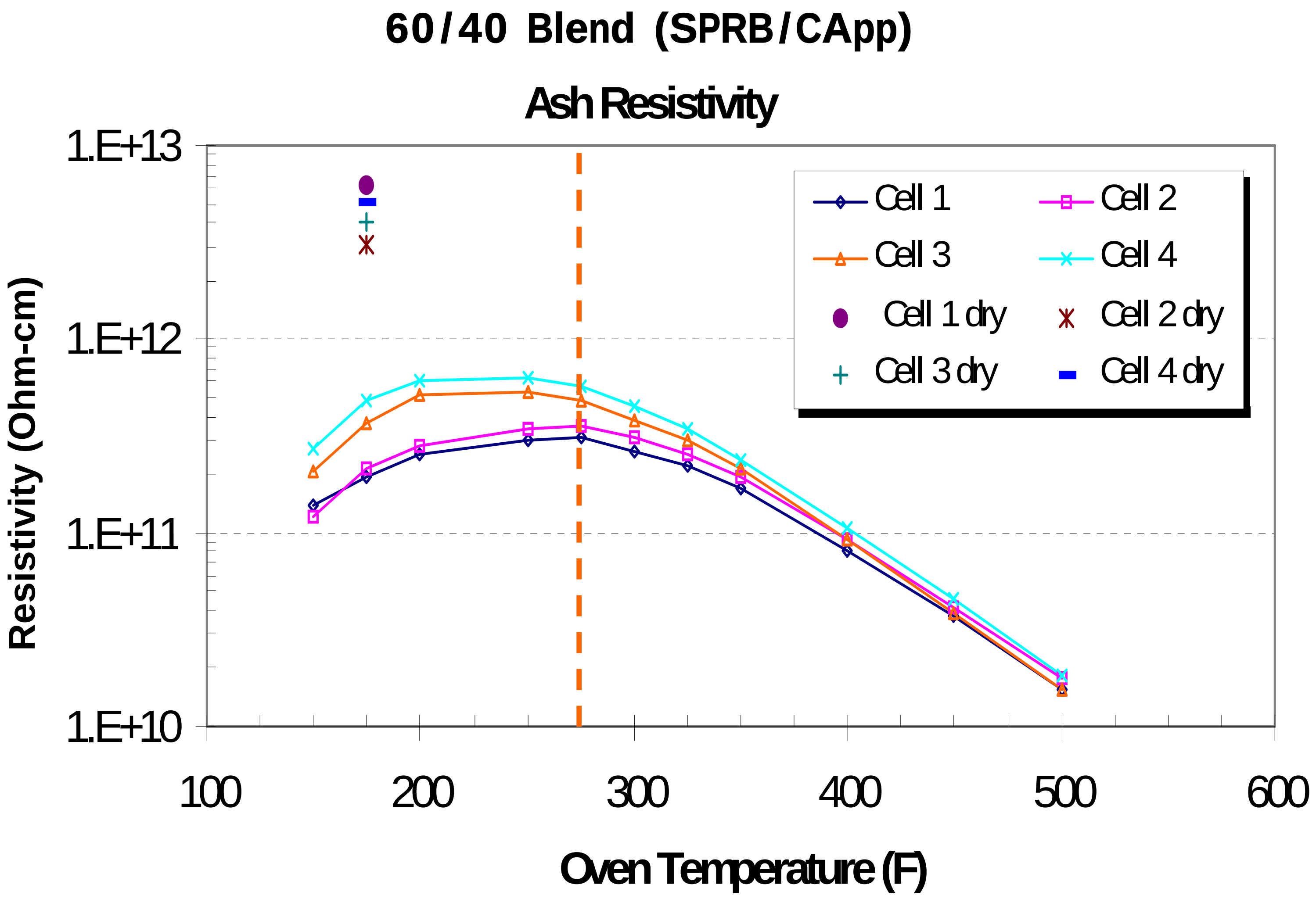
How Does the Choice of Fuel Effect Emissions & NOx

Electrostatic Precipitation

- **Ash Resistivity (Ω-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** < ~80% (ESP Index)
    - Ash resistivity too high for efficient collection
    - "glass"
  - **SiO_2+Al_2O_3+Fe_2O_3** <~98%,
    - Ash resistivity too low
    - Difficult to remove from rappers, re-entrainment



How Does the Choice of Fuel Effect Emissions & NOx



Stan Miller, UND-EERC

21 February 2012

HGI (Hardgrove Grindability Index)

- Indicator of power required to pulverize coal to -200 mesh

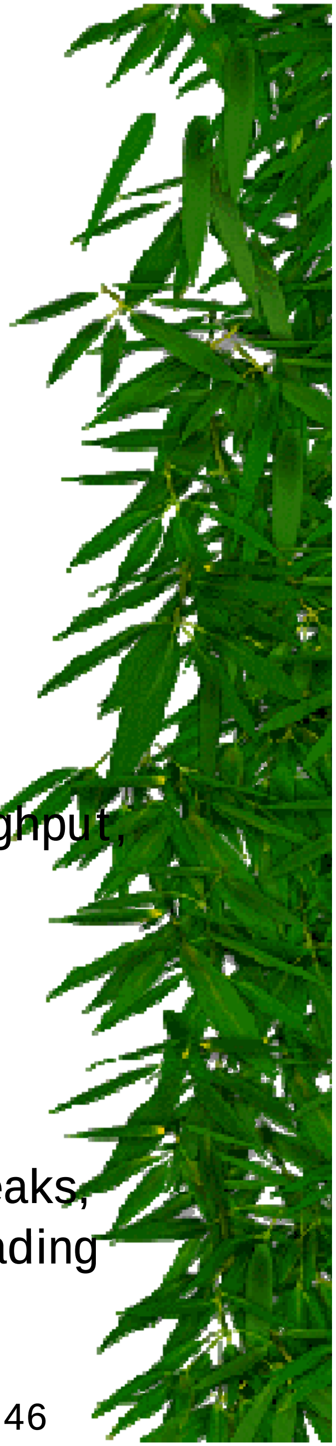
- HGI @x% moisture
  - Moisture is critical value for low-rank coals
  - Higher moisture, higher apparent HGI; coal less friable
  - Lower moisture, lower apparent HGI; coal more friable

- Desired values:
  - 99% passing 50 mesh (99.7% passing 50 mesh for low-rank coals or when firing through a Low NO_x burner
  - 70% passing 200 mesh
  - If either value is exceed,
    - Rerun the test
    - If OK, tune the classifier or other mill maintenance

HGI (Hardgrove Grindability Index)

- Index based on coal from Pocahontas Seam (set = 100)
  - Typical mined range: 35-110+ (harder ⇛ softer)
  - Typical range used by utilities: 38-75 (limestone ~ 35)

- Effects of HGI extremes on pulverizers
  - For example, given 50 HGI as a design value
  - Low HGI (e.g., 39)
    - Coal harder than design
    - Increased wear on mill internals, increased O&M, reduced availability, increased transport line erosion, reduced throughput, increased pyrites, larger particle size, delayed combustion, increased slagging
  - High HGI (e.g., 70)
    - Coal softer than design
    - Reduced wear on mill internals, decreased/increased O&M, increased/decreased availability, increased transport line leaks, increased throughput, decreased pyrites, increased dust loading inside mill. If design bed depth is not maintained, O&M can increase significantly.



Mill Fineness

- Mill fineness and burner line balance are the most important factors for proper combustion; everything downstream is effected by coal particle size and particle size distribution across the boiler
- Many negative environmental, combustion & performance factors can be traced back to mill performance
  - E.g., CO, NO_x, slagging, UBC, LOI, waterwall corrosion, furnace erosion, O_2 mal-distribution, increased H-C emissions, opacity
- Mill Throughput Factors
  - Input coal size
  - Moisture
  - Pyrite concentration
  - Coal recirculation
  - Desired final particle size range
  - Approximately equal mass flow & particle size distribution to each burner

How Does the Choice of Fuel Effect Emissions & NOx

Effect of Missing 50-Mesh Coal Fineness Target

- Target: 99% passing 50-mesh
- Assume actual mill fineness is 98% passing 50-mesh

- Example: 100,000 lb/hr pulverizer
- Target, 1000 lb/hr +50 mesh
- Actual, 2000 lb/hr +50 mesh
- Extra 1000 lb/hr +50 mesh
    - 2x more +50 mesh coal to burn in radiant furnace
    - 2x more plastic ash in convective zone
    - 2x more unburned C
    - Increased ash loading to back pass
    - Increased O_2 requirements
    - Increased air volume required
    - Reduced ESP performance
- Extra 1000 lb/hr equates to:
    - Assuming 5 mills/unit
    - 5000 lbs/hr/unit
    - 120,000 lbs/day/unit (60 tons/day/unit)
    - In reality, mush of this becomes slag instead of fly ash

How Does the Choice of Fuel Effect Emissions & NOx

Mill Fineness

Impacts of Output Fineness

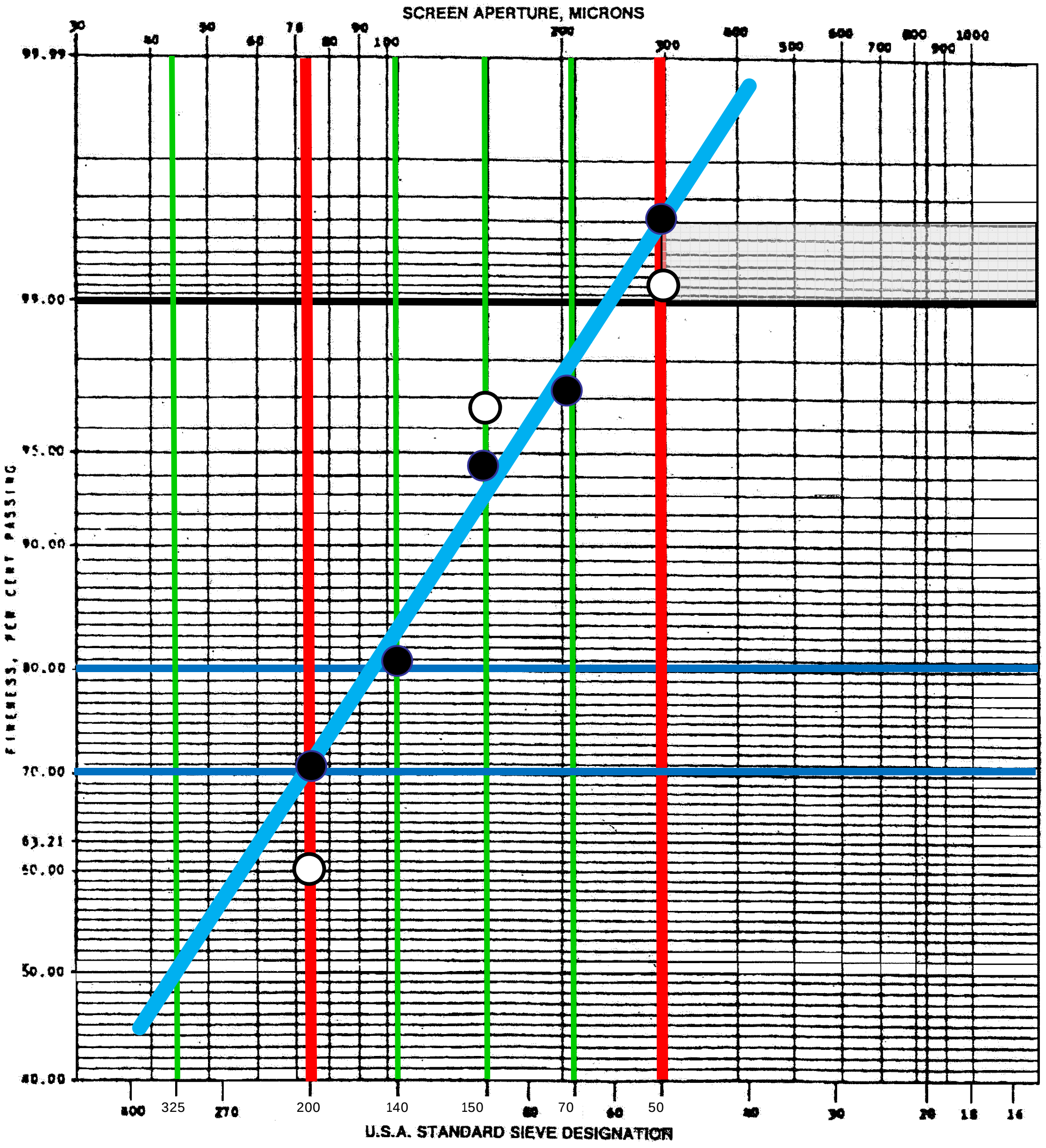
- **Coarse** — Delayed combustion, combustion higher in furnace, higher unburned C (UBC), higher CO, higher O_2 requirement, increased mill throughput, slagging higher in furnace, decreased mill maintenance, larger burner-line bias (particle momentum vs. density), burner-line layout

- **Micro Pulverized** — Rapid combustion, combustion lower in furnace, reduced unburned C (UBC), lower CO, reduced O_2 requirement, reduced mill throughput, increased mill maintenance, too rapid burnout, (decreased NO_x?)

How Does the Choice of Fuel Effect Emissions & NOx

D 197

Rosin-Rammler Chart



Plot of Rosin and Rammler Equation for Use with Pulverized Coal

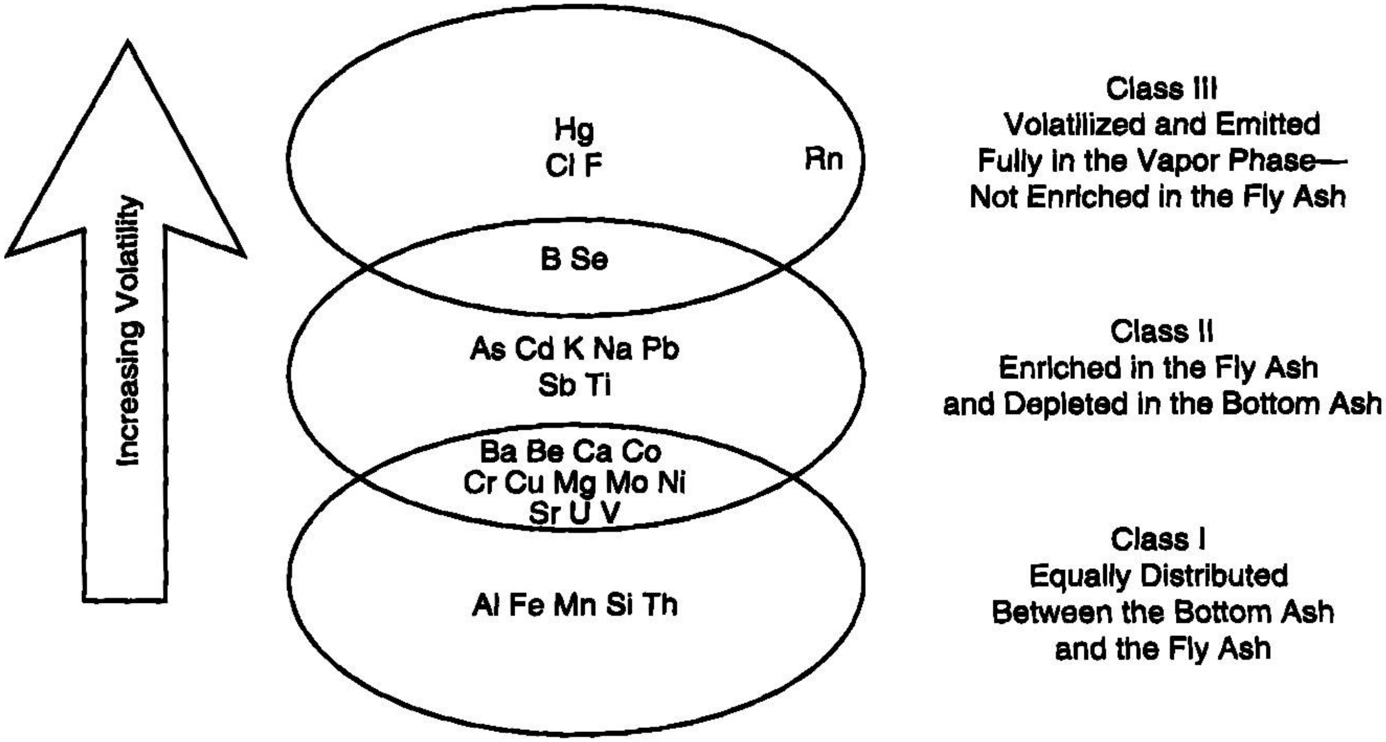
How Does the Choice of Fuel Effect Emissions & NOx

Coal Blending

- Most characteristics can be averaged
- Critical exceptions
  - **Volatile release** — Coals with higher volatile release will reduce NO$_x$ formation
  - **Reactivity** — More reactive coals will reduce NO$_x$ formation
  - **Lower fuel N** — Coals with less fuel-N will reduce NO$_x$ 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

How Does the Choice of Fuel Effect Emissions & NOx

Preferential Elemental Deposition in the Boiler



Increasing Volatility

Hg
Cl F

Rn

B Se

As Cd K Na Pb
Sb Ti

Ba Be Ca Co
Cr Cu Mg Mo Ni
Sr U V

Al Fe Mn Si Th

Class III
Volatilized and Emitted
Fully in the Vapor Phase—
Not Enriched in the Fly Ash

Class II
Enriched in the Fly Ash
and Depleted in the Bottom Ash

Class I
Equally Distributed
Between the Bottom Ash
and the Fly Ash

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].)

How Does the Choice of Fuel Effect Emissions & NOx

Size Segregation,

Coal Classification

&

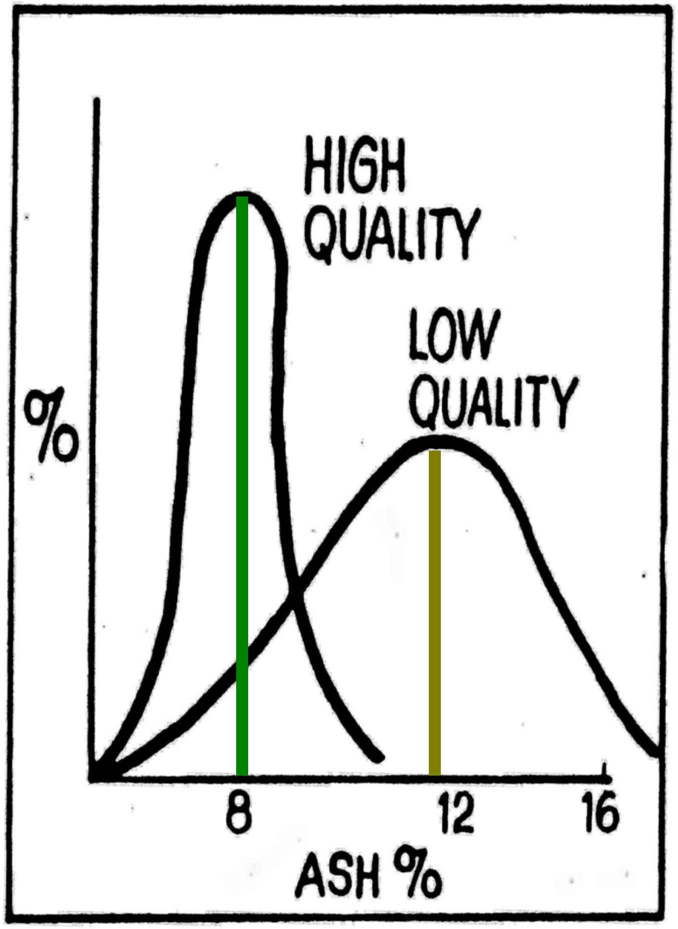
Coal Cleaning

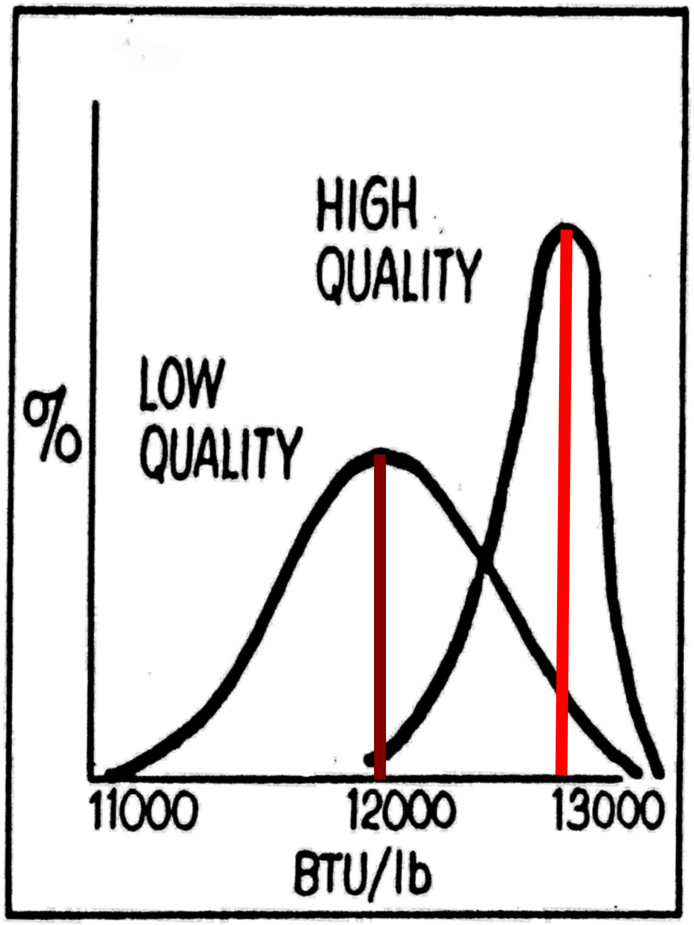
Coal Preparation

- Washing removes ash
  - Mineral matter, pyrites, roof, floor, slate, bone, sulfur balls, partings
  - Raw vs. CROM vs. washed (full vs. partial)
  - Controlled by specific gravity & particle momentum
  - Washing recovers about 97% of the Btus
  - Depending on ash characteristics, 2 tons of raw coal will produce 1 ton of clean coal; remained is reject and goes to off-site valley fill
  - Tightens σ vs. mean (tighter for fully washed coals)
- Washed coals generally spec at 2” x 0; in reality 1½” x 0

Coal Washing (Physical Coal Cleaning)

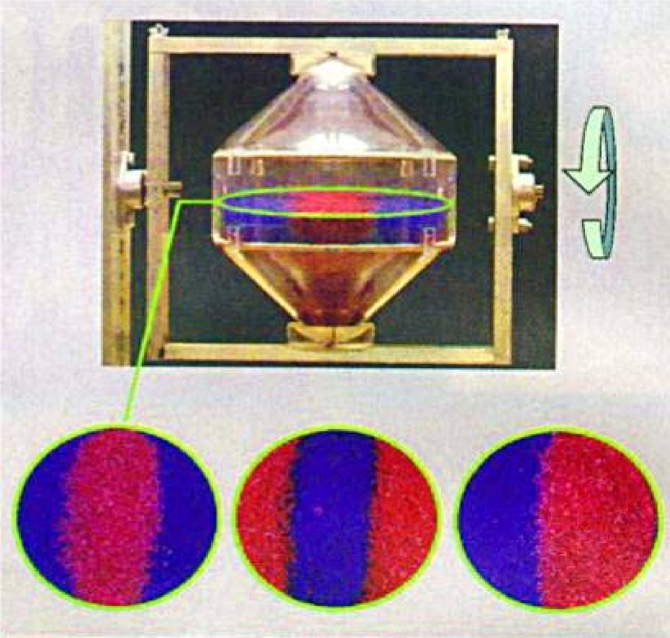
Ash Reduction Increases Heating Value





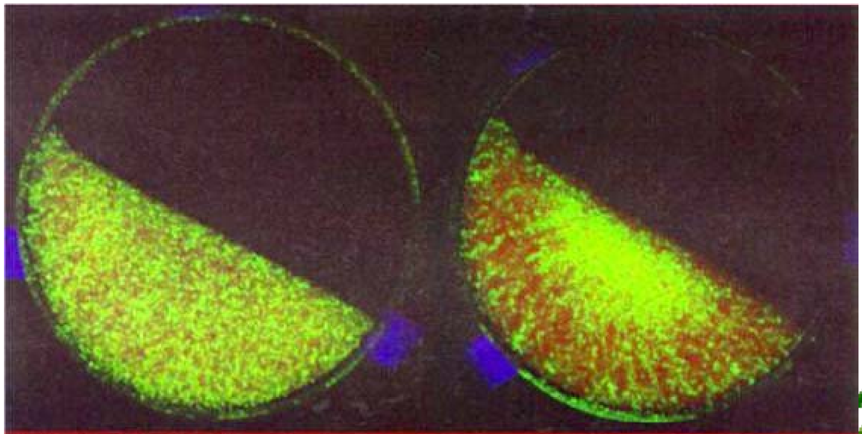
Bob Buckler, Detroit Edison, 1980

How Does the Choice of Fuel Effect Emissions & NOx



YIKES, STRIPES! — Small changes to either the fill level or rotation speed of this industrial-style double-cone blender (top) produce strikingly different segregation patterns (bottom). Bead diameters are 4 millimeters (red) and 1.4 mm (blue).

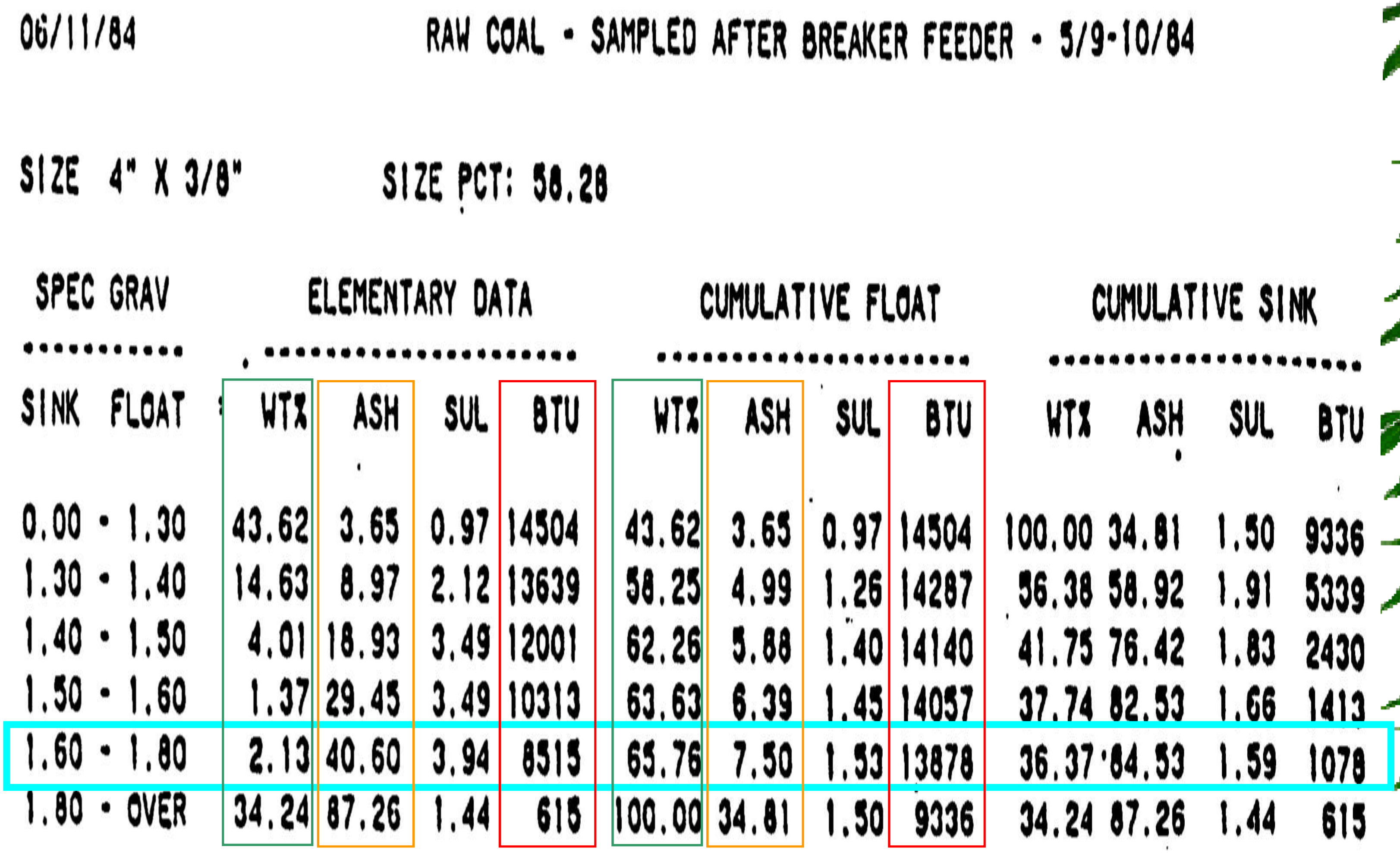
Science News



JUST ADD WATER — In this tumbler experiment, all beads are the same size but coated with a water-attracting film (orange) or a water-repellent one (green). The beads mix well when dry (left). In an odd twist, adding moisture makes them segregate (right).

Science News

Coal Preparation -- Float-Sink Coal Quality



06/11/84 RAW COAL - SAMPLED AFTER BREAKER FEEDER - 5/9-10/84

SIZE 4" X 3/8" SIZE PCT: 58.28

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

Consolidation Coal-1984

CROM Coal

One Lump or Two?

Coal Quality by
Density or Particle Size

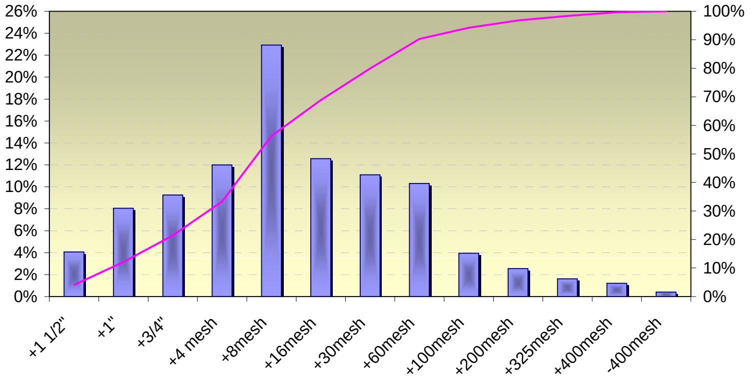
OR

What Number Do You Want?

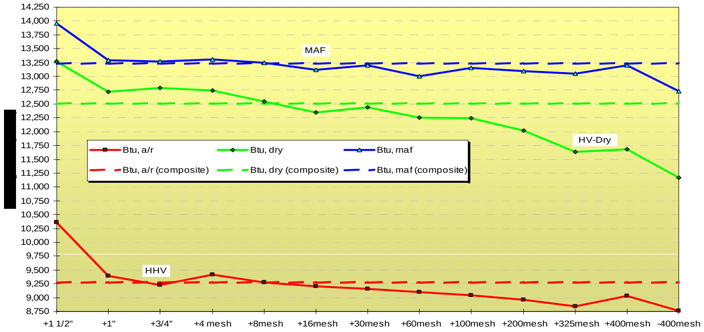
Representative Sampling is Your Only Answer

How Does the Choice of Fuel Effect Emissions & NOx

PRB-MT CROM Size Distribution

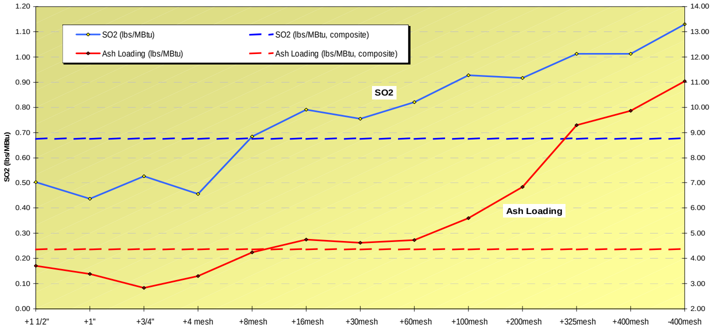


PRB-MT Coal Quality by Size
(As-Received Btu, Dry Btu, MAF Btu)

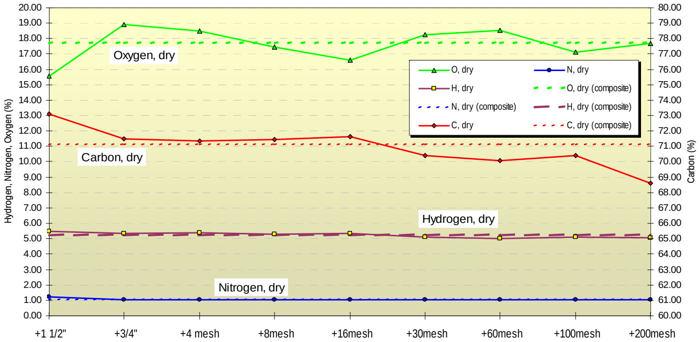


[redacted]

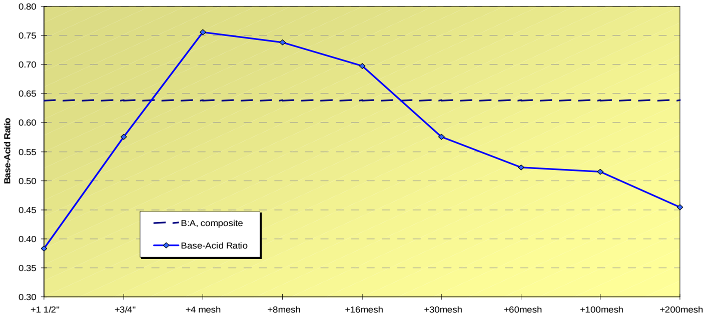
PRB-MT Coal Quality by Size
(SO2, Ash Loading)



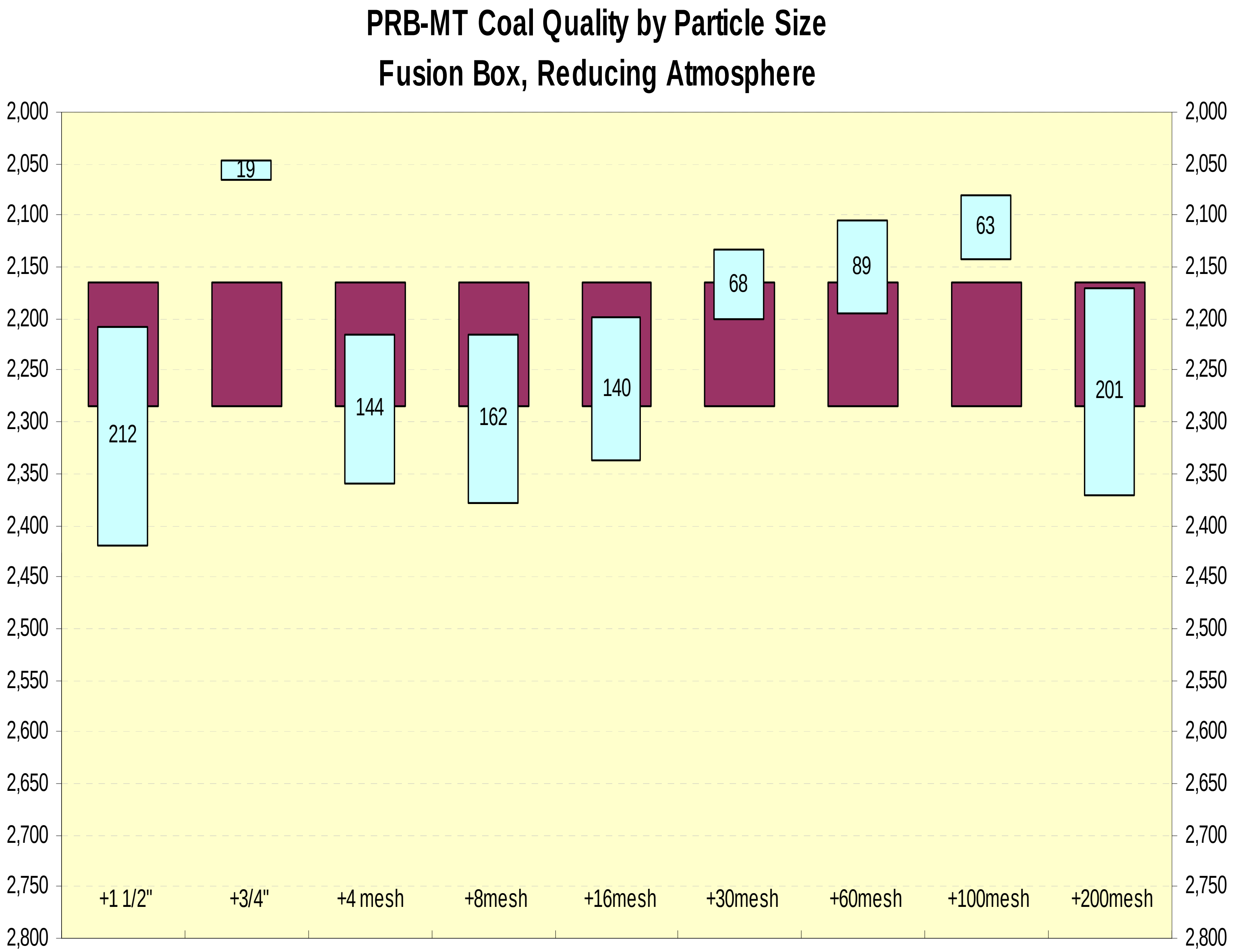
PRB-MT Coal Quality by Size (Ultimate, Dry Basis)



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



How Does the Choice of Fuel Effect Emissions & NOx


PRB-MT Coal Quality by Particle Size
Fusion Box, Reducing Atmosphere

[redacted]

21 February 2012

Pulverized 60-Mesh Coal

One Spoon or Two?

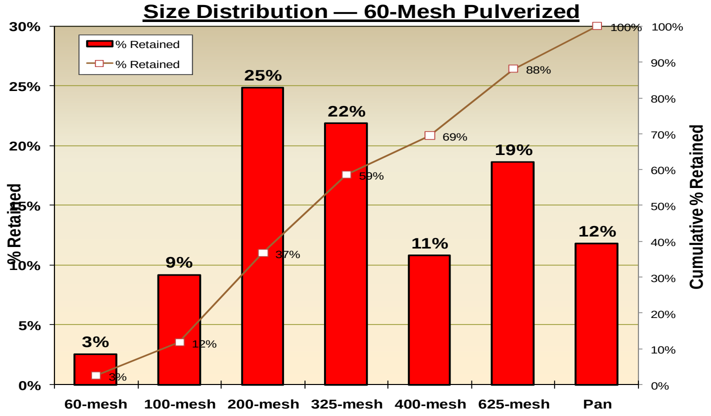
Coal Quality by
Particle Size

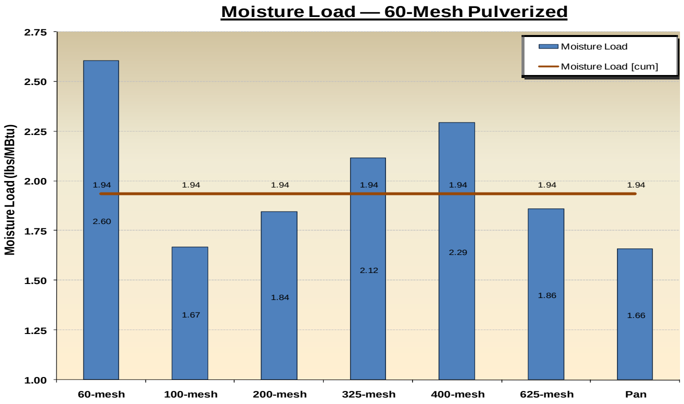
OR

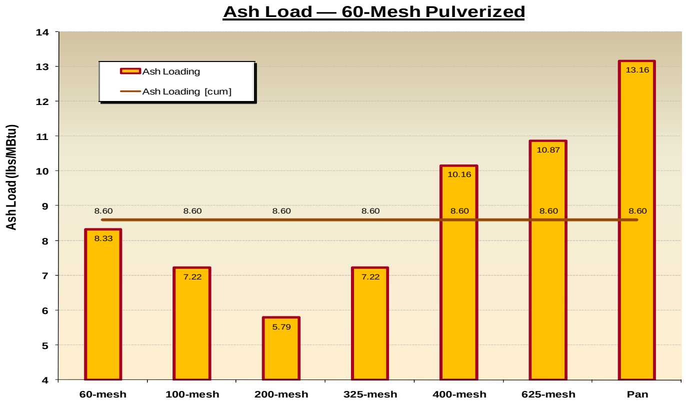
What Number Do You Want?

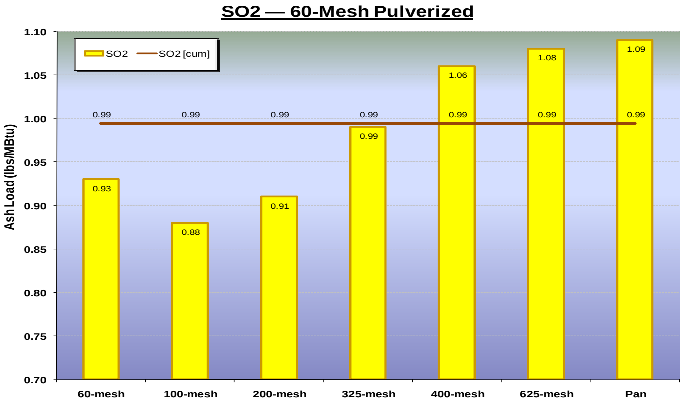
Representative Sampling is Your Only Answer

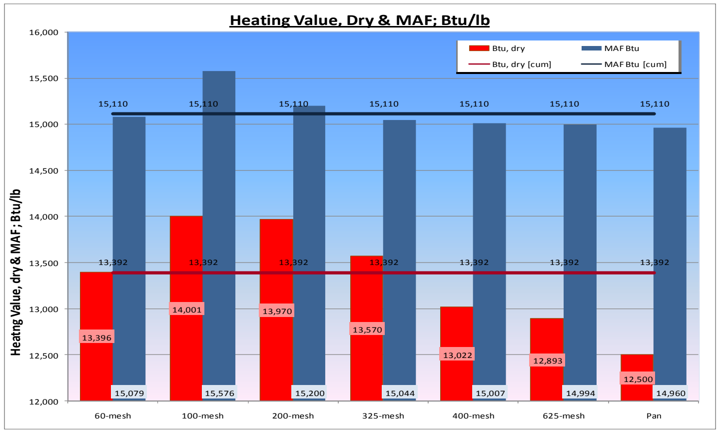
How Does the Choice of Fuel Effect Emissions & NOx


Size Distribution — 60-Mesh Pulverized


Moisture Load — 60-Mesh Pulverized

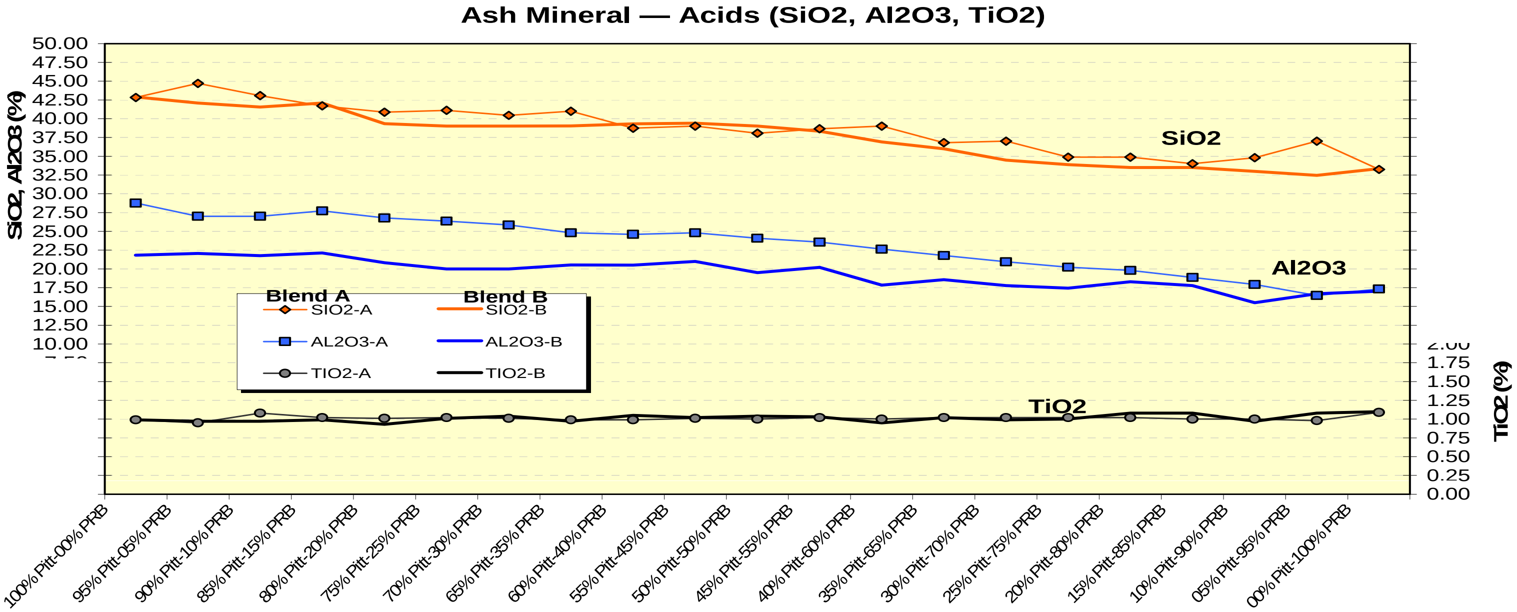

Ash Load — 60-Mesh Pulverized

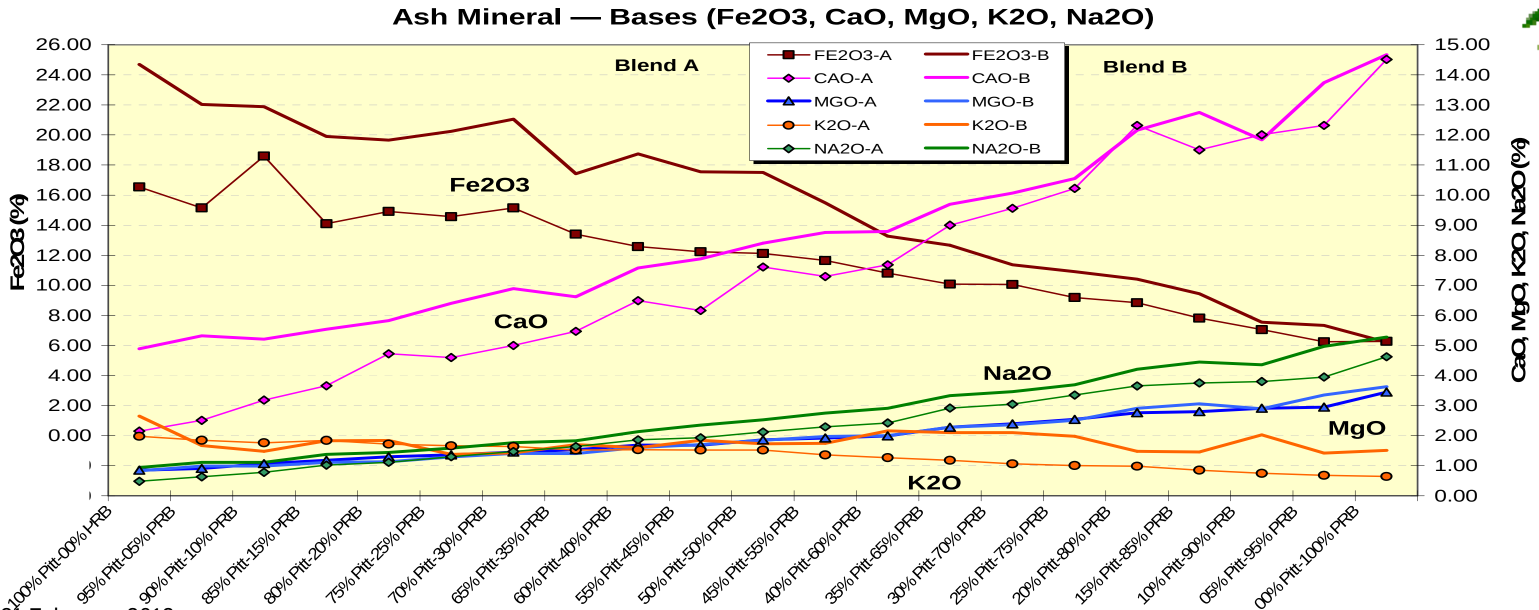

SO2 — 60-Mesh Pulverized


Heating Value, Dry & MAF; Btu/lb

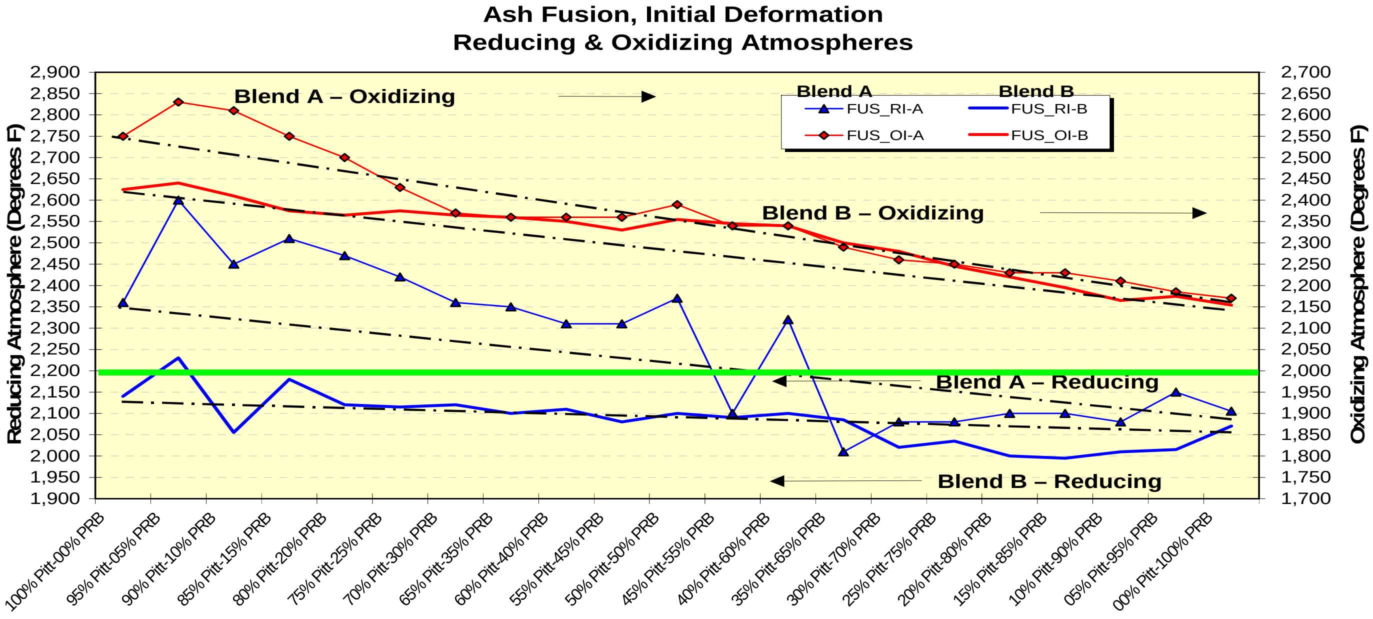
Ash Fusions
&
Fusion Box

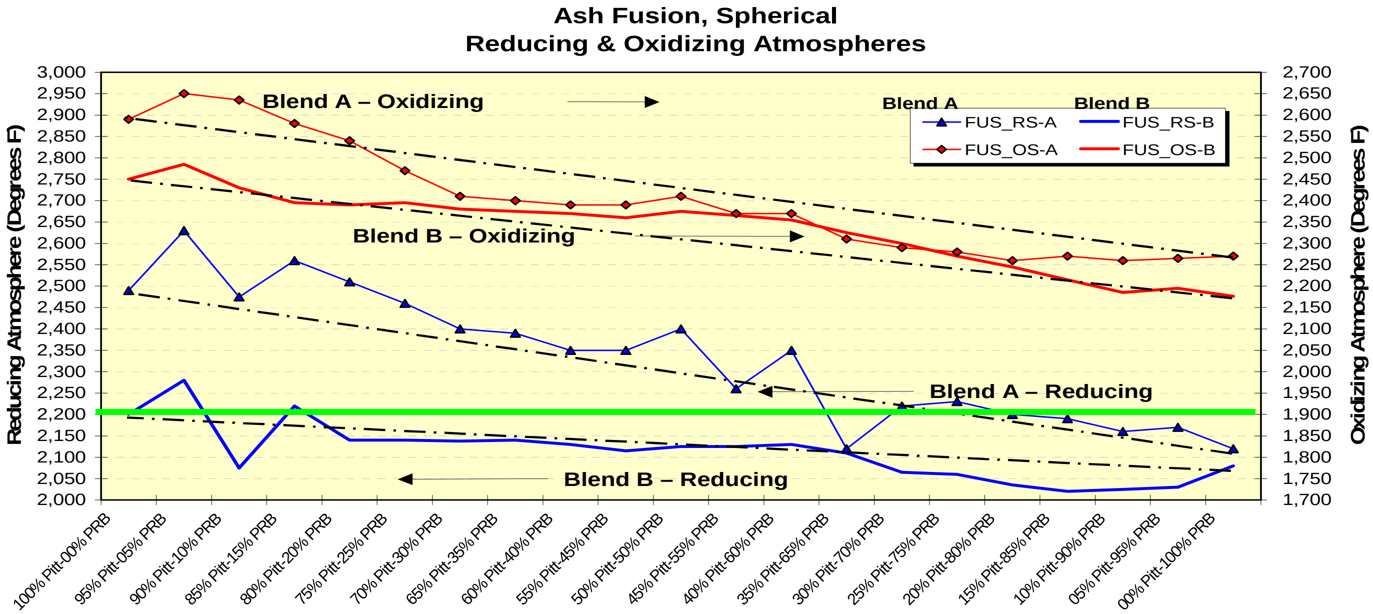
How Does the Choice of Fuel Effect Emissions & NOx


Ash Mineral — Acids (SiO2, Al2O3, TiO2)


Ash Mineral — Bases (Fe2O3, CaO, MgO, K2O, Na2O)

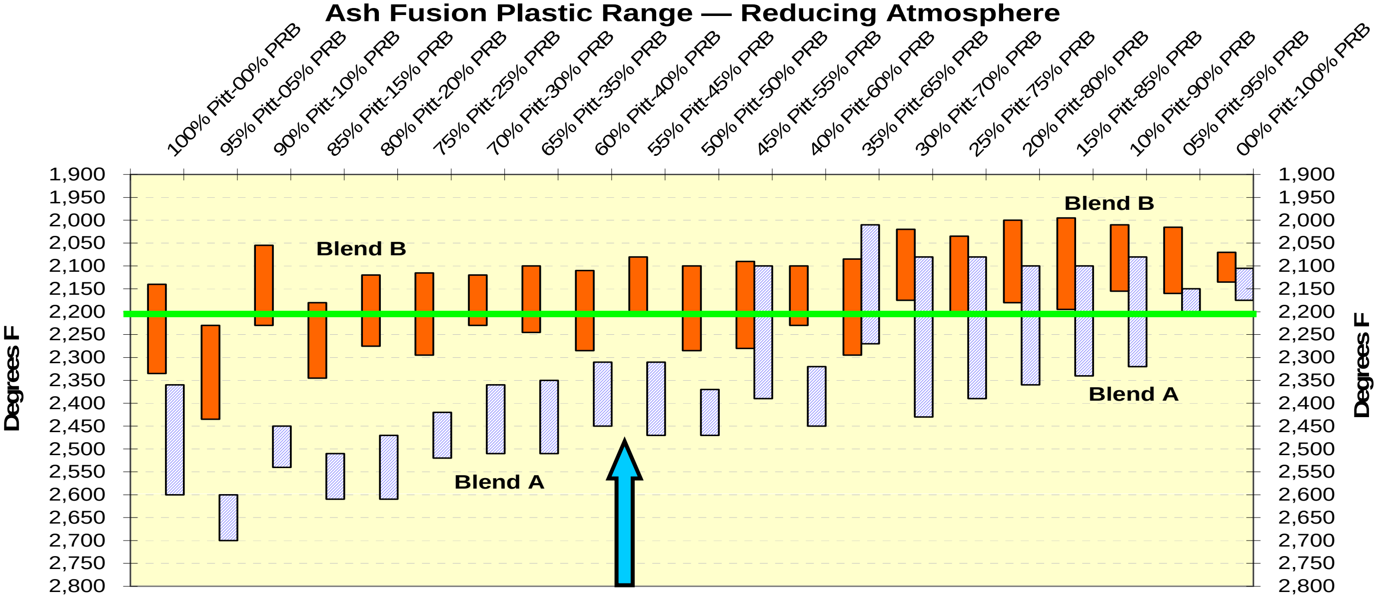
How Does the Choice of Fuel Effect Emissions & NOx


Ash Fusion, Initial Deformation
Reducing & Oxidizing Atmospheres

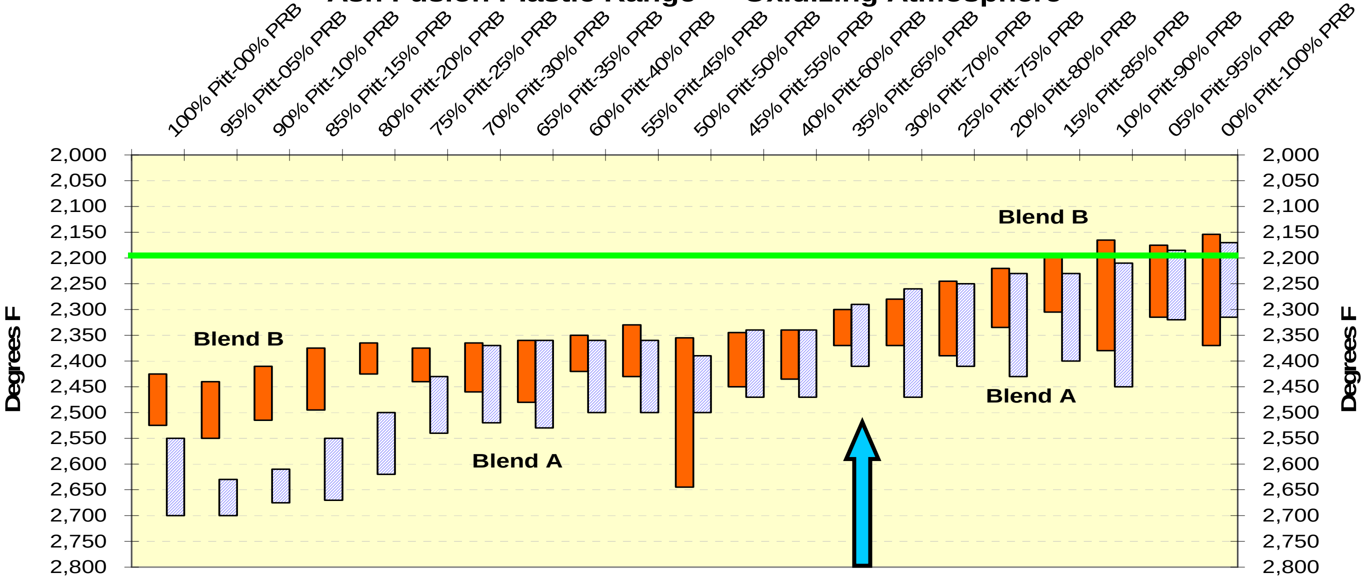

Ash Fusion, Spherical
Reducing & Oxidizing Atmospheres

How Does the Choice of Fuel Effect Emissions & NOx

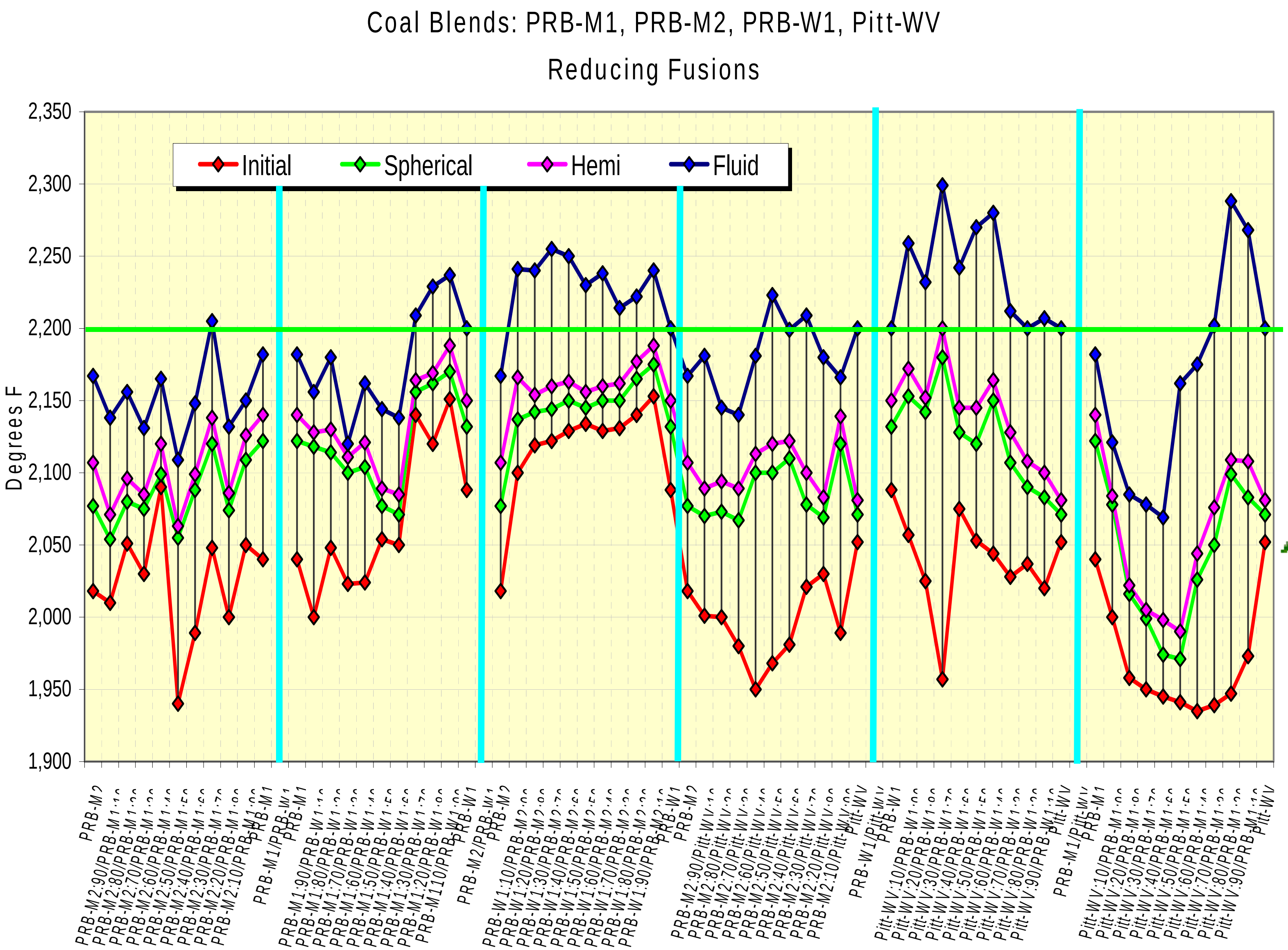
Ash Fusion Plastic Range — Reducing Atmosphere



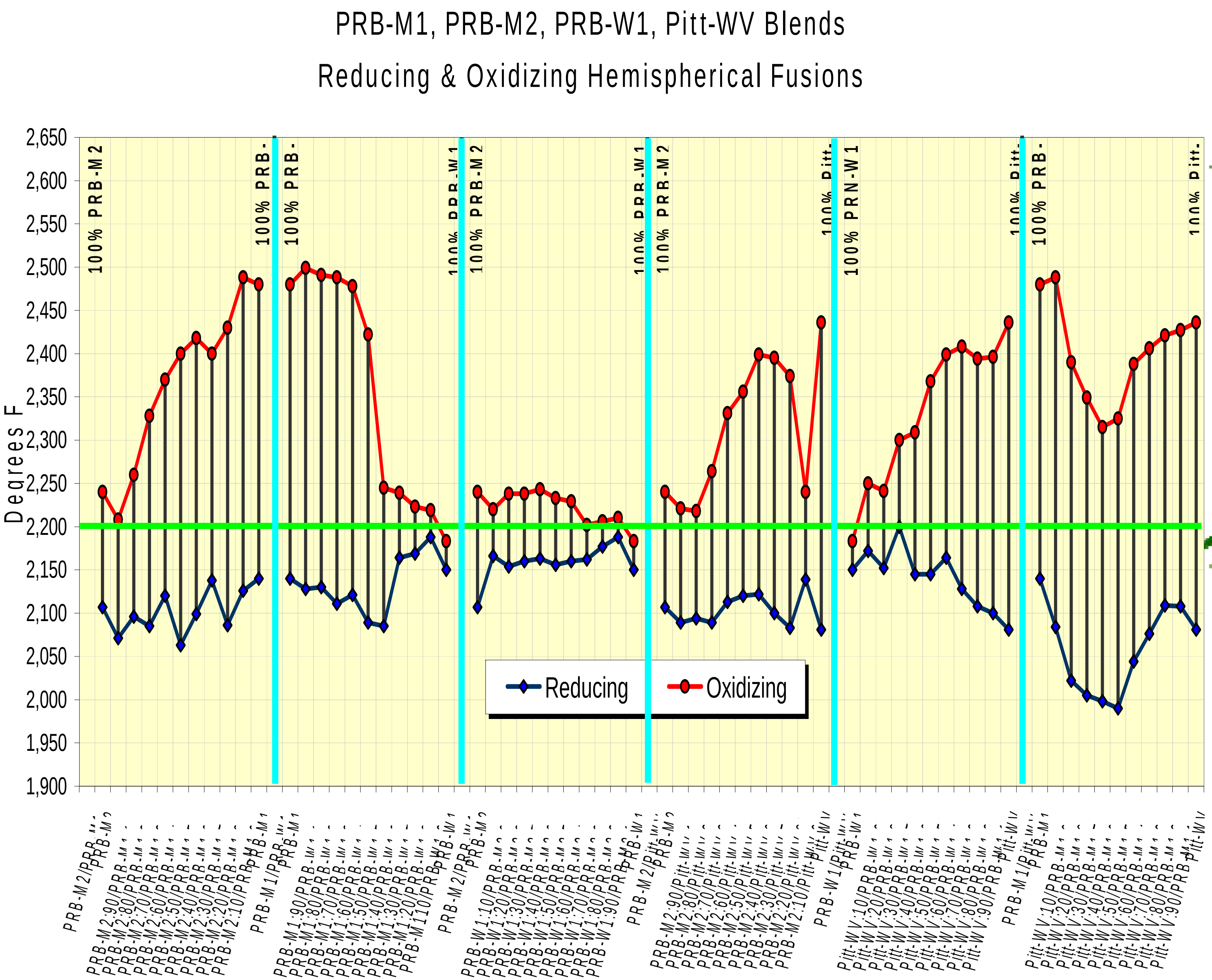
Ash Fusion Plastic Range — Oxidizing Atmosphere

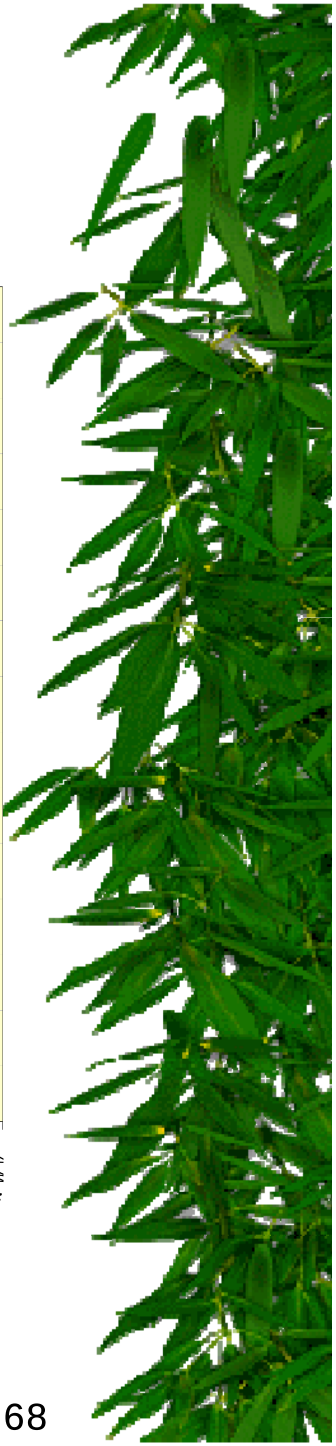


How Does the Choice of Fuel Effect Emissions & NOx



How Does the Choice of Fuel Effect Emissions & NOx





Coal Combustion

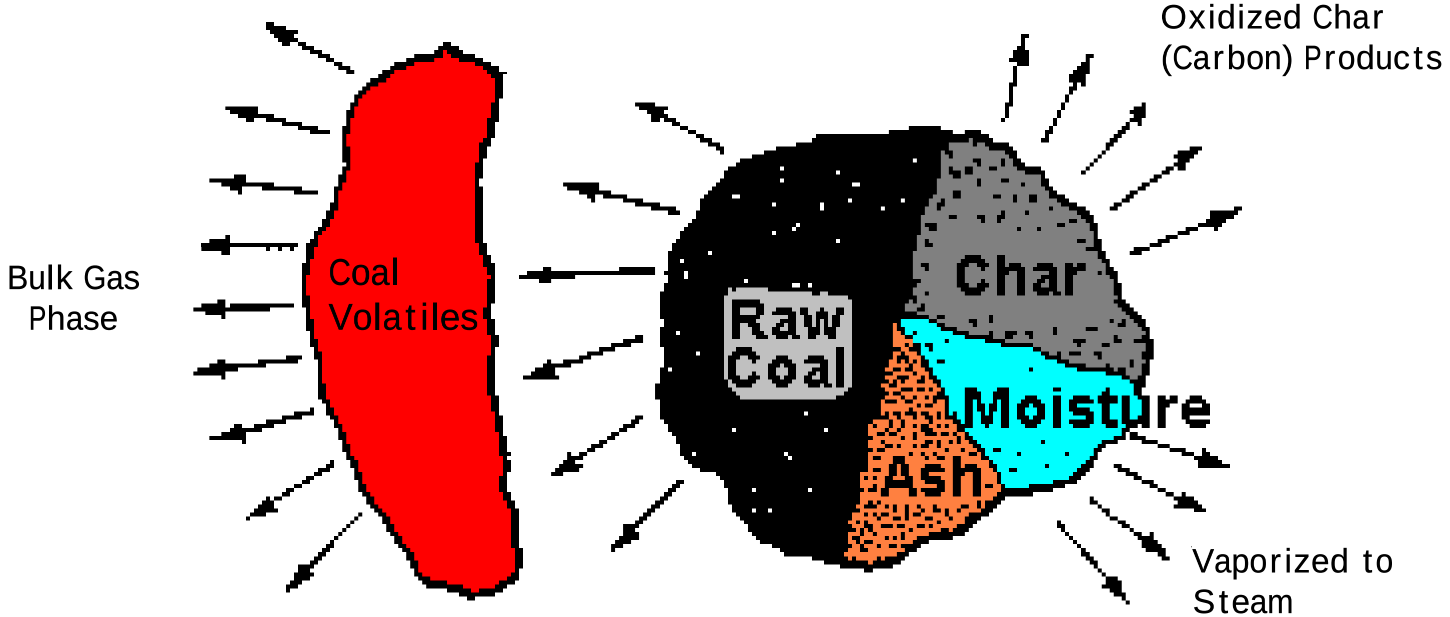
How Does the Choice of Fuel Effect Emissions & NOx

Chemistry of Coal Combustion

- **Particle size is the most important parameter** for the dominant reaction mechanism and other thermal behavior (rate of heating, which controls volatile yield and composition)

- Combustion consists of several steps
  - Moisture driven off as particle is heated
  - Particles undergo devolatilization & release volatile organics
    - Volatile matter combusted in gas phase (homogenous reaction)
  - Prior to or simultaneously w/combustion of char
    - Char is surface (heterogeneous) reaction
    - These reactions are mostly sequential and slowest will determine rate of overall process

Generalized Combustion Depiction



Lump of Coal

David Tillman, Fundamentals of Combustion Tutorial

Combustion Characteristics for Pulverized Coal Furnaces

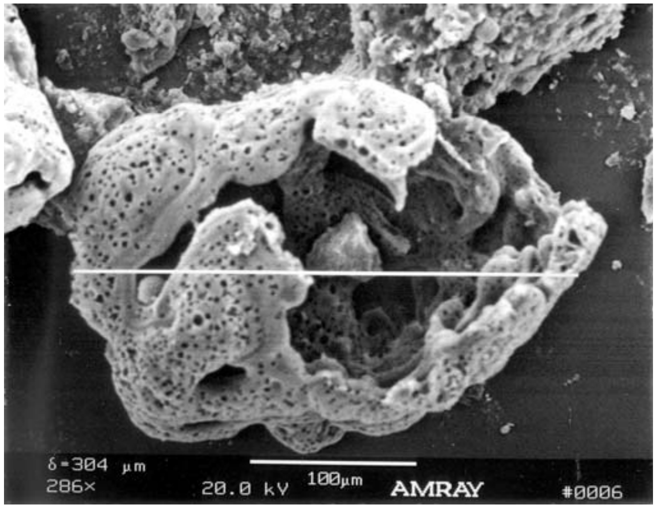
Particle size

~Top size	180 μm
Average size	45 μm
Combustion temperature	2700-3000 °F
Furnace temperature	>2200 °F
Particle heating rate	10^3–10^6 °F/sec

Reaction times

Volatiles	<0.1 sec
Char	1-2 sec
Reactive element	Chemically controlled combustion

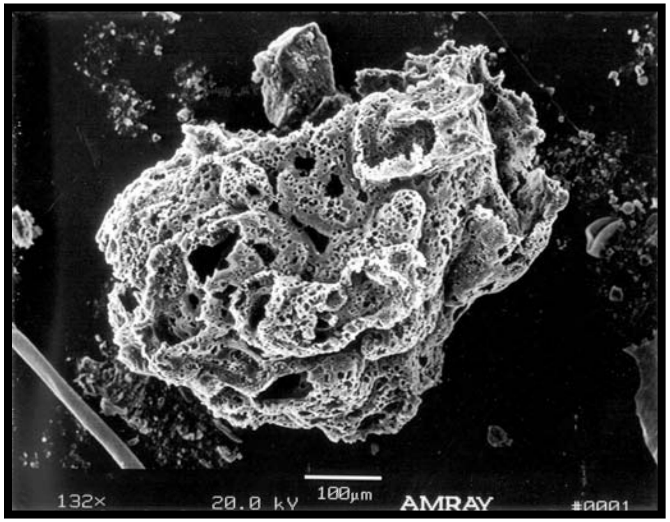
How Does the Choice of Fuel Effect Emissions & NOx



286X, SEM-photomicrograph
Partially Burned Coal Particle

Partially burned coal. Note the “popcorn” appearance.

Particle is about 304-μm across. Note the small seed-like ash particle in the center. Holes on the surface are made by escaping gases during combustion.



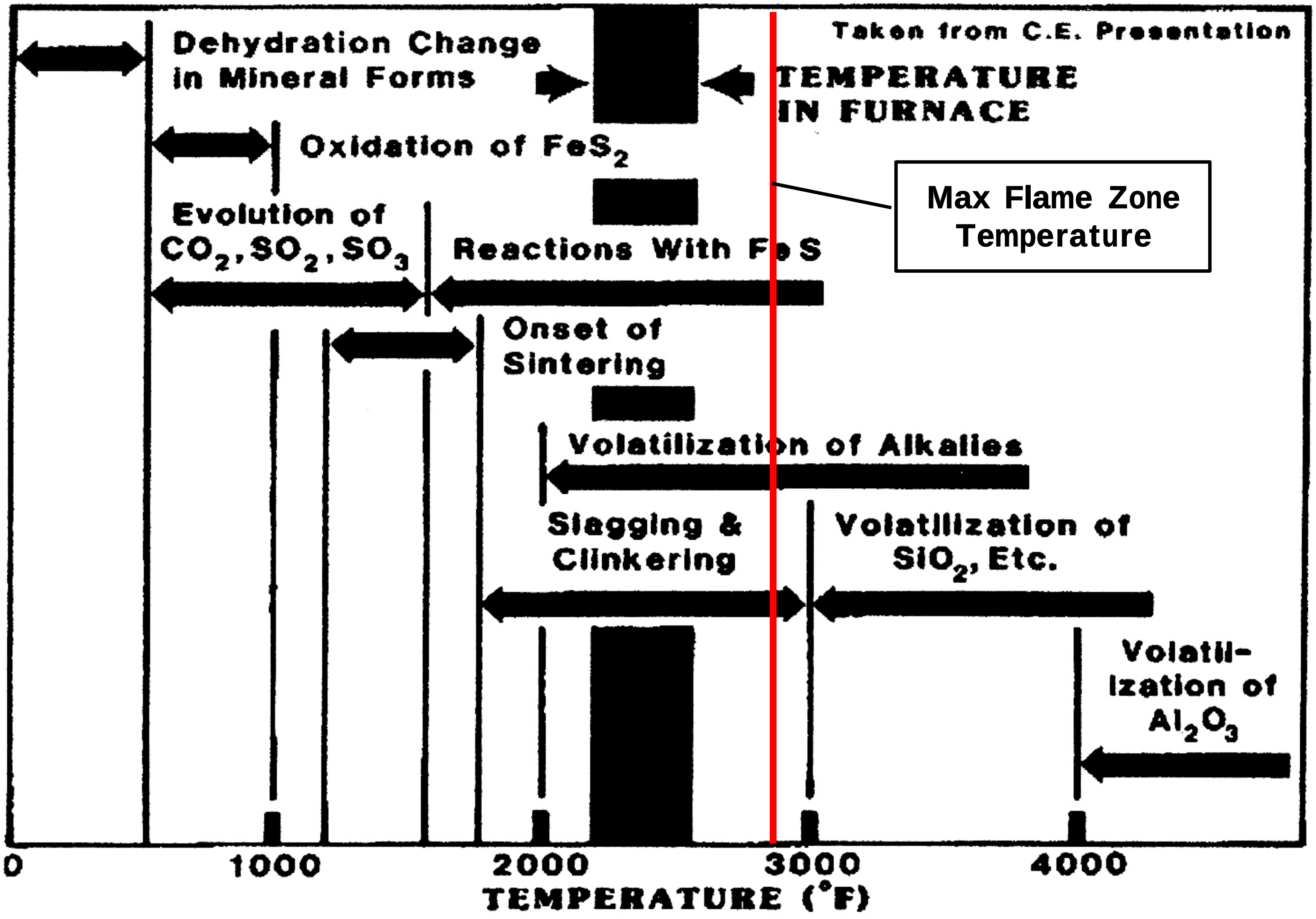
132X, SEM-photomicrograph
Partially Burned Coal Particle

Partially burned coal.

Particle is about 580-μm 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.

How Does the Choice of Fuel Effect Emissions & NOx

Chemical Changes in Coal Ash as a Function of Temperature



Source: *Routine Coal & Coke Analysis,* Dr John Riley, *pg 75, ASTM, 2007*

Coal Blending

- Many Characteristics Can be Averaged
- Critical Exceptions
  - **HGI**
  - **Ash Viscosity**
    - Non-Newtonian
    - Many Interdependencies
      - Gas Temperature & Atmosphere (reducing, oxidizing)
      - Formation Temperature
      - Heating and Cooling Rates
      - Elements and Compounds Originally Present
      - Reaction Mechanism
      - Reaction Rates
  - **Ash Fusion (indirect measure of slag viscosity)**
    - Seldom Linear with Temperature
    - Indirect Measure of Ash Viscosity
    - Eutectics

Representative Sampling

&

Accurate Weighing

You Can’t Control
What You Can’t Measure!

NOT

What number do you want?

Heat Rate

Heat Rate ≡ Btu/kWh

Where:

Btu = Total Btu for 1 hour

≈ Btu/lb * Tons for 1 hour

Where:

- **Btu/lb** = Heating value determined in laboratory from the sample provided by the customer representing 1 hour of burn
- **Tons** = total coal consumed in 1 hr

Where:

- **kWh** = Power output for 1 hour

How Does the Choice of Fuel Effect Emissions & NOx

To Do this

You Must Control Your Process

Samplers & Scales

Cannot cost justify via PV/C?

- ***f*(bias relative to zero)**
- **Seldom works out**
- **Why bother?**
    - Do you buy food or gasoline on approximate uncertified values?
    - What is the accuracy & calibration status of the MWh readout for each unit? I bet it is within the instruments limits of precision & is routinely calibrated
    - **Cost of doing business**
    - **Good business practice**

How Does the Choice of Fuel Effect Emissions & NOx

Sampling

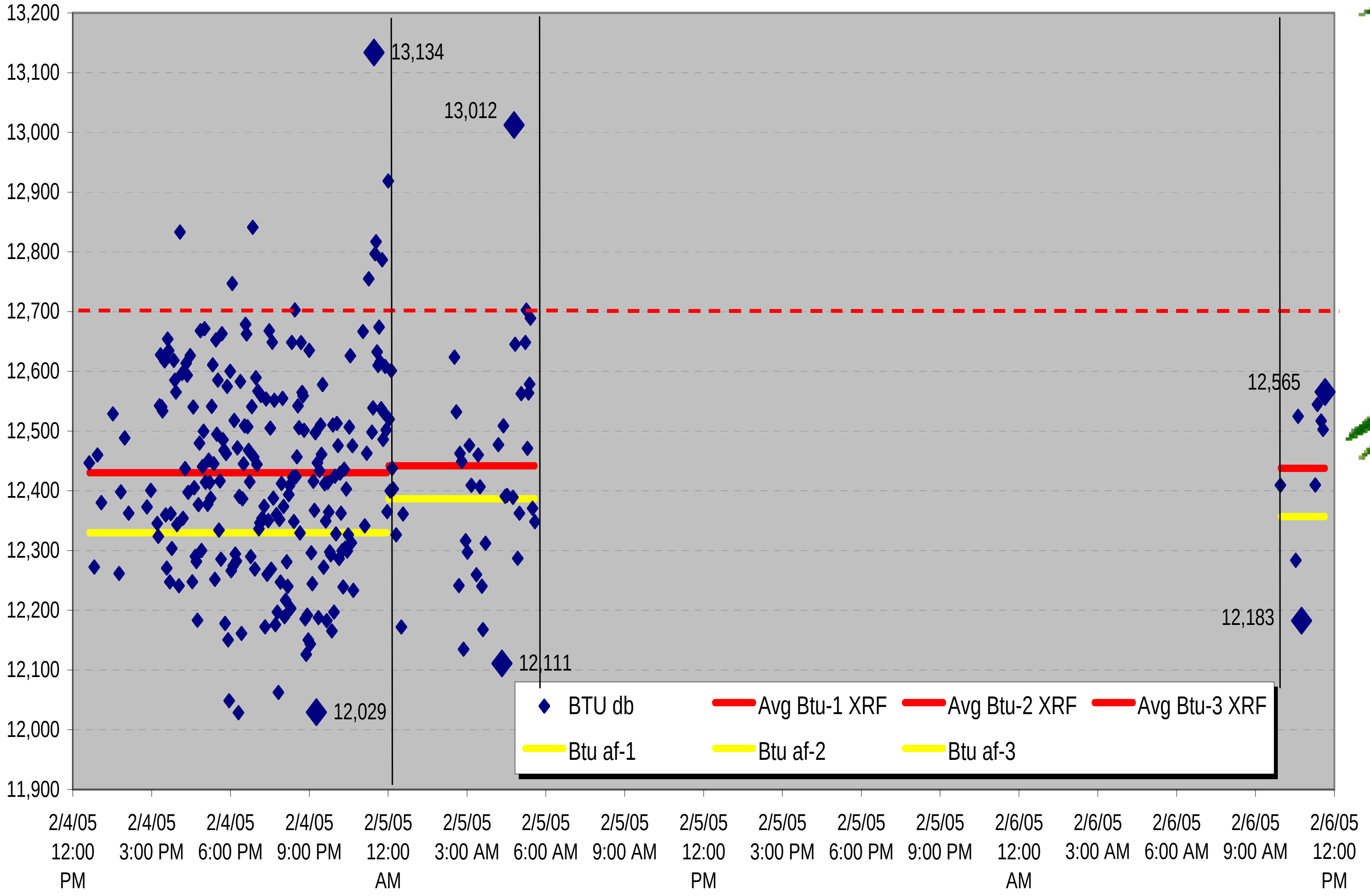
You Can't Control What You Can't Measure!

- **Representative Sampling — *MOST CRITICAL!***
  - Results based on sample received by laboratory
  - Critical for both gross and laboratory samples
  - Coal characteristics vary by particle size
  - Δ1% Moisture or Ash ~130-150 Btu/lb, ~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
    - Sample reports represent the **average** of the lot sampled
    - Both tails of the distribution exist
- **Causes of errors**
  - Laboratory. 5%
  - Sample Preparation. 15%
  - Sampling. 80%

How Does the Choice of Fuel Effect Emissions & NOx

Heating Value — Lab vs. On-Line Analyzer

(After Initial Calibration)



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

- **Effects**
  - Corporate, Regulatory, Government
  - Industry Statistics & Records
  - Production Cost, Dispatch Order, Sales
  - Performance Measurement & Accurate Cost Accounting (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*-Lbs of steam, not *x*-tons to make *y*-Lbs of steam
- To determine accurate Total Btus, a representative sample must be collected

Discussion of Sampling Errors

- Moisture, ash, sulfur, heating value & other coal characteristics reported by the lab from a sample are NOT "TRUE" values. They are only characteristics of the sample
- It is important to your company's bottom line that processes associated with coal quality measurement be conducted in such a way that measurement errors are small enough to meet the requirements of the end uses of the reported data
- Measurement bias must be eliminated or reduced to the smallest level possible. A 1% moisture or ash bias (loss or gain) will result in the over/under stating of cost

How Does the Choice of Fuel Effect Emissions & NOx

- **Operation**
  - Equipment is serially dependent
  - Improper or insufficient maintenance causes frequent sampler failure, low availability & biased results
  - Changing one setting, changes all down stream values
    - Primary cutter(s), primary-save conveyor, sample crusher, secondary-save conveyor, secondary sampler, reject system

- **Sampler Bias Testing**
  - Stop-Belt vs. Other Sampling Methods
  - Statistical Population (based on normal distribution)
  - Mechanical Sampler “Certification”
  - Accepted Bias at the 95% Confidence Level

- **Effects**
  - Corporate, Regulatory, Government
  - Industry Statistics & Records
  - Production Cost, 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

ASTM Sampling Requirements

ASTM D7256 & D7430

- Criteria of Satisfactory Performance
  - Unbiased sample at the desired degree of precision
  - Sampling systems should be give a rough performance check as a matter of routine. This is done by comparing the weight of the collected sample with that of the total coal flow to assure a constant sampling ratio
- Relative Location of Sampling & Weighing
  - The coal should be weighed and sampled at the same time
- Mechanical Features
  - Is essential that the system as a whole, including the sample cutters, chutes, conveyors, crusher and other parts within the system be self-cleaning & non-clogging and be designed in a manner that will minimize the need for other than preventive maintenance

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, Stacked Weights (also certification)
    - Belt Weights (approximate, and not certifiable)
    - Chains (approximate, 1-5%)

- All weights must be traceable to NIST reference weights
    - NIST Handbook 44

  (http://ts.nist.gov/WeightsAndMeasures/h44-07.cfm)

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
- To determine total Btus, accurate total tons is required

So, how do you use your fuel to reduce emissions and NO_x formation:

- Reduce fuel N
- Reduce excess air (reduce O_2)
- Maintain mills to spec for the fuel you are burning
    - EVERYTHING starts with the fuel and then the mills
    - Downstream outages follow from poor mill & burner performance
- Reduce boiler related O&M >25%
- Go back to combustion & boiler fundamentals
    - Stop trying to add band aids
- **Emissions & NO_x are reduced by increasing efficiency & decreasing heat rate**

How Does the Choice of Fuel Effect Emissions & NOx

Now, let's go over the fuel analysis shown at the start of today's tutorial

How Does the Choice of Fuel Effect Emissions & NOx

Coal Analysis

Mine/Supplier:	Pittsburgh Seam	Sampling Method:	Mechanical
Sample #:	99F-00852	Sample Date:	2/25/1999
Sample Description:	S> 1.7%	Sample Receipt:	2/26/1999

Proximate	As=Received	Dry	MAF
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	
Heating Value	13,376	14,010	15,080

ADL	2.30
Residual Moisure	2.27

Moisture Load	3.38
Ash Load	5.07
SO2	3.07
V/FC	0.63

Ultimate	As=Received	Dry	MAF
Carbon	75.23	78.82	84.84
Hydrogen	5.00	5.24	5.64
Nitrogen	1.45	1.52	1.64
Oxygen	4.97	5.21	5.61

Hardgrove Grindability Index

HGI	**50.8 @2.89% Moisture**

How Does the Choice of Fuel Effect Emissions & NOx

Coal Analysis

Mine/Supplier:	Pittsburgh Seam	Sampling Method:	Mechanical
Sample #:	99F-00852	Sample Date:	2/25/1999
Sample Description:	S> 1.7%	Sample Receipt:	2/26/1999

Ash Fusion - 8 point	Reducing	Oxidizing
Initial	2,209	2,535
Spherical	2,280	2,575
Hemispherical	2,372	2,595
Fluid	2,460	2,665
Plastic Range	251	130

Ash Mineral

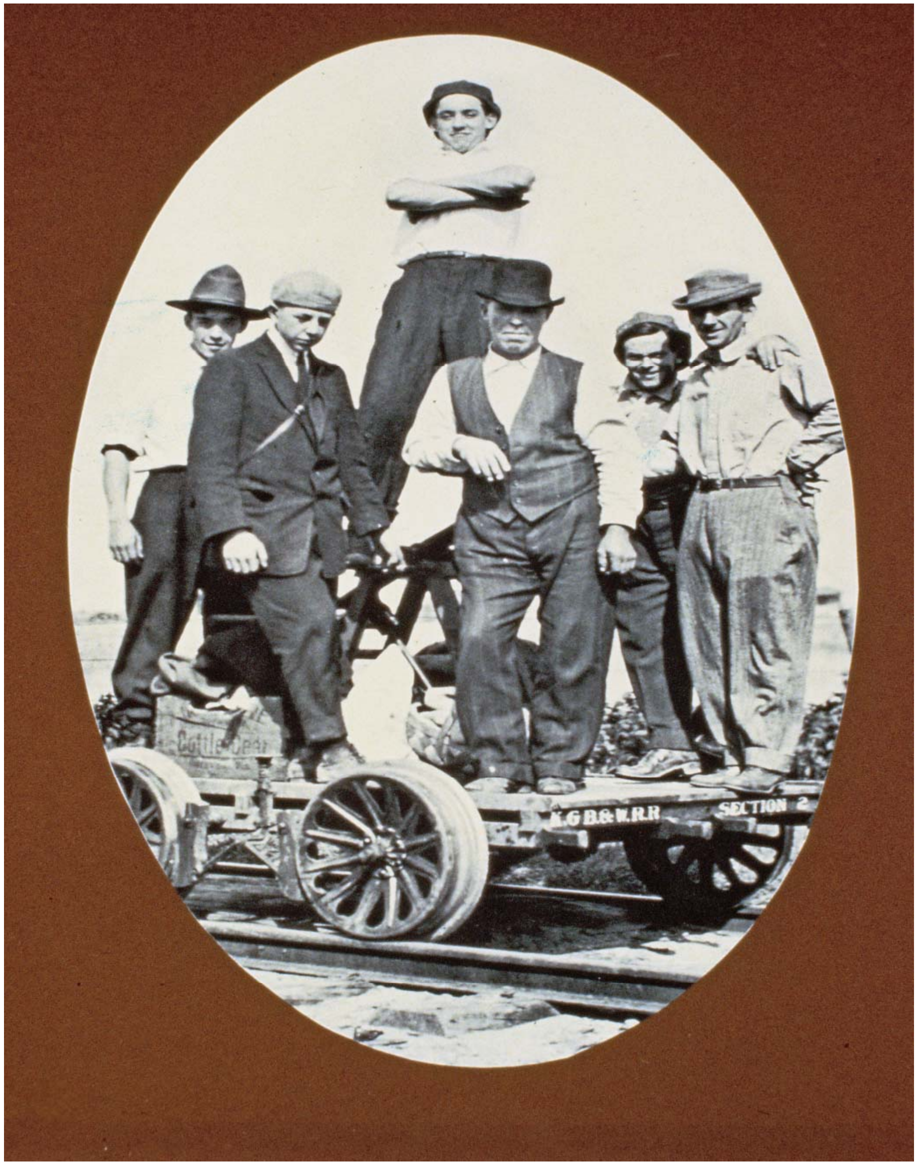
SiO2	50.52
Al2O3	23.10
TiO2	0.93
Fe2O3	15.63
CaO	2.64
MgO	0.78
K2O	1.94
Na2O	0.56
SO3	1.25
P2O5	0.35
BaO	0.26
SrO	0.81
MnO2	0.01
Undetermined	1.22

B/A	0.29
Ash Ratio	0.22
Ash Type	Bituminous
Slagging Index	1
Slagging Type	Medium
Fouling Index	0.16
Fouling Type	Low
Silica Ratio	0.73
Si/Al	2.19
Fe/Ca	5.92
Dolomite %	15.87

Trace Elements	*Units*	*Value*		*Units*	*Value*		*Units*	*Value*
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, Thalium	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						

How Does the Choice of Fuel Effect Emissions & NOx

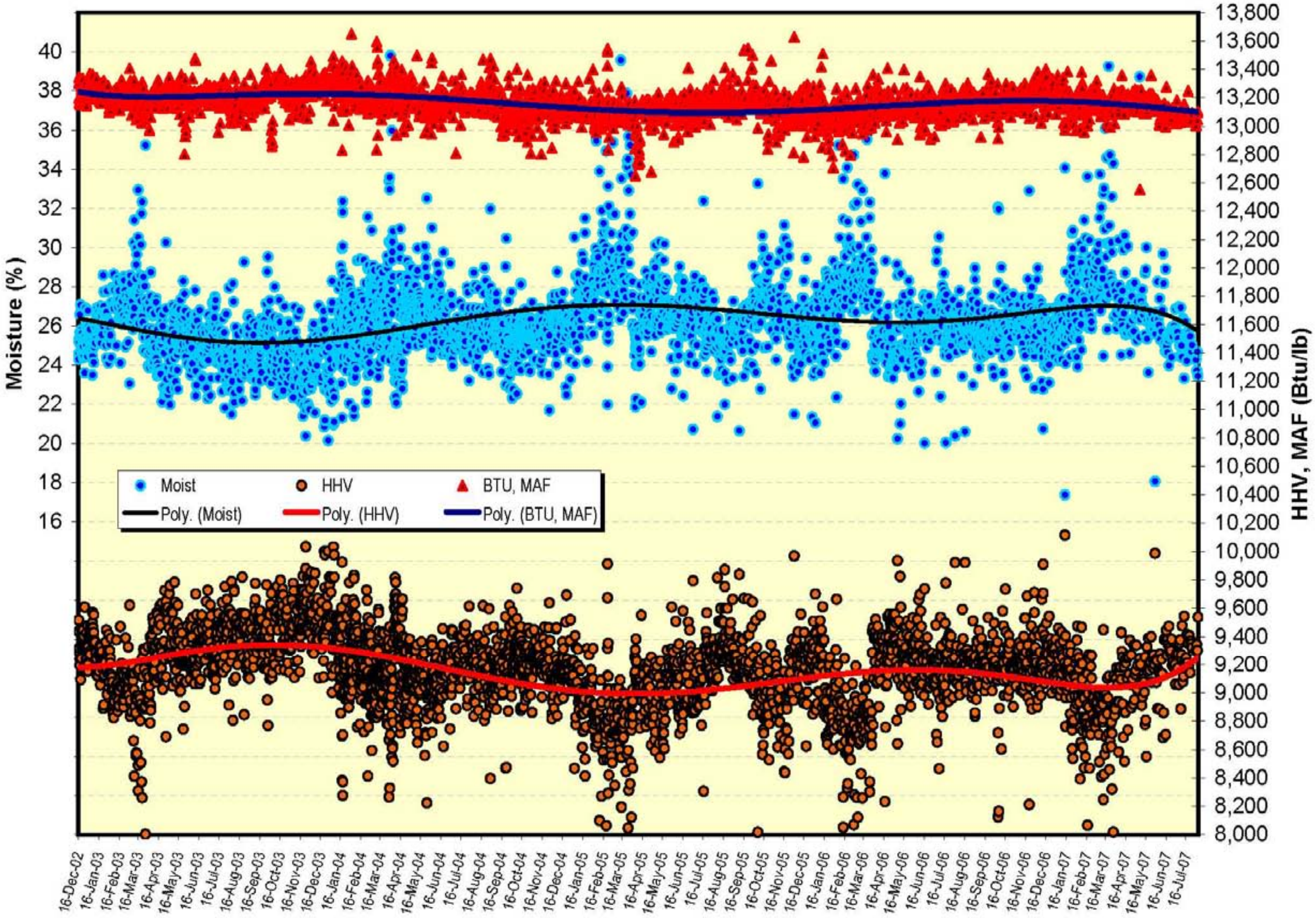
Thank You!



Characteristics of Various US Coals

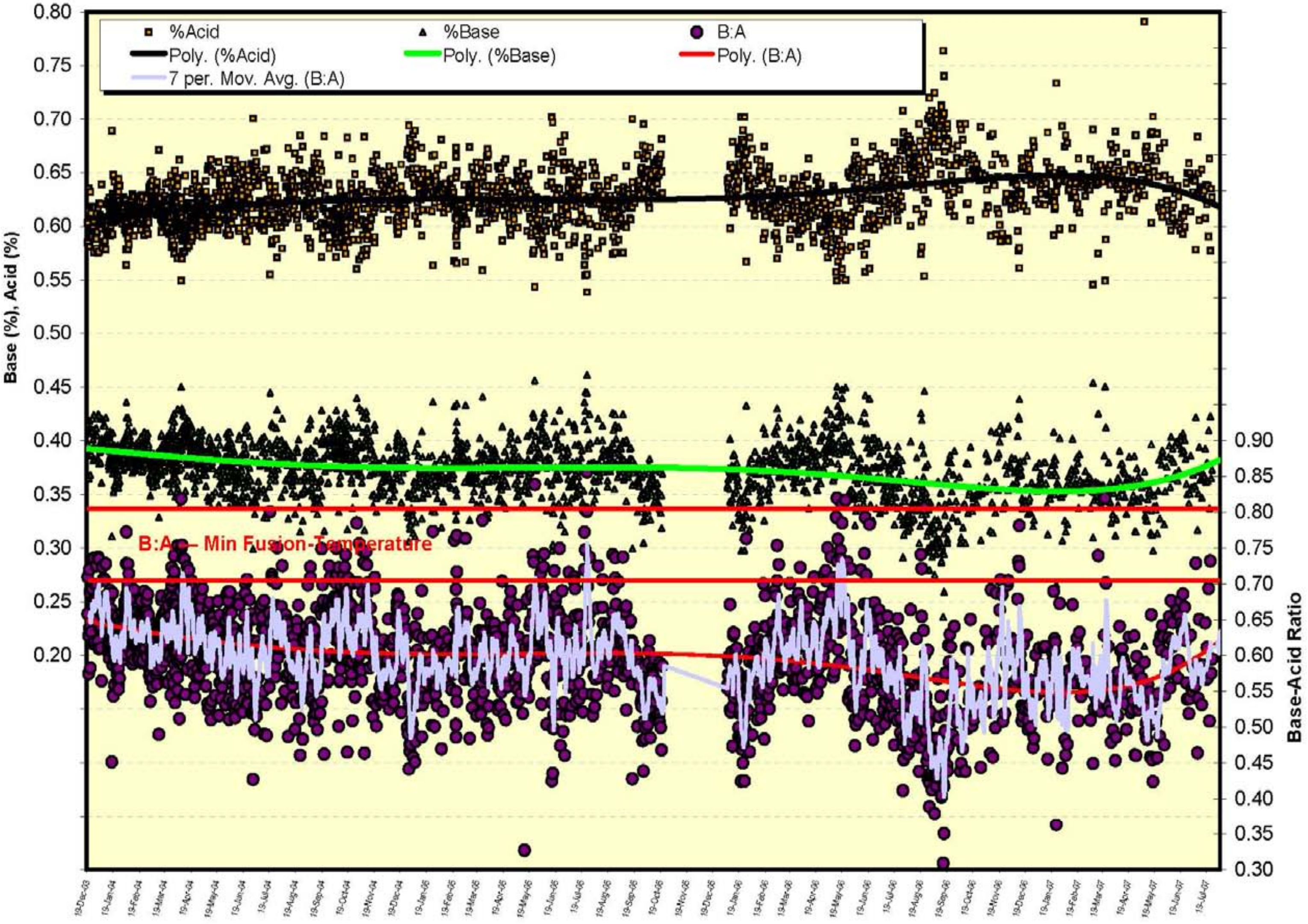
How Does the Choice of Fuel Effect Emissions & NOx

Moisture, HHV, MAF

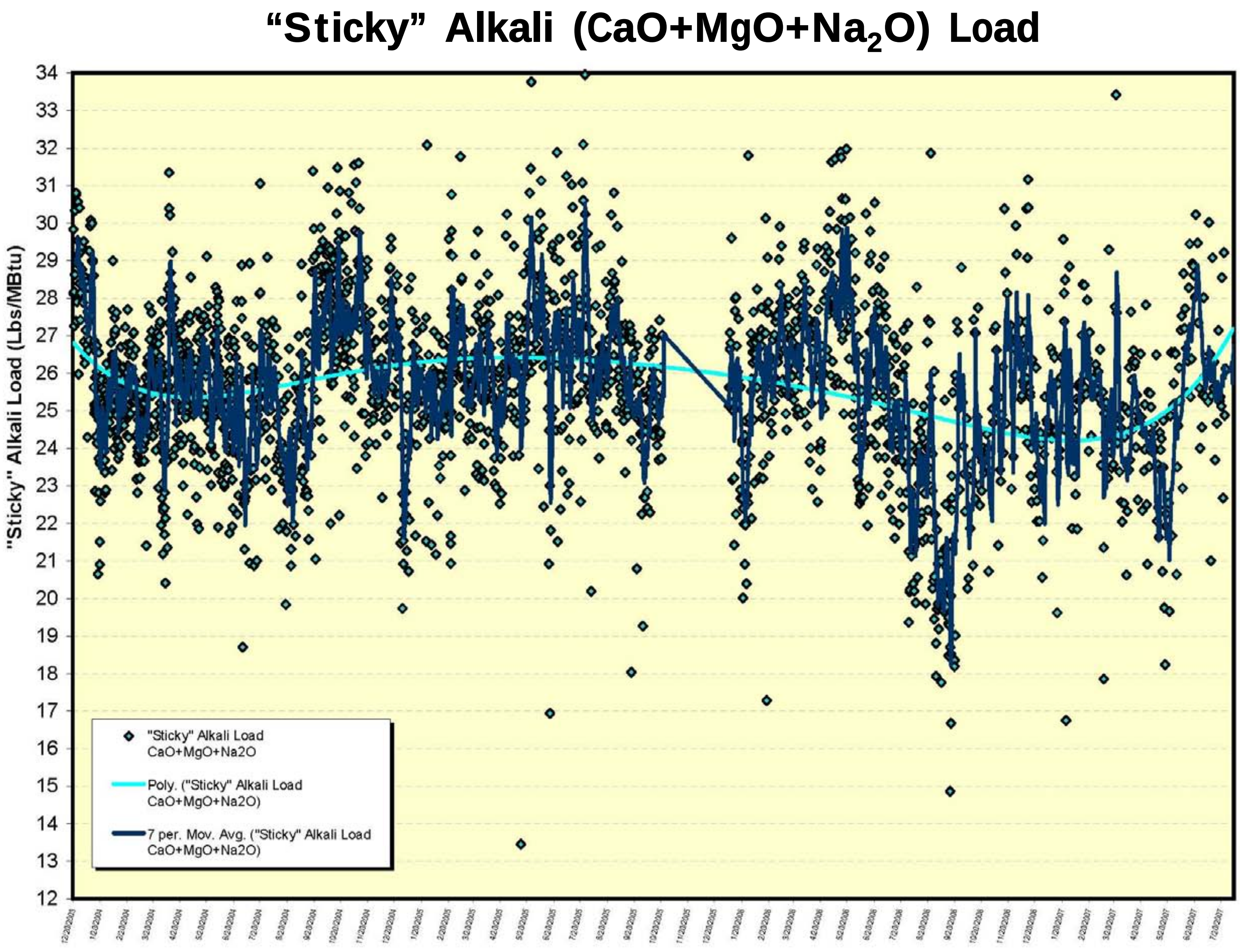


How Does the Choice of Fuel Effect Emissions & NOx

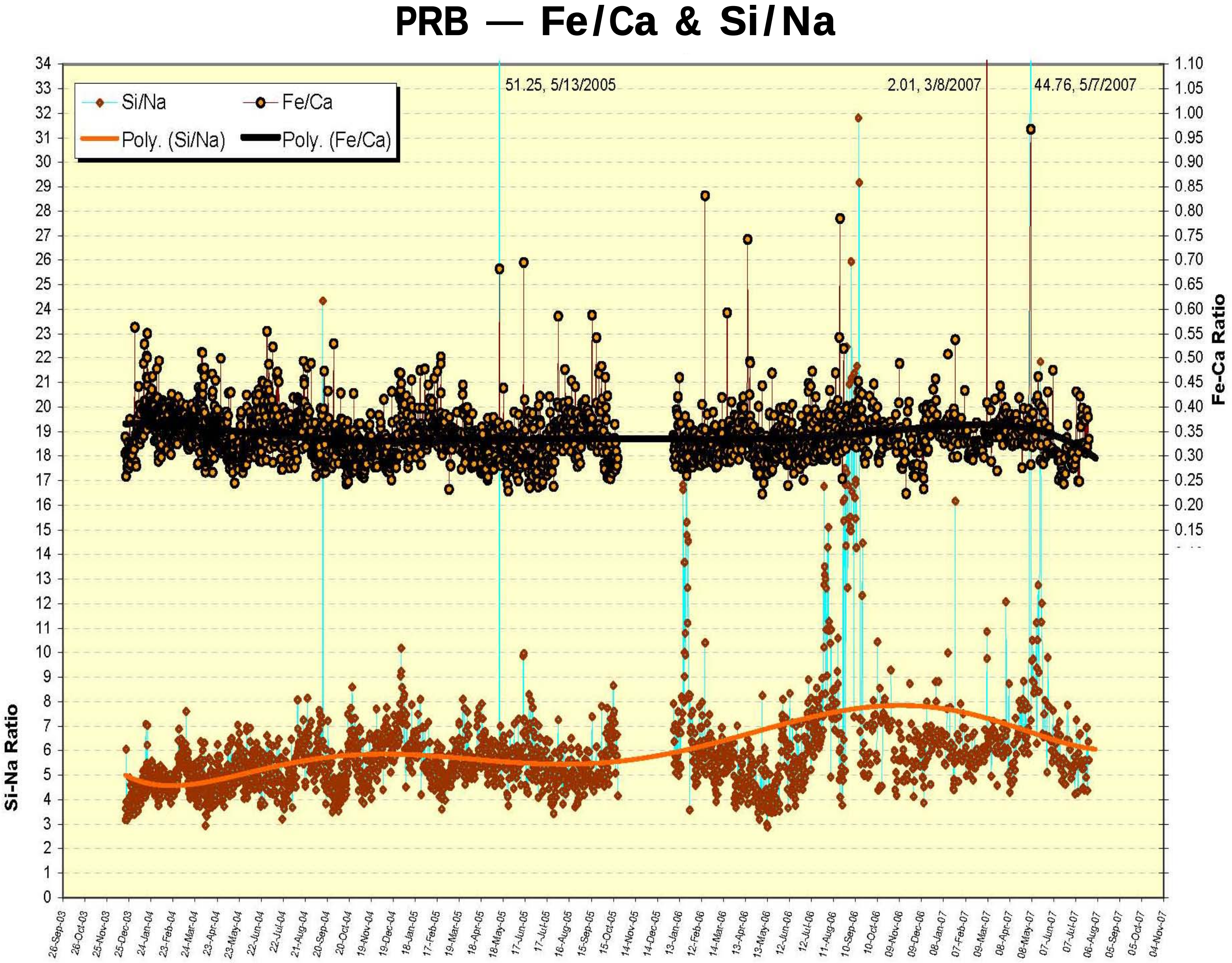
% Base, % Acid, Base-Acid Ratio



How Does the Choice of Fuel Effect Emissions & NOx



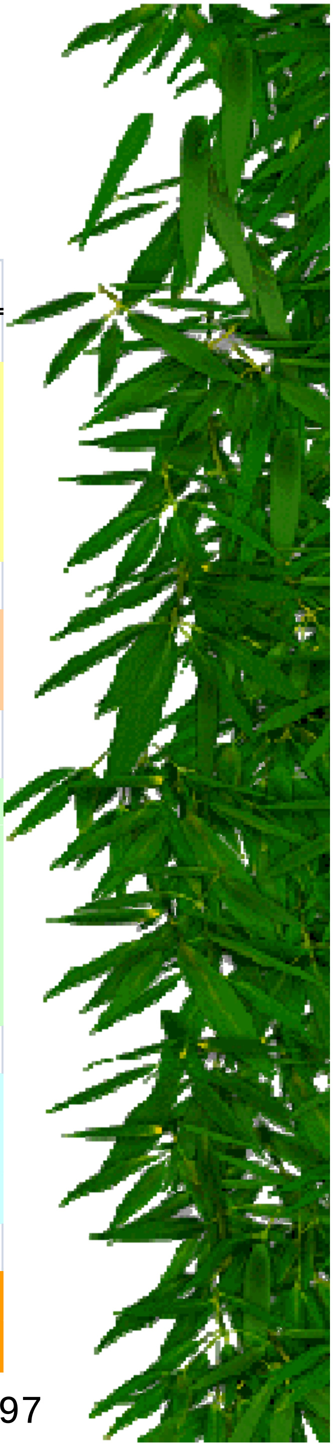
How Does the Choice of Fuel Effect Emissions & NOx



How Does the Choice of Fuel Effect Emissions & NOx

Proximates of Various US Coals

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



How Does the Choice of Fuel Effect Emissions & NOx

Ultimate (dry) & HGI of Various US Coals

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

How Does the Choice of Fuel Effect Emissions & NOx

Ash Mineral of Various US Coals

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

How Does the Choice of Fuel Effect Emissions & NOx

Ash Fusion of Various US Coals

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