REINHOLD ENVIRONMENTAL Ltd.

2013 NOx-Combustion Round Table & Expo Presentations

February 18 & 19, 2013, in Salt Lake City, UT / Hosted by PacifiCorp

Welcome

&

Good Morning!

Now that you've had a great breakfast, get another cup of coffee, boot your computer or tablet or if you are technically challenged, a pen/pencil and paper, and a buddy to keep you awake

Tony Widenman

Fossil Fuel Consultant

Reinhold Environmental

313-819-8191
ajw3fuel@att.net

Tutorial Objectives

— PART I —

Coal Analysis Fundamentals

— PART II —

How correct interpretation of fuel analyses is critical to the understanding of combustion, material handling, engineering design & problem-solving

What is coal?

It's definitely not just black and burns

References

- MNL 61, Guide to ASTM Test Methods for the Analysis of Coal and Coke 2008, R. A. Kishore Nadkarni, ASTM, 2008

- MNL 57, Routine Coal & Coke Analysis: Collection, Interpretation, and Use of Analytical Data, Dr. John T. Riley, ASTM, September 2007

Definitions of Coal

- **A brown or black combustible sedimentary rock (in the geological sense) composed principally of consolidated and chemically altered plant remains.** (ASTM D0121)

- 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)

- Coal is a chemically and physically heterogeneous, “combustible,” sedimentary rock consisting of both organic and inorganic material (Miller)

PANGAEA
Early Triassic, 237 Ma

Image source: www.Scotese.com

- Coal
  - Black (or brown, gray)
  - Burns (usually with difficulty)
- Age & Geology
  - 300-250 million – 20 million years ± few million years

Coalification

Era	Period	Approximate mean age (10^6 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

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

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

Composition

(%wt DMMF Basis)

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

- Increasing Aromatization & Loss of Oxygen with Time

Hypothesized Coal Structures

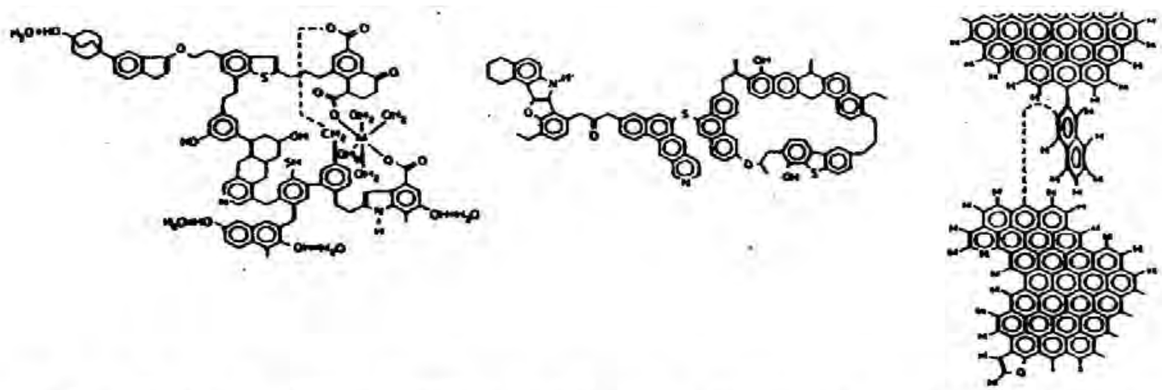


Figure 13. Spiro and Kosky (1982) models for a low-, intermediate-, and high-rank coal.

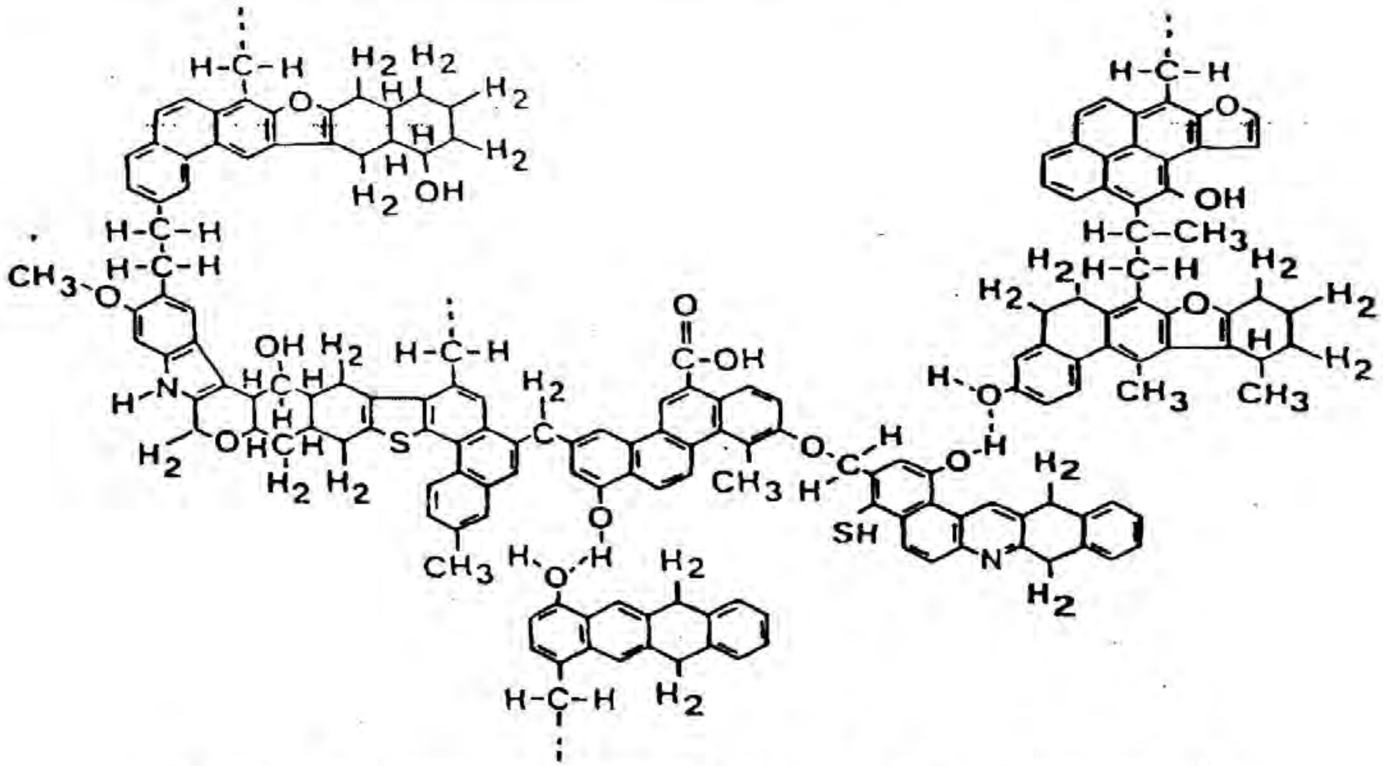
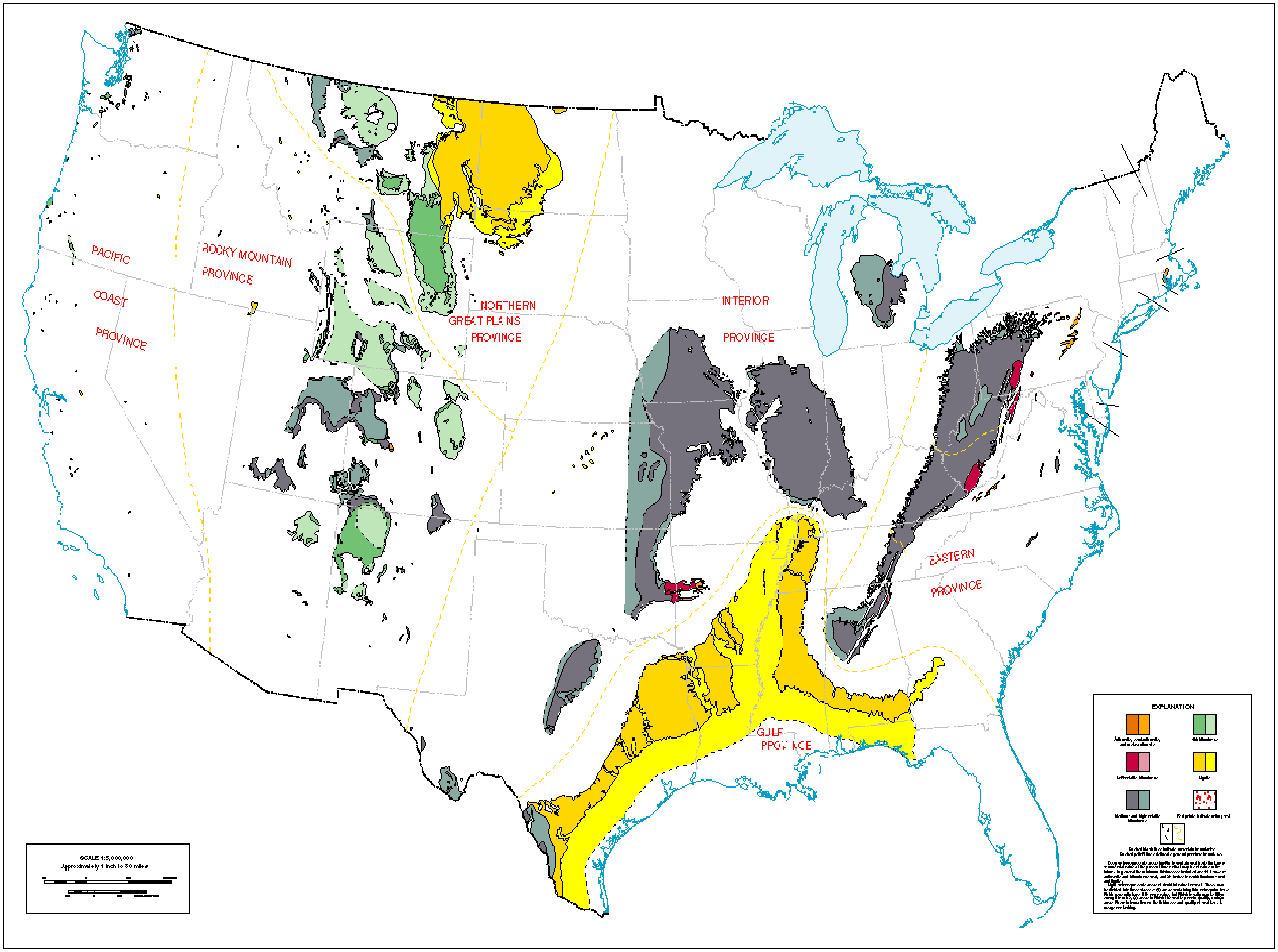
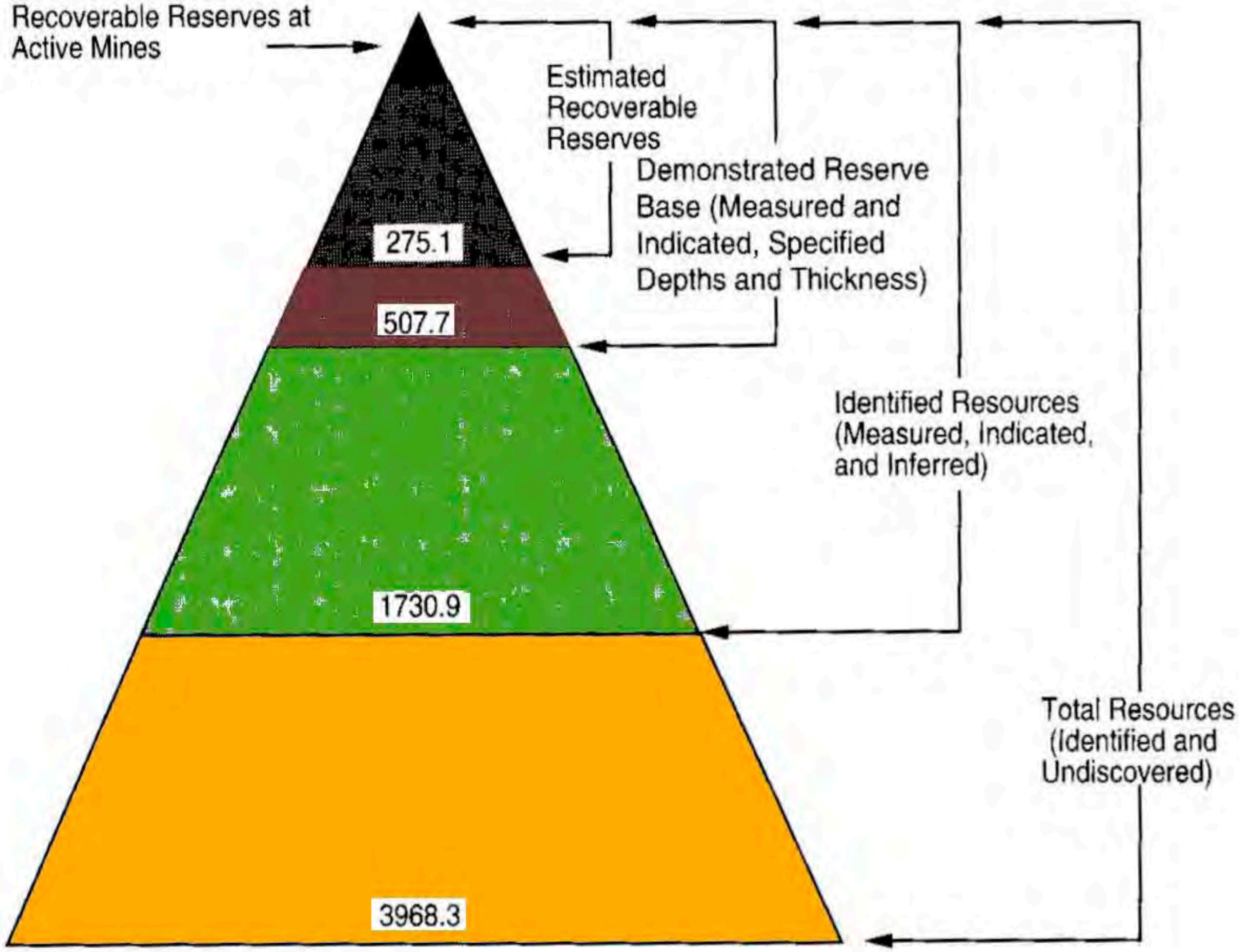


Figure 12. The Solomon (1981) model of a Pittsburgh high-volatile bituminous coal.

Coal Deposits in the USA

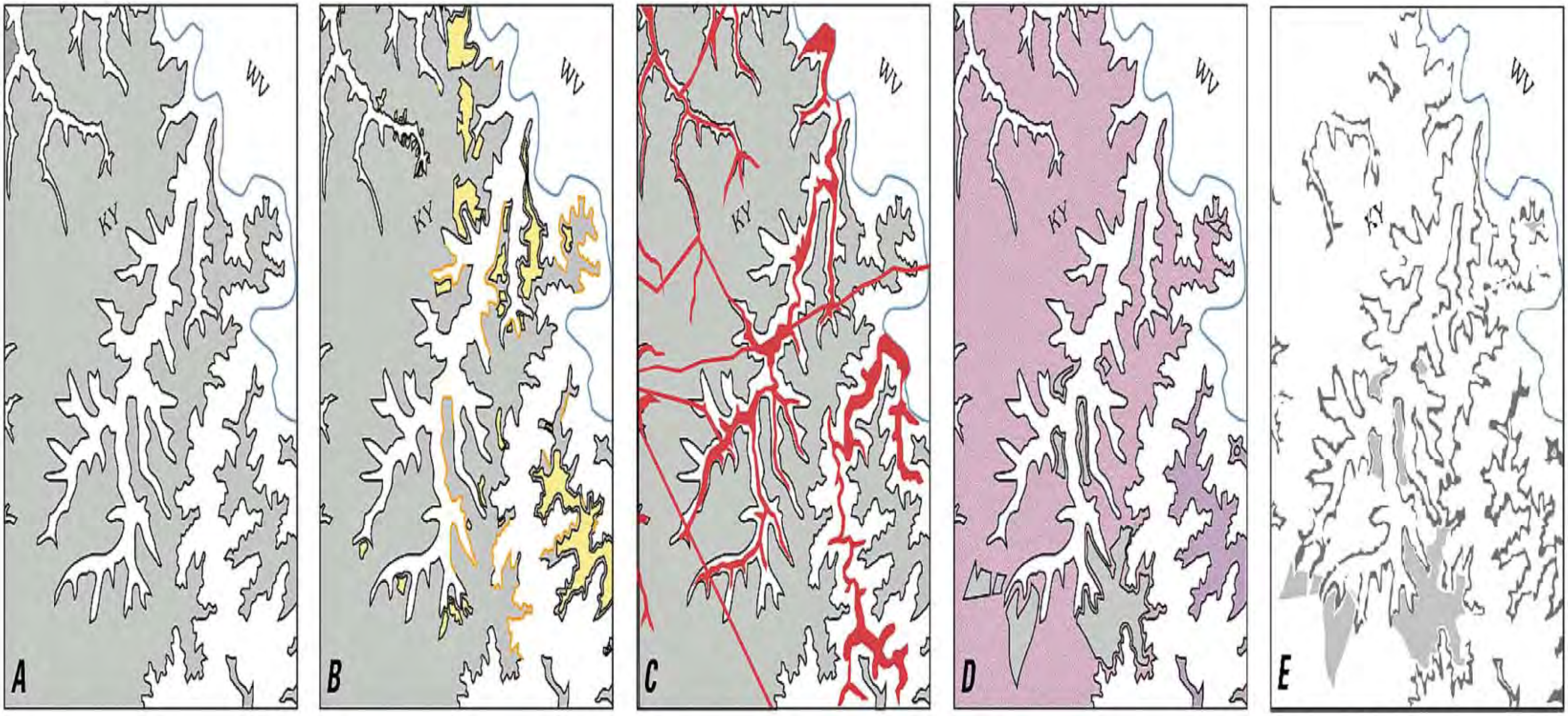


US Coal Resources & Reserves



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.)

Reserves vs. Resources



Coalbed occurrence

Underground mined coal

Surface mined coal

Land-use/Environmental restrictions: powerlines, pipelines, cemeteries, oil and gas wells, streams, towns.

Technological/Geologic restrictions: abandoned mines; areas too shallow or too deep to be underground mined; coal too thin.

Surface minable

Underground minable

Coal Seam — PRB

Coal Seam — Pittsburgh (Northern Appalachia)

[700 Feet Deep]

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)

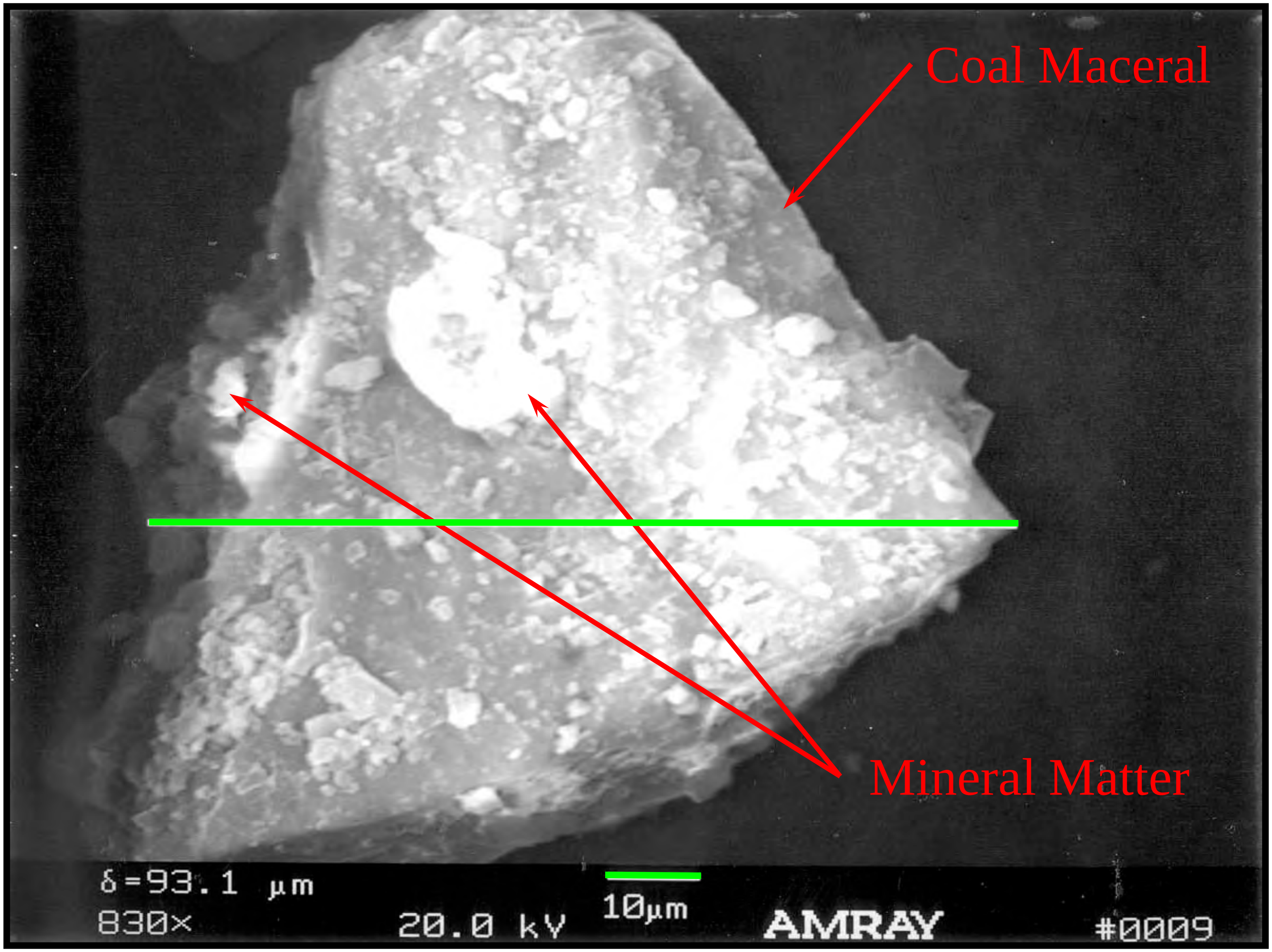
Mineral Matter (ash)

- 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

SEM Photomicrograph of Coal Particle



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

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

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 (diff) (%) (+)	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
Equilbrium Moisture (%)	1.73
Surface Moisture (%)	2.84
Moisture Load (lbs/MBu)	3.38
Ash Load (lbs/MBu)	5.07
SO2 (lbs/MBu)	3.07
V/FC (fuel)	0.63
FC/V (combustion)	1.59

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 (diff) (%)	4.97	5.21	5.61

Hardgrove Grindability Index

HGI	50.8	@ 2.54% Moisture

Coal Analysis

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Sample Description:	S> 1.7%	Sample Receipt:	2/26/1999

ASH FUSION - 8 point

	Reducing	Oxidizing
Initial (°F)	2,209	2,535
Spherical (°F)	2,280	2,575
Hemispherical (°F)	2,372	2,595
Fluid (°F)	2,460	2,665
Plastic Range (°F)	251	130
T250 (°F)	2,530	

ASH MINERAL (Dry Ash Basis)

SiO2 (%)	50.52	% Acid	77.58%
Al2O3 (%)	23.10	% Base	22.42%
TiO2 (%)	0.93	B/A	0.29
Fe2O3 (%)	15.63	Ash Ratio	0.22
CaO (%)	2.64	Ash Type	Bituminous
MgO (%)	0.78	Slagging Index	0.56
K2O (%)	1.94	Slagging Type	Medium
Na2O (%)	0.56	Fouling Index	0.16
		Fouling Type	Low
SO3 (%)	1.25		
P2O5 (%)	0.35	Silica Ratio	0.73
BaO (%)	0.26	Si/Al	2.19
SrO (%)	0.81	Fe/Ca	5.92
MnO2 (%)	0.01	Dolomite %	15.87
Undetermined (%)	1.22	ESP Index	74

Proximate & Short Prox

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

Included by convention

- MAF Heating Value
- Moisture Load
- Ash Load
- SO_2
- Volatile/Fixed Carbon

Proximate

- [-] Moisture
- [-] Ash (really Mineral Matter)
- [+] Volatile (gas)
- [+] Fixed Carbon (char)

- Calorific Value (HHV)
- Sulfur

- Moisture Load (lbs SO_2/MBtu)
- SO_2 (lbs SO_2/MBtu)
- Ash loading (lbs ash/MBtu)
- Volatile / Fixed Carbon
- C + H + N + O + …

Coal Analysis Standard Tests

Total Moisture

- Must determine ADL & Residual Moisture (M_R)
  - $M_T = (M_R * (100 - ADL) / 100) + ADL$

    Where:

    ADL = Air Dry Loss

    M_R = Residual Moisture

- DO NOT confuse
  - ADL with Surface Moisture
  - Residual Moisture with Inherent or Equilibrium Moisture
  - They are NOT the same

Ash With Your Coal? — No Thank You!

Coal Analysis Standards Tests

Ash & Ash Load

Potential back-end grain loading is based on ash load, not % Ash.

- **ƒ**(particle size, ash deposition rate & ash viscosity)

Lbs Ash/MBtu ≡ Ash% * 10,000 / Calorific Value (Btu/lb)

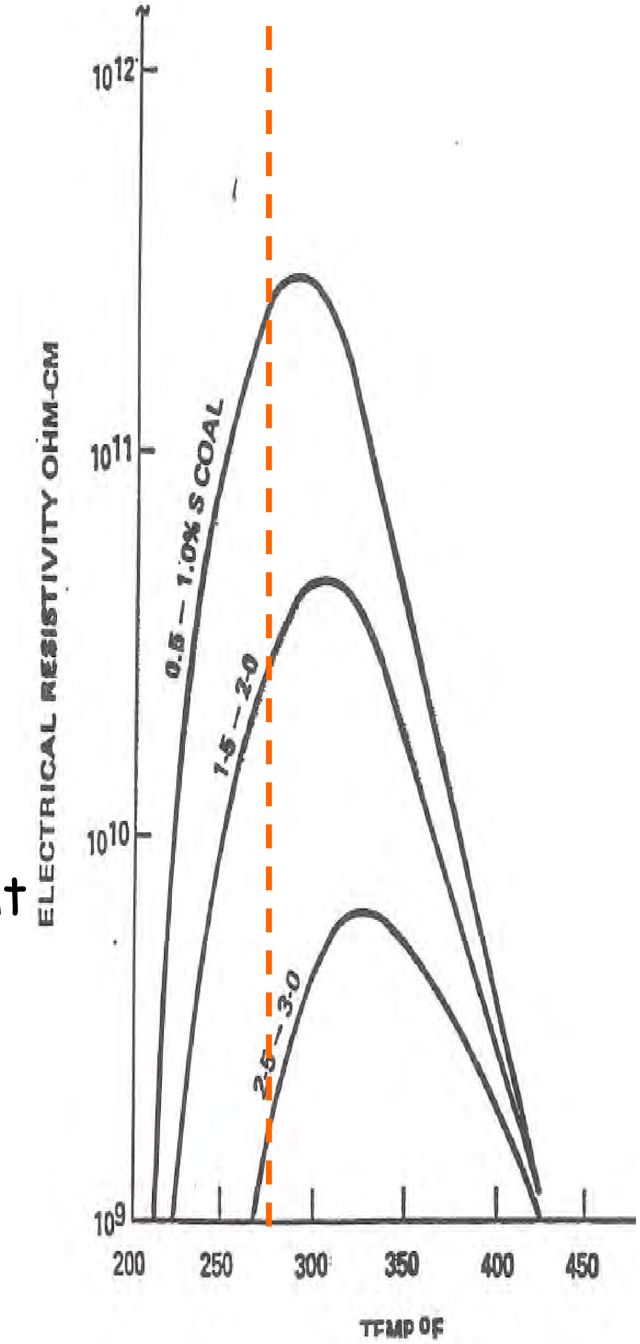
- 6.4% Ash @8,000 Btu/lb = **8.0** lbs Ash/MBtu
- 8.0% Ash @10,000 Btu/lb = **8.0** lbs Ash/MBtu
- 9.6% Ash @12,000 Btu/lb = **8.0** lbs Ash/MBtu

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 hold more ash in furnace and pendants in the form of slag
  - Low rank coals (PRB) have finer fly ash than high rank
- Fly Ash Sales effected by S, Ca, Na+Mg, C, SO_3
  - Class C & Class F Fly Ash
  - C: concrete air entrainment & appearance
  - S, SO_3: concrete strength
  - Ca: concrete pozzalonic properties
  - Na+Mg: concrete strength

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 its 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 – re-entrainment
- Base %*: <15, good; 15-40, medium; >40, poor
- Base/Na_2O*: <20, good; 20-30, medium; >30, poor
- K_2O*: <1, good
- CaO+MgO*: >20 poor

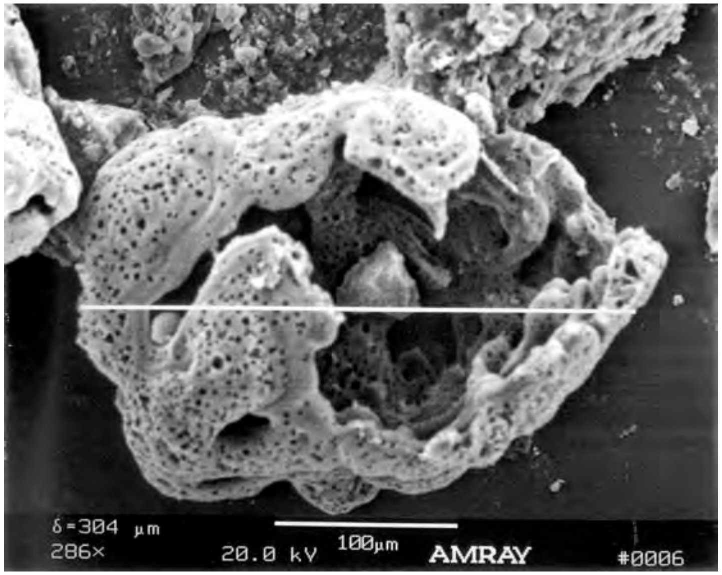


* Source: *Routine Coal & Coke Analysis,* Dr John Riley, *pg 74, ASTM, 2007*

Coal Analysis Standards Tests

Volatility & Fixed Carbon

- Volatile is the gaseous material that evolves ~300-500°F and burns by diffusion
  - Provides heat for char oxidation
- Fixed Carbon (by difference)
  - Carbon char burns by oxidation heated by burning volatile fed by O in fuel and O_2 in air
  - $C \leftrightarrow CO \leftrightarrow CO_2$
- Volatile/FC ["fireball" location driver]
- Coal Volatility
  - High-Vol (>28%) [steam coal]
    - If 3<FSI<7, could be met-coal
  - Mid-Vol (20%-28%) [met-coals, sometimes steam coal]
  - Low-Vol (<20%) [met coals]



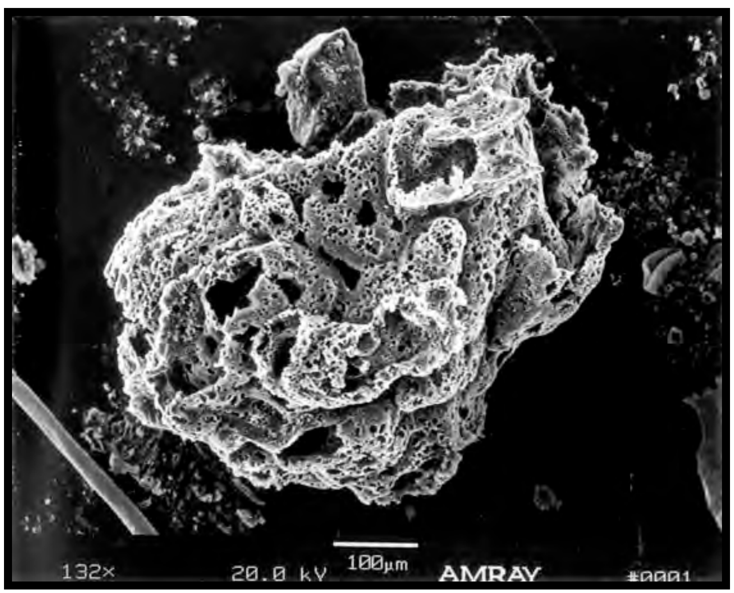
286X, SEM-photomicrograph

Char Particle

Char.

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

Char Particle

Char.

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.

Coal Analysis Standards Tests

Sulfur & SO_2

Air emission regulations are based on SO_2, not % Sulfur, although the regulations seldom state it this way.

$$\text{Lbs } SO_2/\text{MBtu} \equiv S\% * 20{,}000 / \text{Calorific Value (Btu/lb)}$$

- 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

Btu (Heating Value, Calorific Value)

- **As-Received**
  - Contractual, regulatory
  - HHV (higher heating value)
  - Performance
- ***As- Determined***
  - *All calculations are based on these values*
  - *Laboratory basis*
  - *Seldom reported*
  - *Air-dried only*
- **Dry**
  - Lab comparison
  - Quality comparison
  - Corrects for moisture bias
- **MAF**
  - Fingerprint
  - Theoretical total energy
    - volatile + fixed carbon
    - C + H + N + O + …

Ultimate

- Moisture
- Ash
- Sulfur
- Carbon
- Hydrogen
- Nitrogen
- *Chlorine*
- Oxygen (diff)

Atomic Ratios

- H:C
- O:C
- N:C

Coal Analysis Standards Tests

Ultimate (C, H, N, O)

- Performance calculations (as-fired basis)
- Fuel rank & comparison (dry basis)
  - **C** (55-98%)
  - **H** (3-5%)
  - **N** (0.5-2%)
  - **O** (2-25% calculated by difference)
    - **O** difference =
      100 – (Moisture + Ash + S + C + H + N + Cl + …)
- Combustion reactivity calculated from **H:C** & **O:C** atomic ratios

Coal Analysis Standard Tests

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 and "Sticky Alkali" Loads
- Fe/Ca
- ESP Index

Coal Analysis Standard Tests

Ash Mineral (continued)

- Slagging & Fouling Predictors
- Base-Acid Ratio
  - $(Fe_2O_3 + CaO + MgO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2)$
- Fe, Na, Ca, Mg, K (contributes to plastic-phase deposition)
- Minimum fusion temperature, B:A ~ 0.6-0.8
- High slagging probability, B:A ~ 0.4-1.2
- Highly resistant to collection, B:A < 0.2
  - Silica vs. Silicates or “glass” vs. clay
  - Material handling & combustion considerations
- Na (vapor deposition, especially MT-PRB)
- Fe & Ca act as fluxes to depress the ash’s melting temperature
- S generally trends with Fe (especially bituminous coals)
- Na, organic vs. inorganic compounds

Mineral Melting Temperatures 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*

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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*

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-	$\sim K(Al,Fe)_4(Si,Al)_8O_{20}(OH)$	
	Chlorite	$(MgFeAl)_6(SiAl)_4O_{10}(OH)_8$	
	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

Coal Analysis Standard Tests

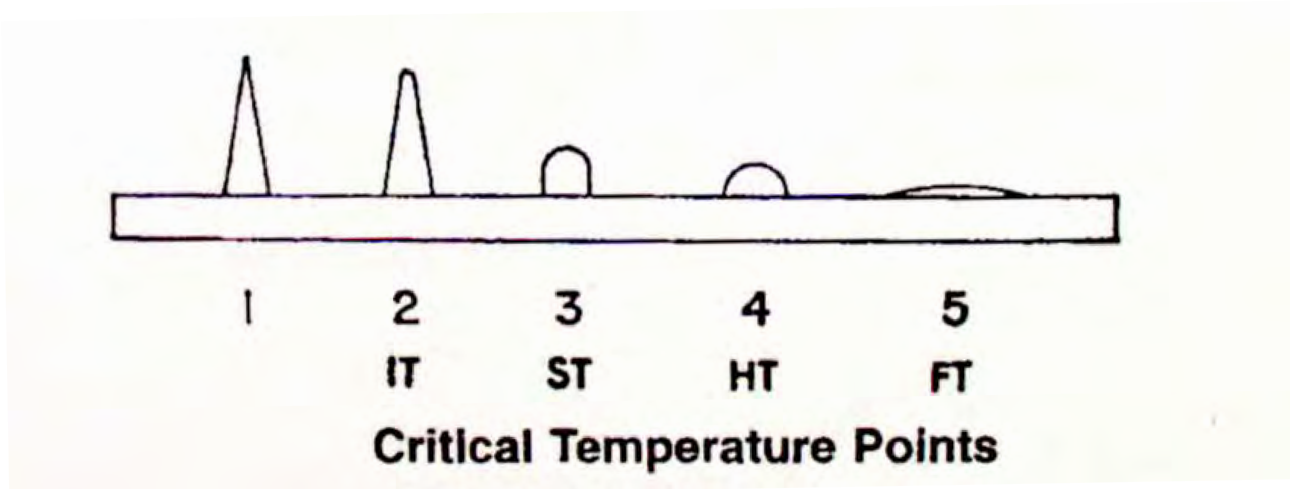
Ash Fusion

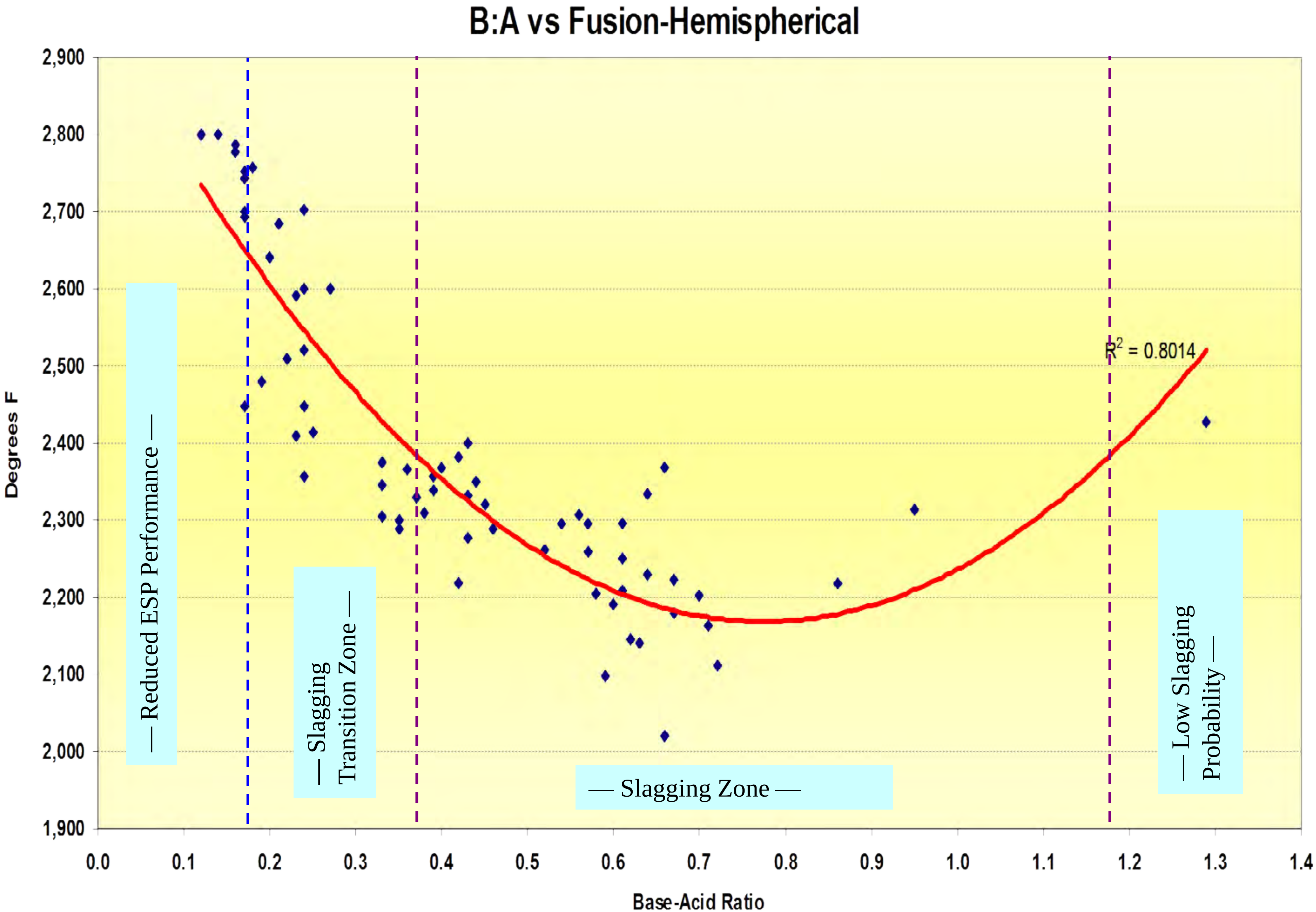
- Slagging & Fouling Predictor
  - Eutectics & Eutectoids in blends
- Plastic Deformation
  - Initial Deformation
  - Spherical Softening
  - Hemispherical Softening
  - Fluid

- Plastic range (fusion box) (Δ fluid - initial deformation)
- Both oxidizing (air) & reducing (60/40 mixture of co/co_2) atmospheres
- Ash melting temperatures follows a hysteresis curve
  - Lab furnace vs. operating boiler
- Need to correlate with unit operation
  - Compare relative changes
  - Cannot always use absolute values

Coal Analysis Standards Tests

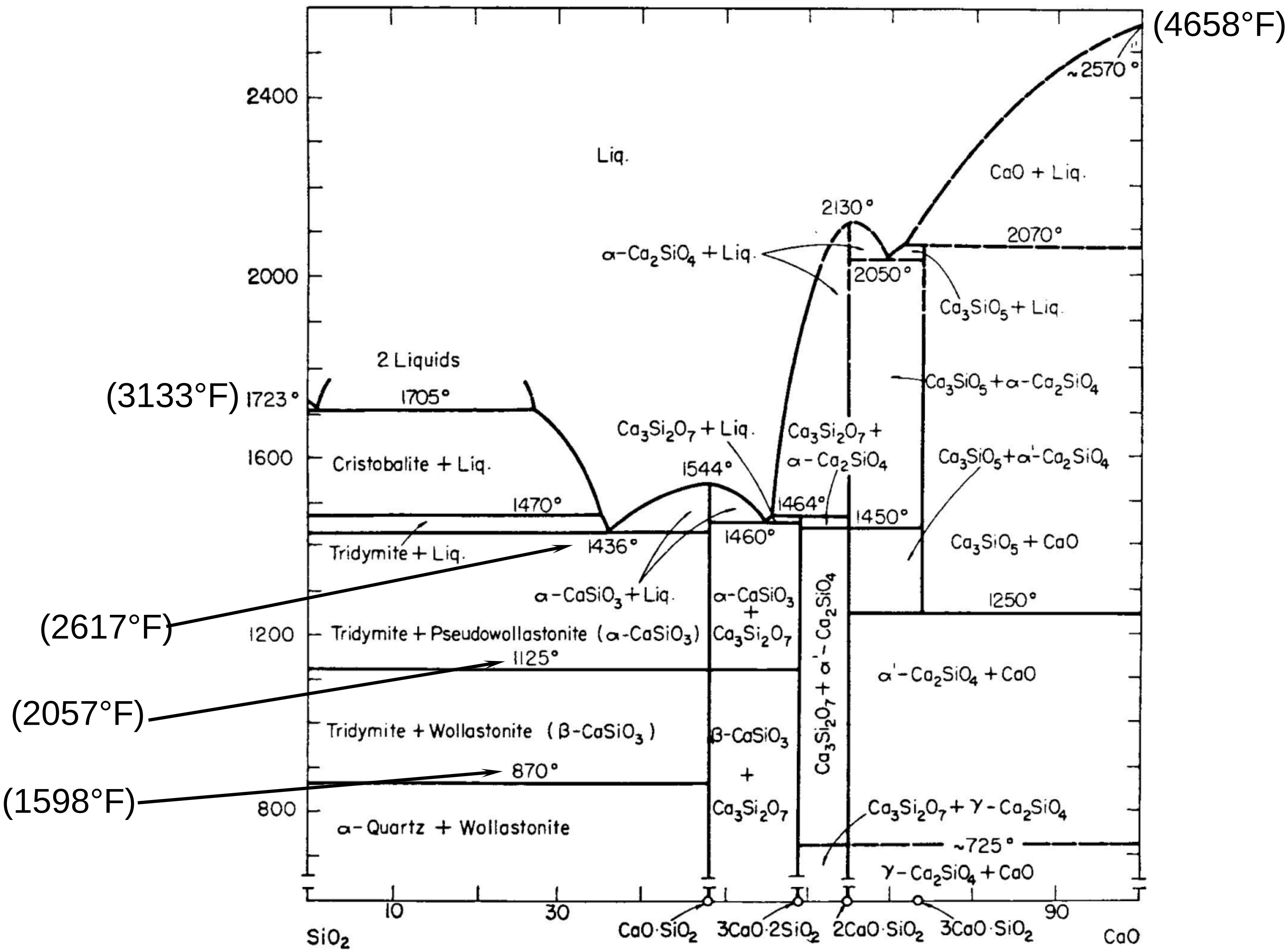
Ash Fusion

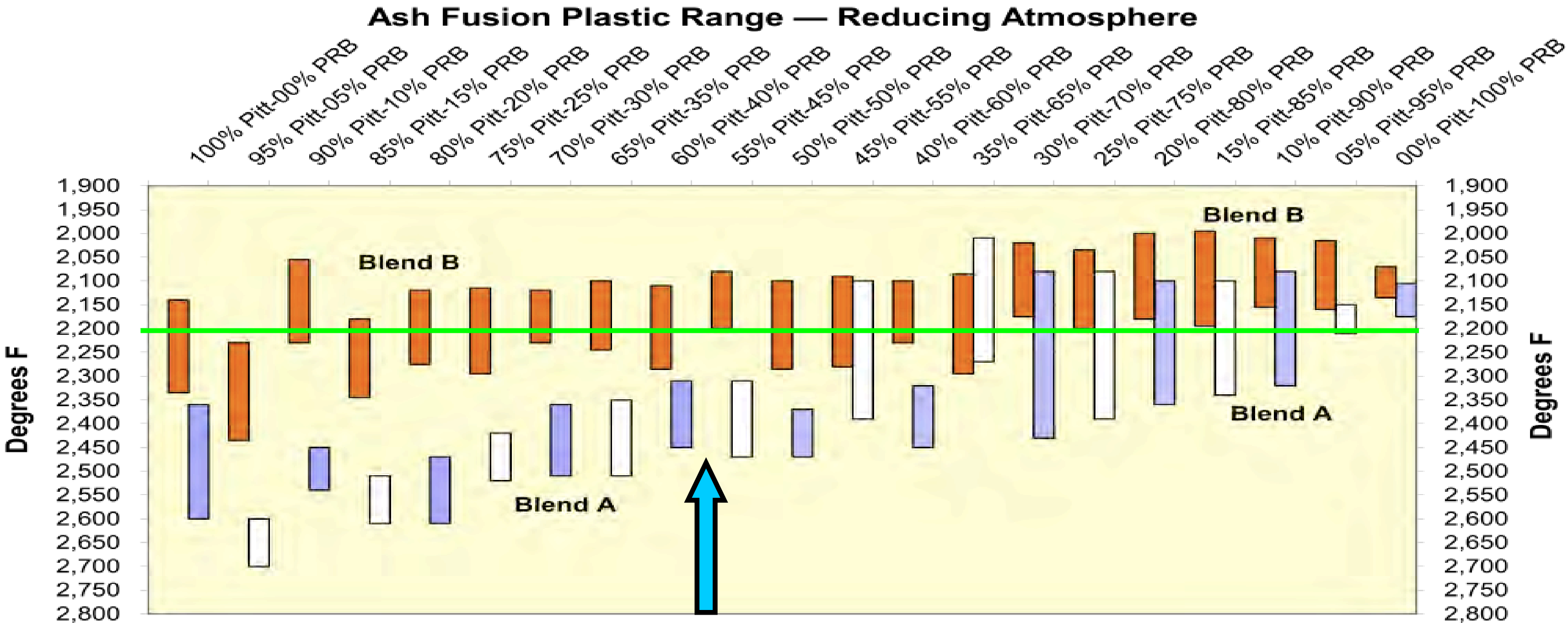


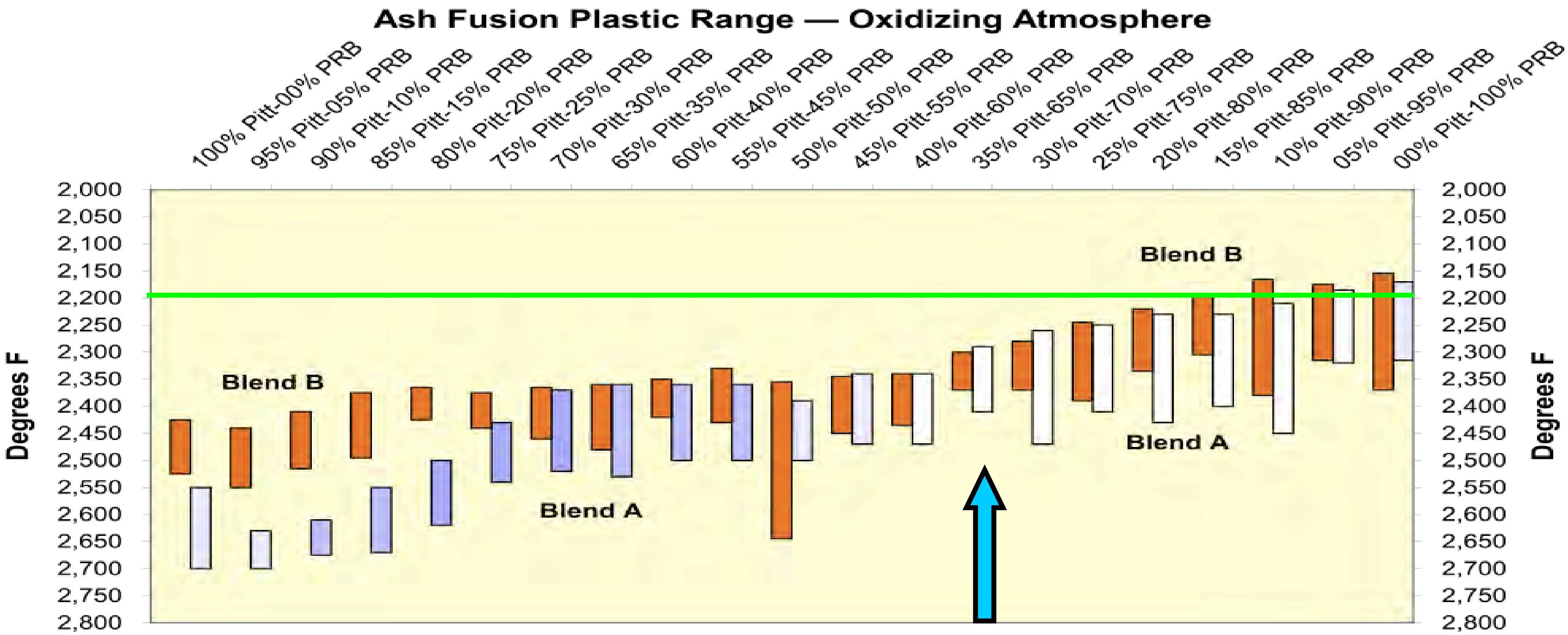


B:A vs Fusion-Hemispherical
Degrees F
Base-Acid Ratio
2,900
2,800
2,700
2,600
2,500
2,400
2,300
2,200
2,100
2,000
1,900
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
R^2 = 0.8014
— Reduced ESP Performance —
— Slagging Transition Zone —
— Slagging Zone —
— Low Slagging Probability —

2 Parameter Model: CaO and SiO_2




Ash Fusion Plastic Range — Reducing Atmosphere
100% Pitt-00% PRB
95% Pitt-05% PRB
90% Pitt-10% PRB
85% Pitt-15% PRB
80% Pitt-20% PRB
75% Pitt-25% PRB
70% Pitt-30% PRB
65% Pitt-35% PRB
60% Pitt-40% PRB
55% Pitt-45% PRB
50% Pitt-50% PRB
45% Pitt-55% PRB
40% Pitt-60% PRB
35% Pitt-65% PRB
30% Pitt-70% PRB
25% Pitt-75% PRB
20% Pitt-80% PRB
15% Pitt-85% PRB
10% Pitt-90% PRB
05% Pitt-95% PRB
00% Pitt-100% PRB
Degrees F
1,900
1,950
2,000
2,050
2,100
2,150
2,200
2,250
2,300
2,350
2,400
2,450
2,500
2,550
2,600
2,650
2,700
2,750
2,800
Blend B
Blend A
Blend B
Blend A


Ash Fusion Plastic Range — Oxidizing Atmosphere
100% Pitt-00% PRB
95% Pitt-05% PRB
90% Pitt-10% PRB
85% Pitt-15% PRB
80% Pitt-20% PRB
75% Pitt-25% PRB
70% Pitt-30% PRB
65% Pitt-35% PRB
60% Pitt-40% PRB
55% Pitt-45% PRB
50% Pitt-50% PRB
45% Pitt-55% PRB
40% Pitt-60% PRB
35% Pitt-65% PRB
30% Pitt-70% PRB
25% Pitt-75% PRB
20% Pitt-80% PRB
15% Pitt-85% PRB
10% Pitt-90% PRB
05% Pitt-95% PRB
00% Pitt-100% PRB
Degrees F
2,000
2,050
2,100
2,150
2,200
2,250
2,300
2,350
2,400
2,450
2,500
2,550
2,600
2,650
2,700
2,750
2,800
Blend B
Blend A
Blend B
Blend A

Coal Analysis Standard Tests

HGI (Hardgrove Grindability Index)

- An estimate of the pulverizer power required to produce a minus 200-mesh product
  - Developed for early B&W ball mills
  - Does not directly apply to modern mills such as the B&W MPS series
  - Regardless, good indicator and still used as a specification in coal contracts
- Must start w/95% minus 4-mesh, then stage crush to 16 x 30 mesh
  - Many labs start with minus 8-mesh
- Index based on % passing 200-mesh
- Always report moisture of 16 x 30-mesh product
  - Especially for low-rank coals

Coal Analysis Standard Tests

Dry Screens for Coal > ½"
(CROM, Raw, Washed, Stockpiled, etc)

- Size distribution > 4" to 4 mesh
- Start w/large screens such:
  - Gilson Bucking Screens
  - 12" rocking screens
- Add only enough coal so as not to flood any screen
- Stop at 4-mesh square
- Combine retained 4 mesh and smaller and split into 50g increments to allow the use of 8" full-height screens
- When splitting the plus 4-mesh sample, use alternating sides on the sample splitter to minimize bias

Coal Analysis Standard Tests

Dry Screens (Mill Performance, Fly Ash)

- Select screen stack for desired particle size distribution
- When using 8" screens, never add more than 50 ±5g to the top screen
  - Otherwise all screens in the screen stack may be blinded yielding incorrect results
- Make sure each screen has been cleaned both top & bottom before using again
  - Otherwise round holes instead of square
  - If any screen is stretched or frame is warped, toss
- Best to carefully wash each screen w/laboratory glassware detergent in warm DI water, and air dry (~150°F, ~1 hr) each screen before reuse
- Screens must be thoroughly dry before use
- Repeatability comparable to Gilson 3" Sonic-screens

Coal Analysis Standard Tests
Mill Fineness

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

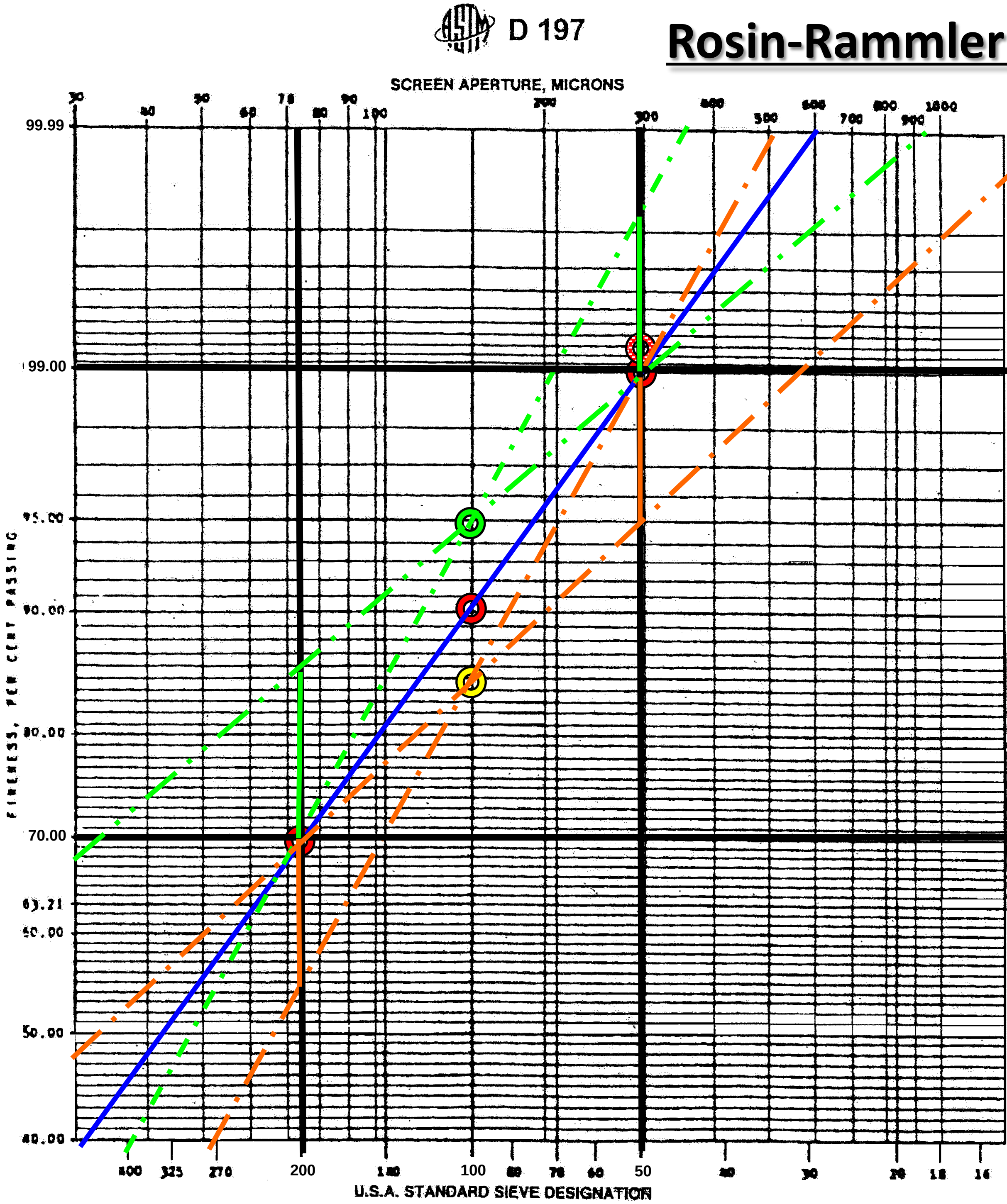
- **Coarse** — Delayed combustion, combustion higher in furnace, increased slagging, fouling & unburned C (UBC), higher CO, increased O_2 requirements, larger burner bias (particle momentum vs. particle density), increased mill throughput, reduced mill maintenance

- **Fine** — Rapid combustion, combustion lower in furnace, reduced slagging, fouling & unburned C (UBC), lower CO, reduced O_2 requirements, reduced mill throughput, increased mill maintenance

- Nominally, particles <34um behave as a fluid and Bernoulli relationships can be applied. Bernoulli relationships do not show good correlation for larger particles; hence invalid conclusions come about based on Bernoulli assumptions.

- Check sample representativeness by plotting the results on a Rosin-Rammler Chart

Rosin-Rammler Chart



Plot of Rosin and Rammler Equation for Use with Pulverized Coal

Coal Analysis Special Tests

Equilibrium Moisture (EQ moisture)

- Very difficult test to perform w/good repeatability
  - Especially for low-rank fuels
- Use same trained & experienced operator
- Good to use for coal quality adjustments when total moisture is reported < EQ moisture
  - Recommend changing total moisture to EQ moisture + 2%; then recalculate as-received values
  - Easily defendable for high-rank coals
  - Since low-rank coals are not washed, this technique is more difficult to defend

Coal Analysis Special Tests

Equilibrium Moisture

- Must determine ADL & Residual Moisture (M_R)
  - $M_T = (M_R * (100 - ADL) / 100) + ADL$
  - $M_T = (EQ * (100 - M_S) / 100) + M_S$

  Where:

  ADL = Air Dry Loss

  M_R = Residual Moisture

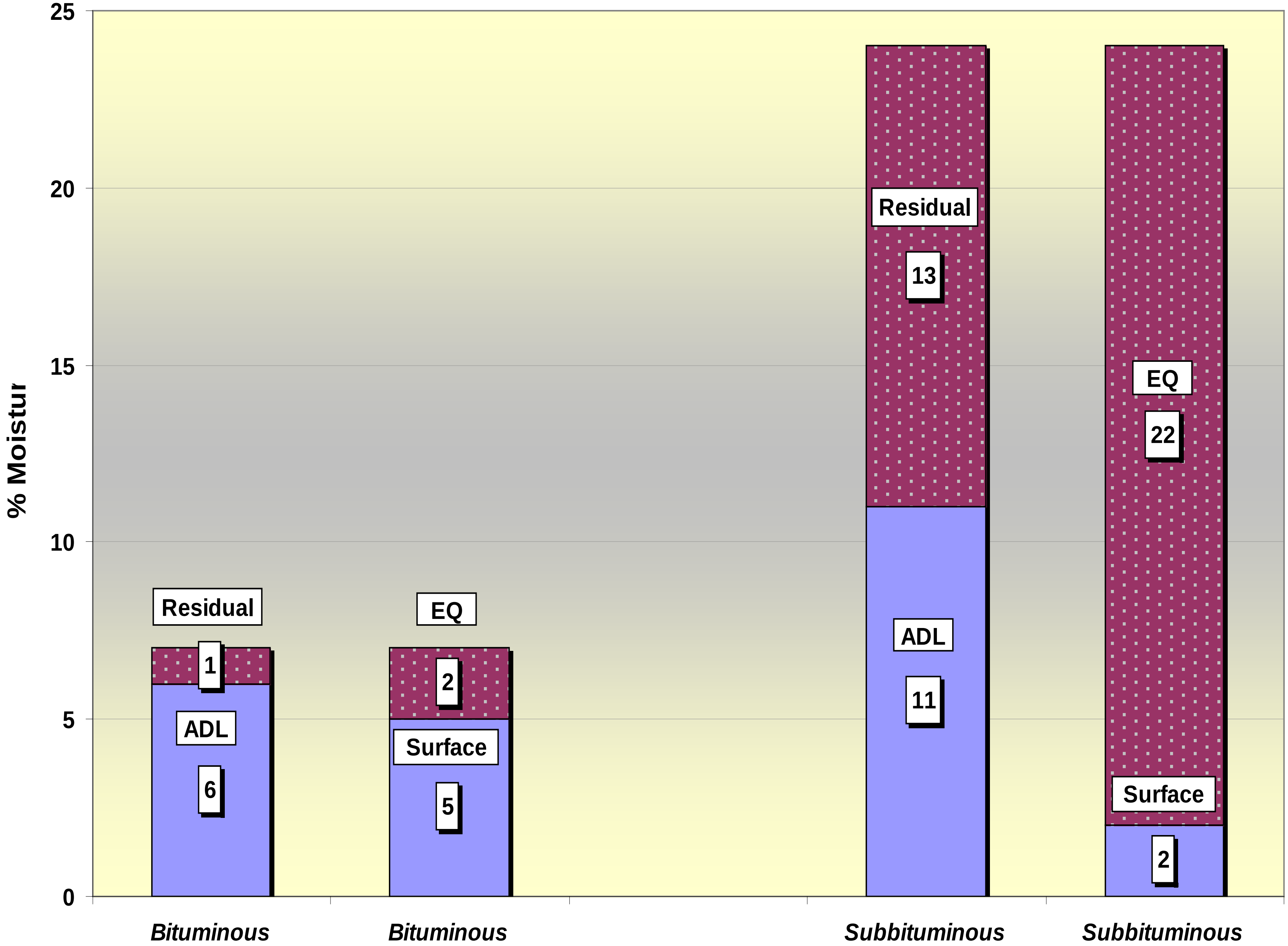
  EQ = Equilibrium Moisture

  M_S = Surface Moisture

M_S cannot be determined directly. Use the 2 M_T equations and solve for M_S.

- DO NOT confuse:
  - ADL with Surface Moisture
  - Residual Moisture with Inherent or Equilibrium Moisture
  - They are NOT the same

Moisture Components



Coal Analysis Special Tests

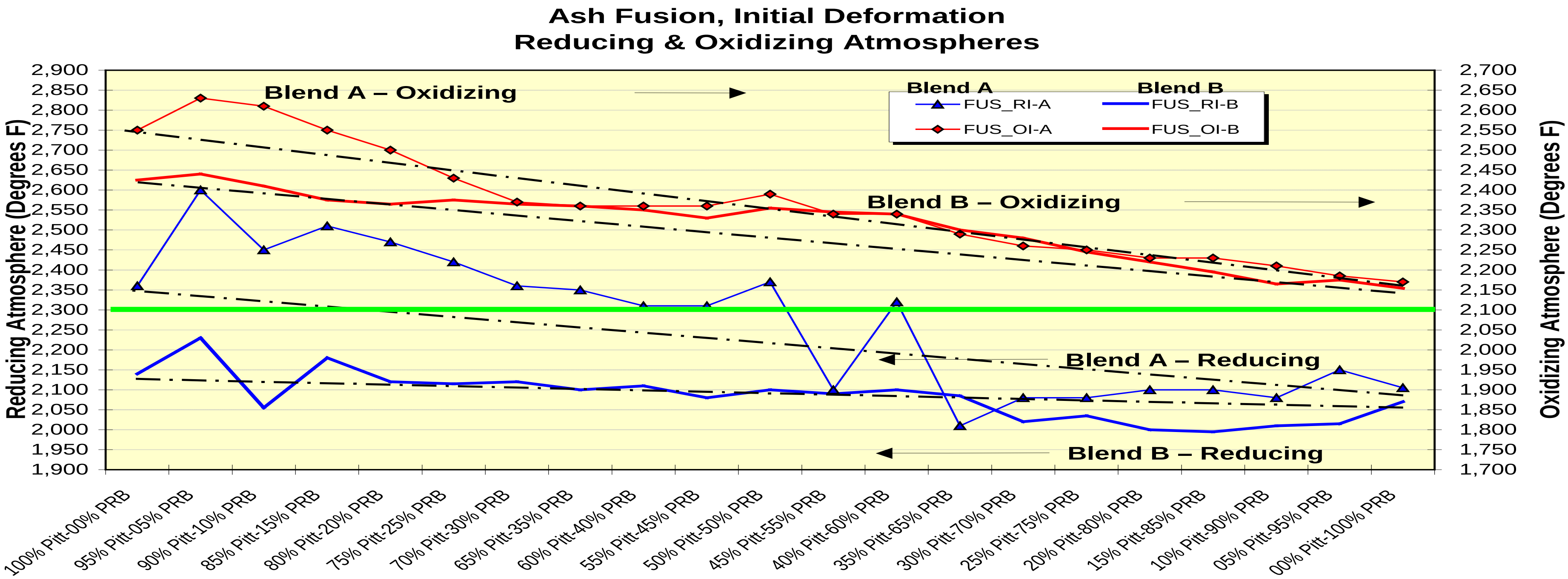
Others

- Mercury
- Halogens (Br, Cl, F)
- Trace Elements
- Sulfur Forms (organic, pyritic, sulfate)
- Reactive C in coal
- FSI
- Specific gravity
- pH
- Dust Index
- Particle size (2000 μm – 0.4 μm)
- TGA burning profile
- TGA proximate
- 1-step moisture (not recommended)

Ash Fusions

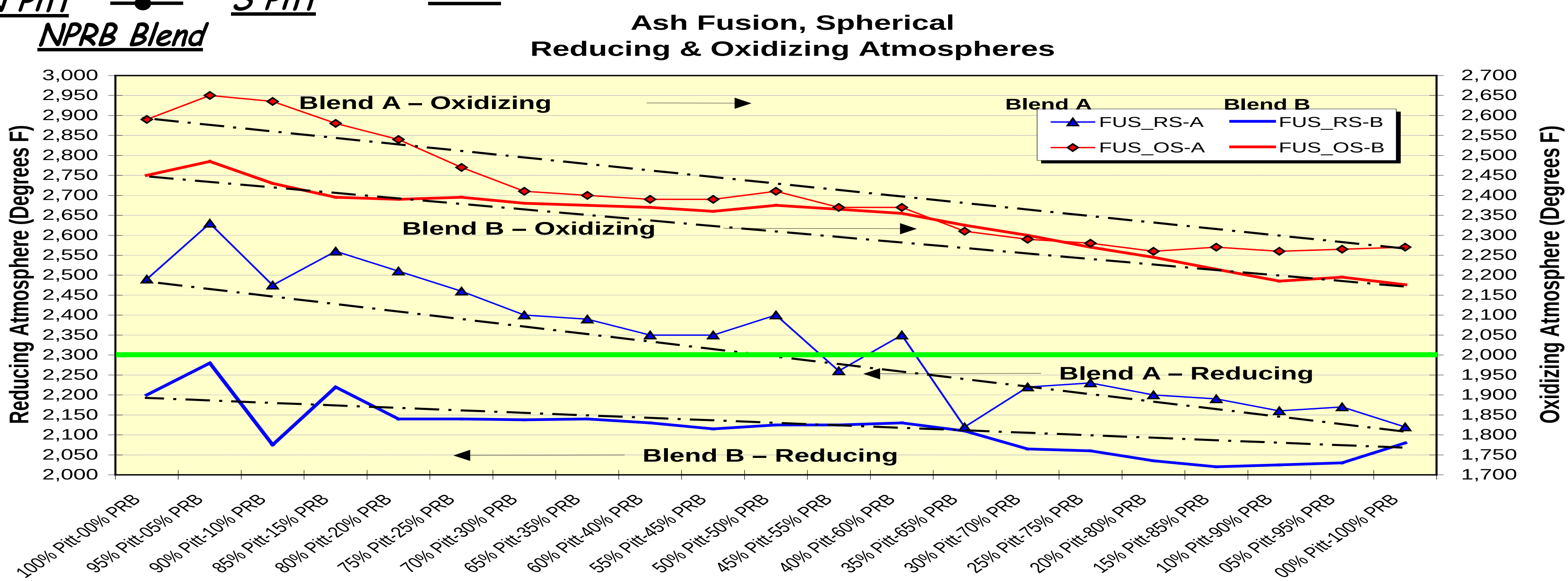
&

Fusion Box

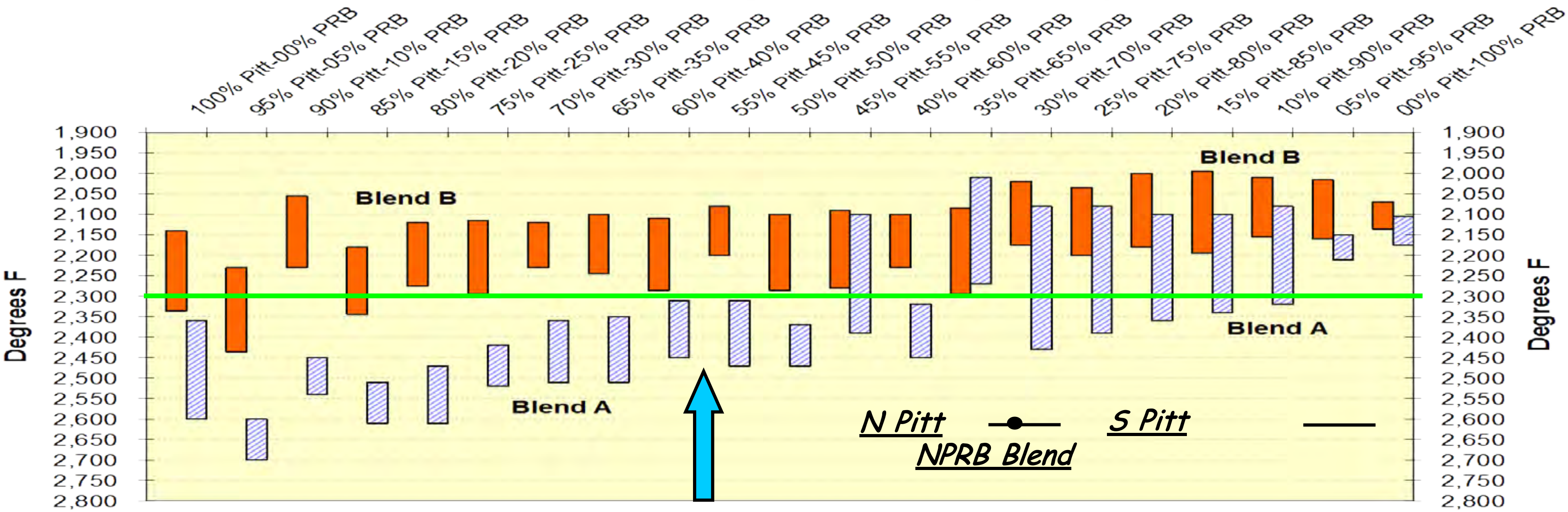


N Pitt S Pitt

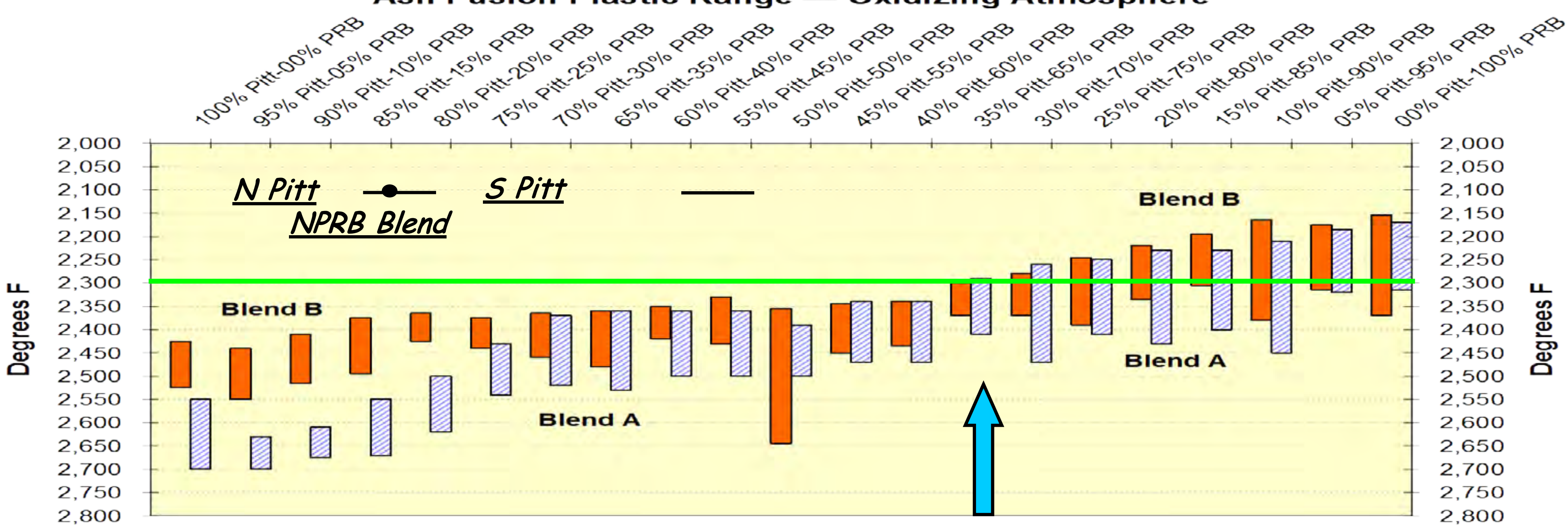
NPRB Blend

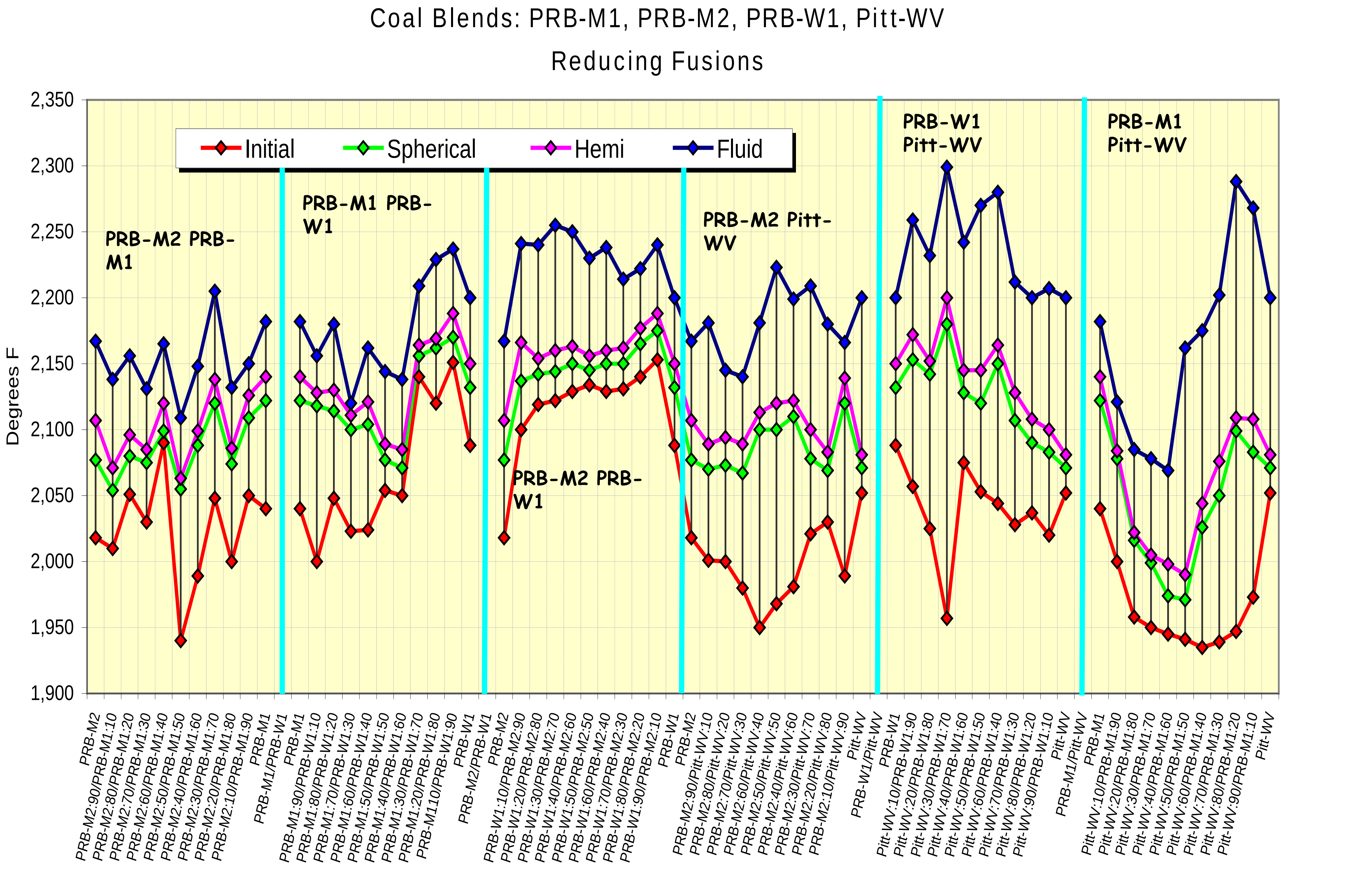


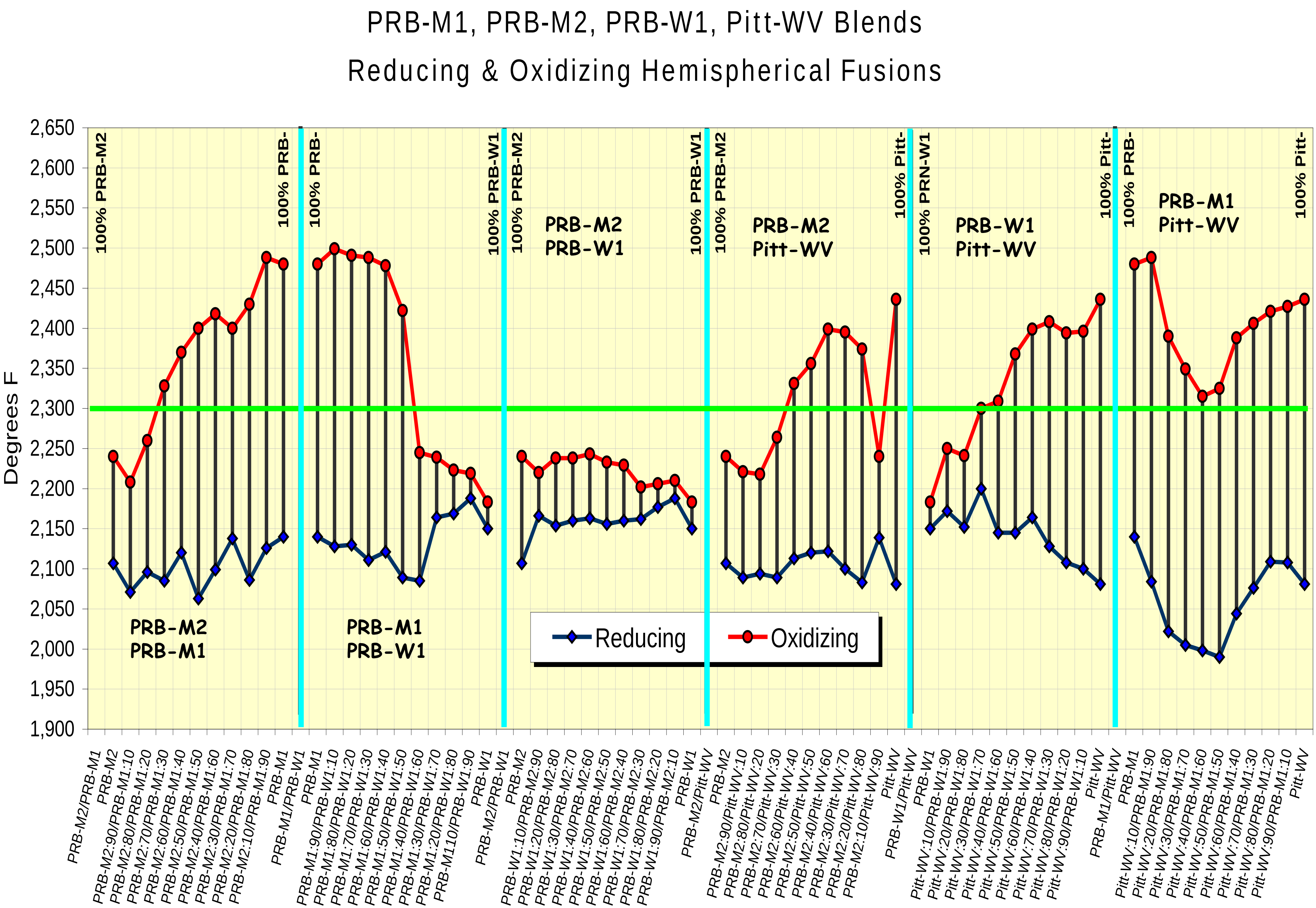
Ash Fusion Plastic Range — Reducing Atmosphere



Ash Fusion Plastic Range — Oxidizing Atmosphere




Coal Blends: PRB-M1, PRB-M2, PRB-W1, Pitt-WV
Reducing Fusions
Initial
Spherical
Hemi
Fluid
PRB-M2 PRB-M1
PRB-M1 PRB-W1
PRB-M2 PRB-W1
PRB-M2 Pitt-WV
PRB-W1 Pitt-WV
PRB-M1 Pitt-WV
Degrees F
2,350
2,300
2,250
2,200
2,150
2,100
2,050
2,000
1,950
1,900
PRB-M2
PRB-M2:90/PRB-M1:10
PRB-M2:80/PRB-M1:20
PRB-M2:70/PRB-M1:30
PRB-M2:60/PRB-M1:40
PRB-M2:50/PRB-M1:50
PRB-M2:40/PRB-M1:60
PRB-M2:30/PRB-M1:70
PRB-M2:20/PRB-M1:80
PRB-M2:10/PRB-M1:90
PRB-M1
PRB-M1/PRB-W1
PRB-M1
PRB-M1:90/PRB-W1:10
PRB-M1:80/PRB-W1:20
PRB-M1:70/PRB-W1:30
PRB-M1:60/PRB-W1:40
PRB-M1:50/PRB-W1:50
PRB-M1:40/PRB-W1:60
PRB-M1:30/PRB-W1:70
PRB-M1:20/PRB-W1:80
PRB-M110/PRB-W1:90
PRB-W1
PRB-M2/PRB-W1
PRB-M2
PRB-W1:10/PRB-M2:90
PRB-W1:20/PRB-M2:80
PRB-W1:30/PRB-M2:70
PRB-W1:40/PRB-M2:60
PRB-W1:50/PRB-M2:50
PRB-W1:60/PRB-M2:40
PRB-W1:70/PRB-M2:30
PRB-W1:80/PRB-M2:20
PRB-W1:90/PRB-M2:10
PRB-W1
PRB-M2
PRB-M2:90/Pitt-WV:10
PRB-M2:80/Pitt-WV:20
PRB-M2:70/Pitt-WV:30
PRB-M2:60/Pitt-WV:40
PRB-M2:50/Pitt-WV:50
PRB-M2:40/Pitt-WV:60
PRB-M2:30/Pitt-WV:70
PRB-M2:20/Pitt-WV:80
PRB-M2:10/Pitt-WV:90
Pitt-WV
PRB-W1/Pitt-WV
PRB-W1
Pitt-WV:10/PRB-W1:90
Pitt-WV:20/PRB-W1:80
Pitt-WV:30/PRB-W1:70
Pitt-WV:40/PRB-W1:60
Pitt-WV:50/PRB-W1:50
Pitt-WV:60/PRB-W1:40
Pitt-WV:70/PRB-W1:30
Pitt-WV:80/PRB-W1:20
Pitt-WV:90/PRB-W1:10
Pitt-WV
PRB-M1/Pitt-WV
PRB-M1
Pitt-WV:10/PRB-M1:90
Pitt-WV:20/PRB-M1:80
Pitt-WV:30/PRB-M1:70
Pitt-WV:40/PRB-M1:60
Pitt-WV:50/PRB-M1:50
Pitt-WV:60/PRB-M1:40
Pitt-WV:70/PRB-M1:30
Pitt-WV:80/PRB-M1:20
Pitt-WV:90/PRB-M1:10
Pitt-WV


PRB-M1, PRB-M2, PRB-W1, Pitt-WV Blends
Reducing & Oxidizing Hemispherical Fusions
Degrees F
100% PRB-M2
100% PRB-
100% PRB-
100% PRB-W1
100% PRB-M2
100% PRB-W1
100% PRB-M2
100% Pitt-
100% PRN-W1
100% Pitt-
100% PRB-
100% Pitt-
PRB-M2
PRB-M1
PRB-M1
PRB-W1
PRB-M2
PRB-W1
PRB-M2
Pitt-WV
PRB-W1
Pitt-WV
PRB-M1
Pitt-WV
Reducing
Oxidizing

To Be Successful

Your Process Must Be Controlled

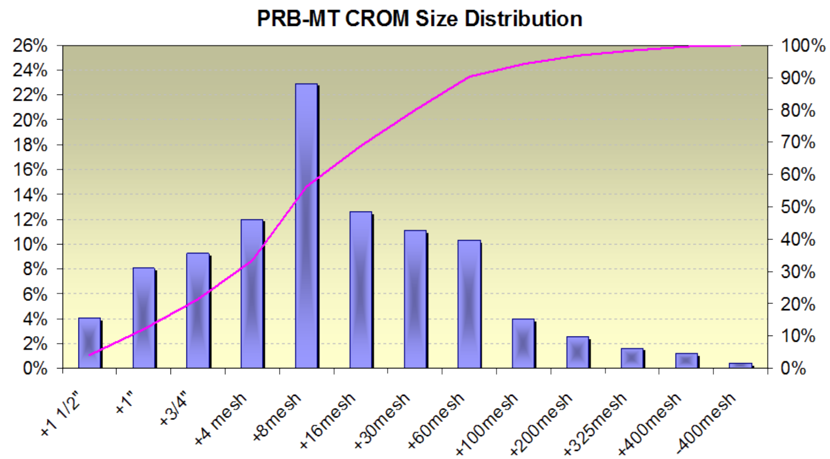
How Is This Done?

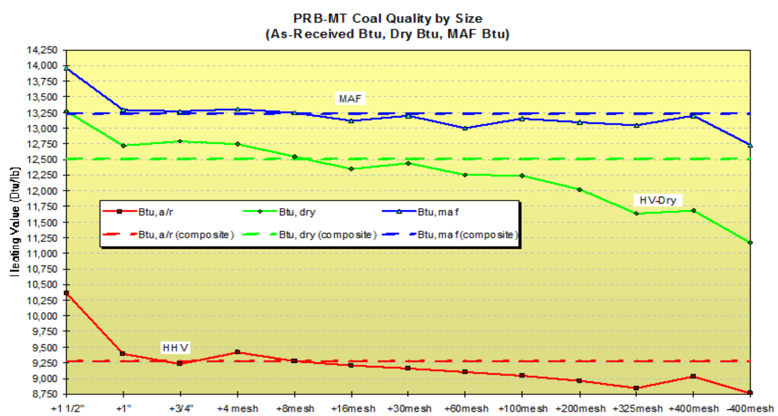
Representative Sampling

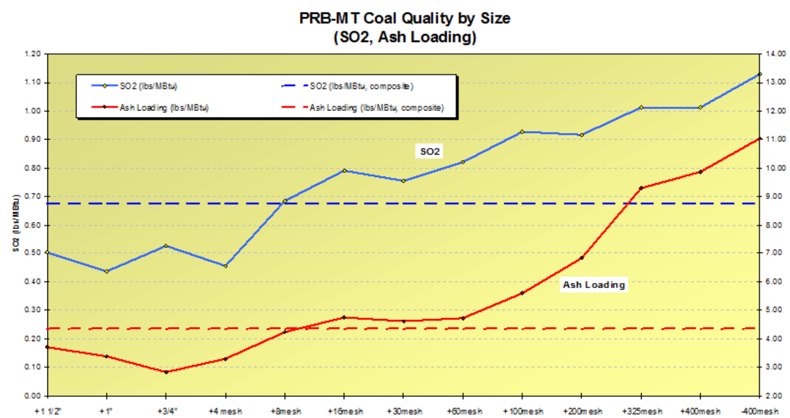
You Can't Control What You Can't Measure!

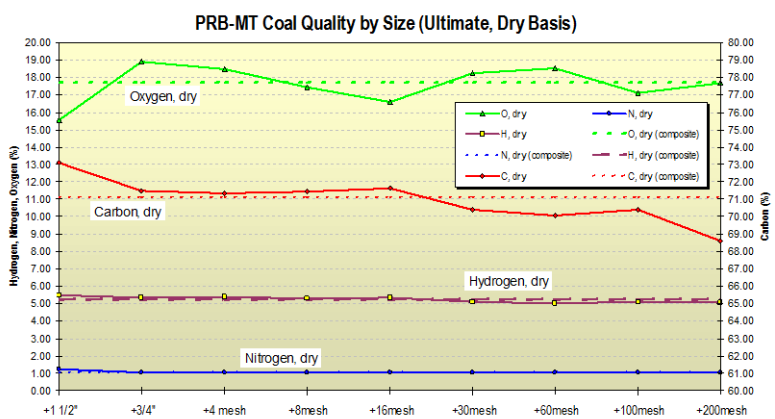
NOT

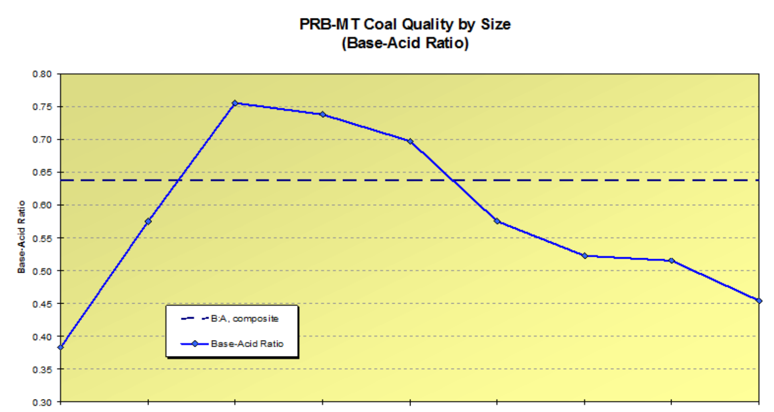
What number do you want
(or is it)?

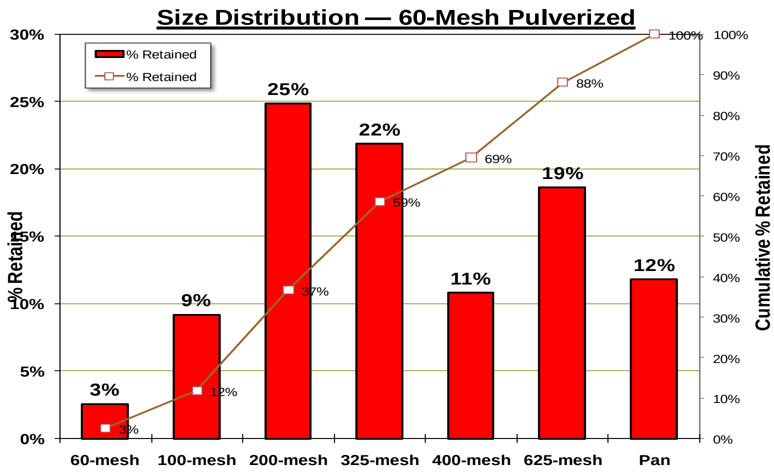

PRB-MT CROM Size Distribution
26%
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
+1 1/2"
+1"
+3/4"
+4 mesh
+8mesh
+16mesh
+30mesh
+60mesh
+100mesh
+200mesh
+325mesh
+400mesh
-400mesh


PRB-MT Coal Quality by Size
(As-Received Btu, Dry Btu, MAF Btu)
Heating Value (Btu/lb)
MAF
HV-Dry
HHV
Btu, a/r
Btu, dry
Btu, maf
Btu, a/r (composite)
Btu, dry (composite)
Btu, maf (composite)
+1 1/2"
+1"
+3/4"
+4 mesh
+8mesh
+16mesh
+30mesh
+60mesh
+100mesh
+200mesh
+325mesh
+400mesh
-400mesh

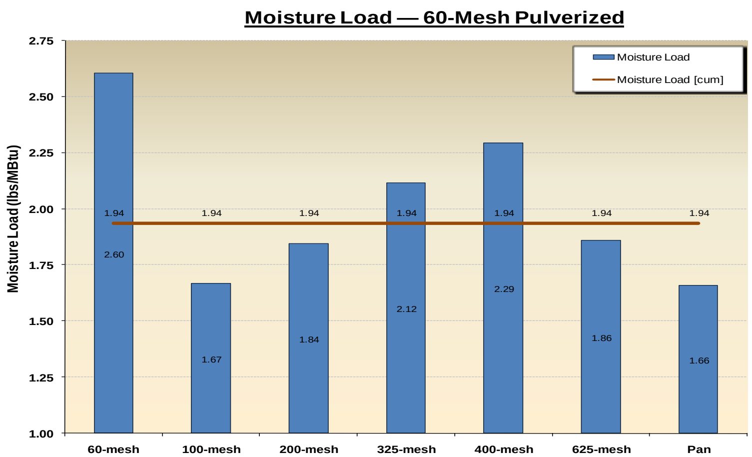

PRB-MT Coal Quality by Size
(SO2, Ash Loading)
SO2 (lbs/MBtu)
SO2 (lbs/MBtu, composite)
Ash Loading (lbs/MBtu)
Ash Loading (lbs/MBtu, composite)
SO2
Ash Loading


PRB-MT Coal Quality by Size (Ultimate, Dry Basis)
Hydrogen, Nitrogen, Oxygen (%)
Carbon (%)
Oxygen, dry
Carbon, dry
Hydrogen, dry
Nitrogen, dry
O, dry
N, dry
H, dry
O, dry (composite)
N, dry (composite)
H, dry (composite)
C, dry
C, dry (composite)
+1 1/2"
+3/4"
+4 mesh
+8mesh
+16mesh
+30mesh
+60mesh
+100mesh
+200mesh

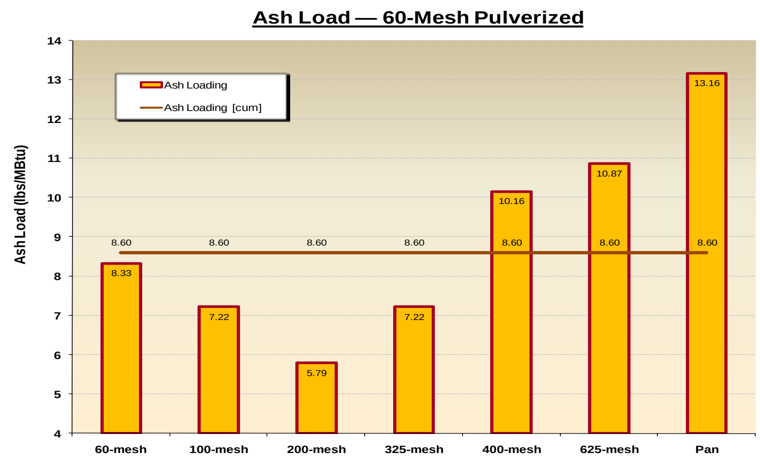

PRB-MT Coal Quality by Size
(Base-Acid Ratio)
Base-Acid Ratio
B:A, composite
Base-Acid Ratio
+1 1/2"
+3/4"
+4 mesh
+8mesh
+16mesh
+30mesh
+60mesh
+100mesh
+200mesh



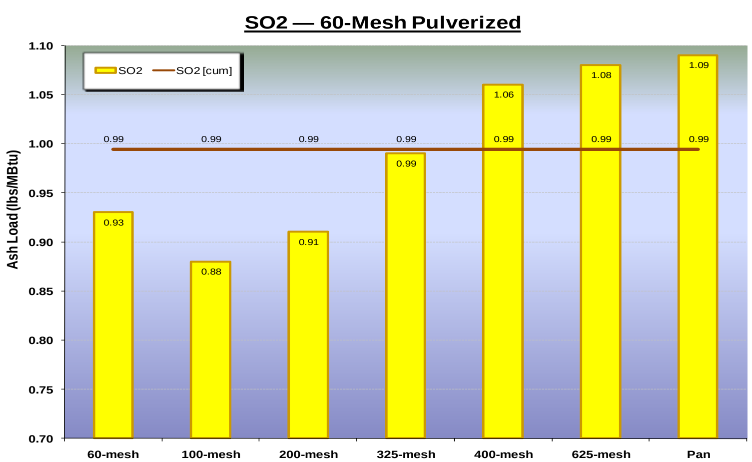
Size Distribution — 60-Mesh Pulverized
% Retained
% Retained
Cumulative % Retained
3%
9%
25%
22%
11%
19%
12%
3%
12%
37%
59%
69%
88%
100%
60-mesh
100-mesh
200-mesh
325-mesh
400-mesh
625-mesh
Pan



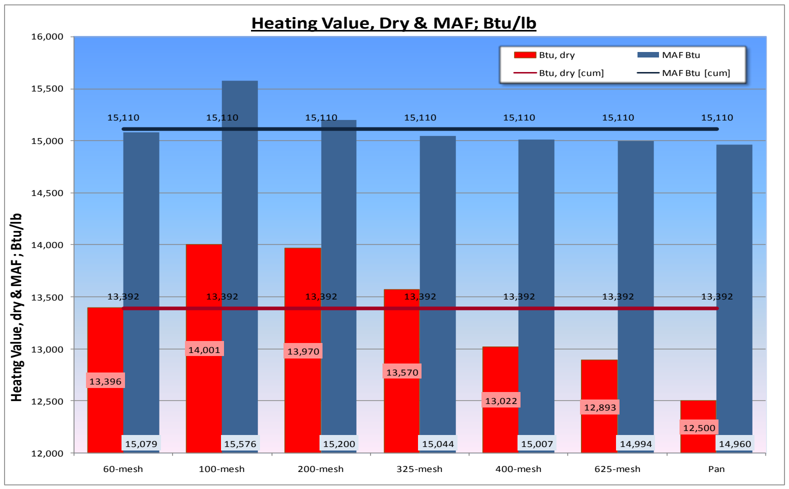
Moisture Load — 60-Mesh Pulverized
Moisture Load
Moisture Load [cum]
Moisture Load (lbs/MBtu)
2.60
1.67
1.84
2.12
2.29
1.86
1.66
1.94
60-mesh
100-mesh
200-mesh
325-mesh
400-mesh
625-mesh
Pan



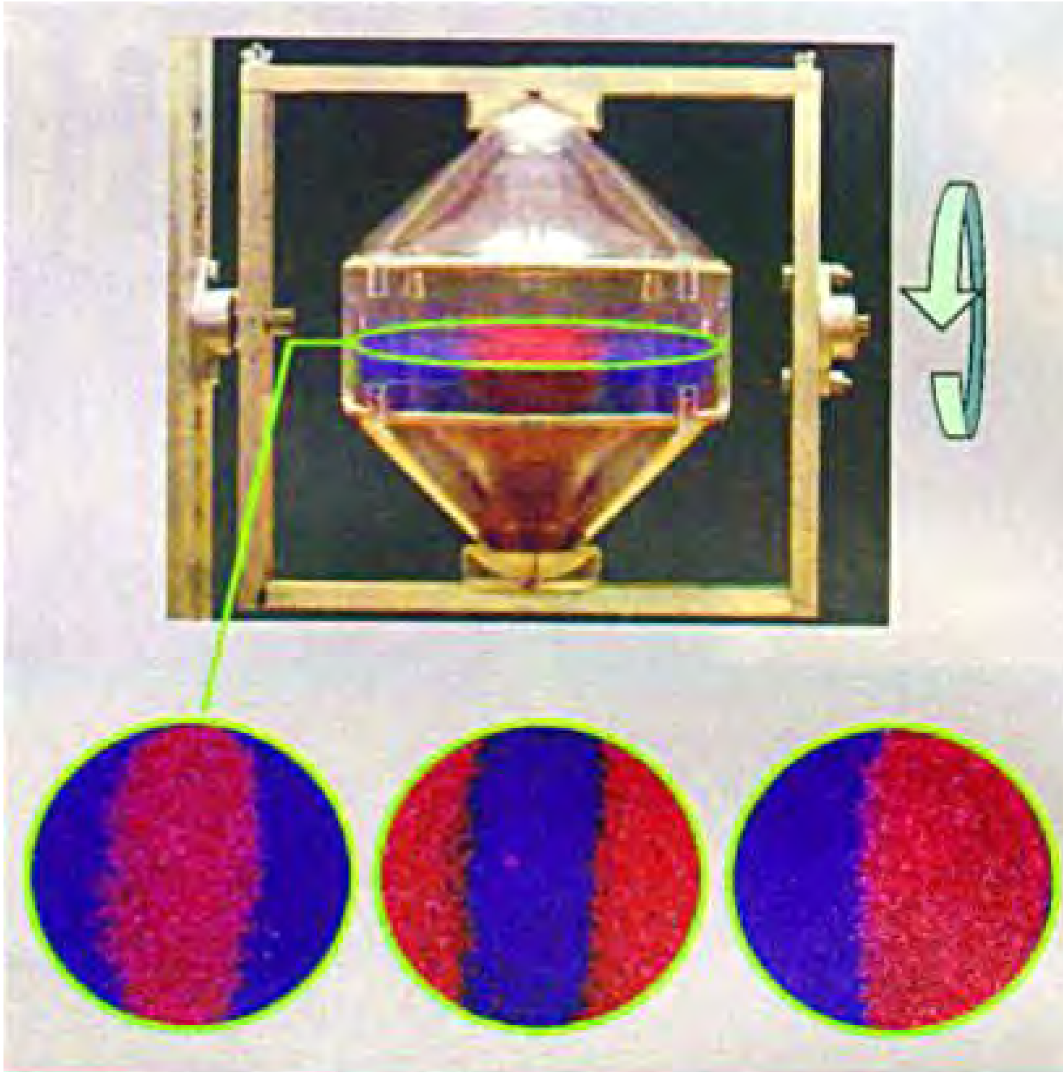
Ash Load — 60-Mesh Pulverized
Ash Loading
Ash Loading [cum]
Ash Load (lbs/MBtu)
8.33
7.22
5.79
7.22
10.16
10.87
13.16
8.60
60-mesh
100-mesh
200-mesh
325-mesh
400-mesh
625-mesh
Pan



SO2 — 60-Mesh Pulverized
SO2
SO2 [cum]
Ash Load (lbs/MBtu)
0.93
0.88
0.91
0.99
1.06
1.08
1.09
0.99
60-mesh
100-mesh
200-mesh
325-mesh
400-mesh
625-mesh
Pan

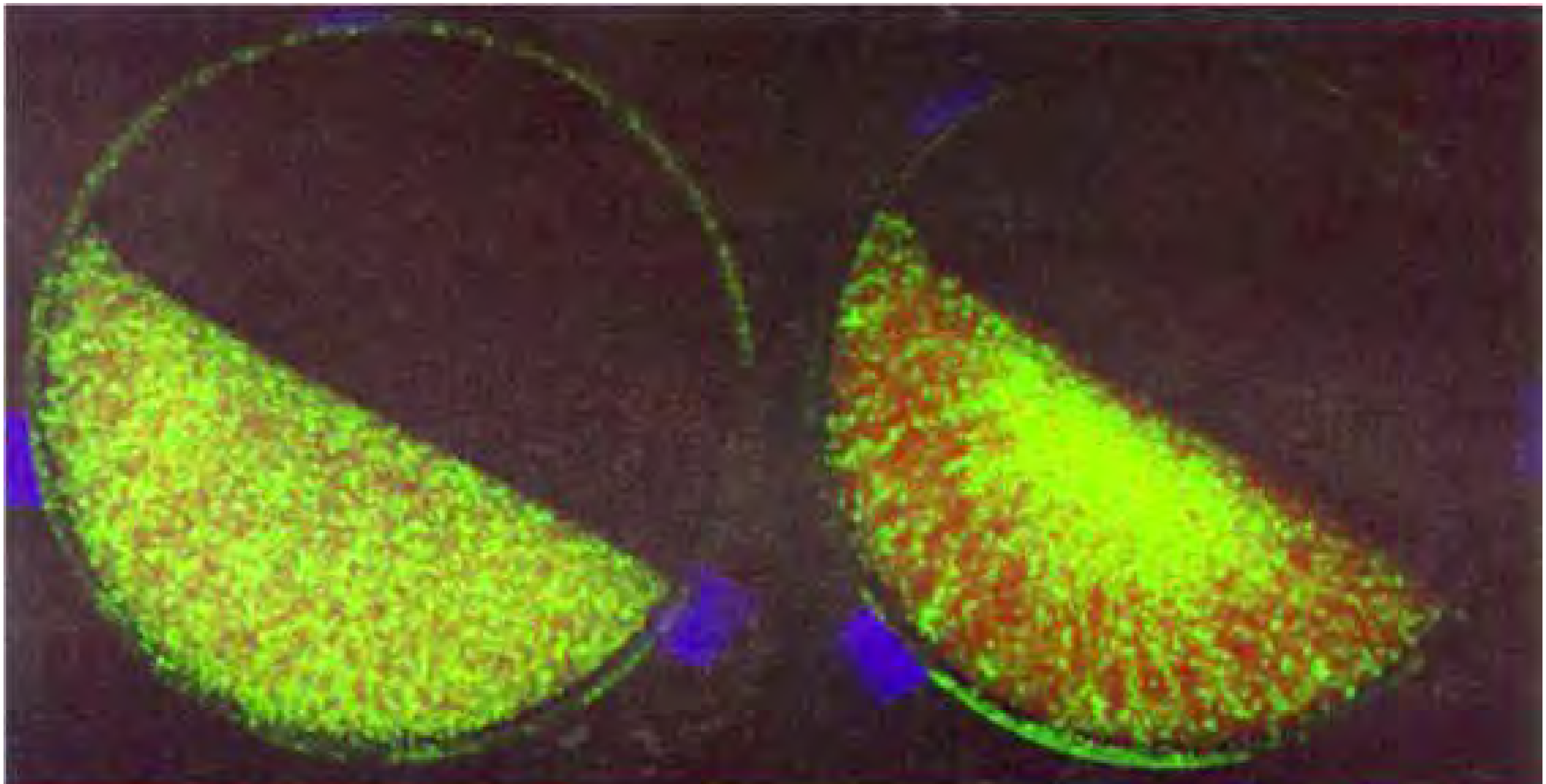


Heating Value, Dry & MAF; Btu/lb
Btu, dry
MAF Btu
Btu, dry [cum]
MAF Btu [cum]
Heatng Value, dry & MAF; Btu/lb
15,110
13,392
13,396
14,001
13,970
13,570
13,022
12,893
12,500
15,079
15,576
15,200
15,044
15,007
14,994
14,960
60-mesh
100-mesh
200-mesh
325-mesh
400-mesh
625-mesh
Pan



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

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

Examples of Coal Quality Impacts on Plant Performance

Moisture	Mill Output	Close Loop w/Fuel Procurement	Coal Quality Impact	Contract Quality Price Adjustments
Ash	Mills	Boiler Performance	Slagging & Fouling	Emissions
	Ash Collection	Erosion	Aux Power	EFOR
Ash Chemistry	ESP Performance	Boiler Optimization	SO_3 Injection	Aux Power
	Regulatory Costs	Slagging & Fouling	Emissions	
Sulfur	Scrubber Reagent	CEMS	CEM Validation	Scrubber Performance
	Corrosion	Slagging	Emissions	Sorbent Costs
	Aux Power	SO_2 Trading	SO_3 Emissions	
Heating Value	Slag Control	Stoichiometry	Efficiency	Heat Rate
	Consumption	Aux Power	MW Output	$/MWh
	Market Opportunity Cost			
Coal Quality	Blending	Plant Performance	Optimized Fuel Cost	Opportunity Fuels

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 (diff) (%) (+)	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
Equilbrium Moisture (%)	1.73
Surface Moisture (%)	2.84
Moisture Load (lbs/MBu)	3.38
Ash Load (lbs/MBu)	5.07
SO2 (lbs/MBu)	3.07
V/FC (fuel)	0.63
FC/V (combustion)	1.59

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 (diff) (%)	4.97	5.21	5.61

Hardgrove Grindability Index

HGI	50.8	@ 2.54% Moisture

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 (°F)	2,209	2,535
Spherical (°F)	2,280	2,575
Hemispherical (°F)	2,372	2,595
Fluid (°F)	2,460	2,665
Plastic Range (°F)	251	130
T250 (°F)	2,530	

ASH MINERAL (Dry Ash Basis)

SiO2 (%)	50.52	% Acid	77.58%
Al2O3 (%)	23.10	% Base	22.42%
TiO2 (%)	0.93	B/A	0.29
Fe2O3 (%)	15.63	Ash Ratio	0.22
CaO (%)	2.64	Ash Type	Bituminous
MgO (%)	0.78	Slagging Index	0.56
K2O (%)	1.94	Slagging Type	Medium
Na2O (%)	0.56	Fouling Index	0.16
		Fouling Type	Low
SO3 (%)	1.25		
P2O5 (%)	0.35	Silica Ratio	0.73
BaO (%)	0.26	Si/Al	2.19
SrO (%)	0.81	Fe/Ca	5.92
MnO2 (%)	0.01	Dolomite %	15.87
Undetermined (%)	1.22	ESP Index	74

Our Problem

Two very different coals slag in different parts of separate boilers. Both coals are known slaggers, but slagging was controllable. Now slagging is uncontrollable, causing shortened run times and forced outages. Why?

Coal 1:

- Subbituminous PRB from Montana
- Strip-mined using dragline, trucks & shovels
- No preparation other than crushing to spec (CROM)
- Crushed to 3" x 0
- Flood-loaded at mine
- Travel time from mine to power plant is 12 days

Coal 2:

- Bituminous NApp from Pittsburgh seam
- Deep-mined using long-wall & continuous miners
- Fully washed to 1 ½" x 100 mesh
- Flood-loaded at preparation plant
- Travel time from preparation plant to power plant is 3 days

Coal Comparisons

	Bituminous		Sub-Bituminous	
Proximate	Pitt (S<1.7)	Pitt (S>1.7)	PRB (Na<4)	PRB (Na>4)
Moisture (%) **(-)**	6.24	4.52	23.13	24.60
Ash (%) **(-)**	6.70	6.78	4.22	3.60
Volatile (%) **(+)**	31.89	34.31	32.97	31.57
Fixed Carbon (%) **(+)**	54.75	54.39	39.68	40.23
Sulfur (%)	1.42	2.05	0.29	0.25
HHV (Btu/lb)	13,061	13,376	9,554	9,507
MAF (Btu/lb)	15,002	15,080	13,152	13,241
Moisture Load (lbs/MBtu)	4.78	3.38	24.21	25.88
Ash Load (lbs/MBtu)	5.13	5.04	4.41	3.79
SO2 (lbs/MBtu)	2.17	3.07	0.62	0.53
V/FC (%/%)	0.58	0.63	0.83	0.78

Coal Comparisons

Ultimate	Pitt (S<1.7)	Pitt (S>1.7)	PRB (Na<4)	PRB (Na>4)
Carbon	79.36	78.82	68.65	71.47
Hydrogen	5.14	5.24	4.48	5.03
Nitrogen	1.57	1.52	0.93	1.14
Chlorine	0.095	0.103	0.013	0.010
Oxygen	5.27	5.17	20.06	17.25
Atomic Ratios				
H:C	0.772	0.792	0.778	0.838
O:C	0.050	0.049	0.219	0.181

Coal Comparisons

Ash Mineral	Pitt (S<1.7)	Pitt (S>1.7)	PRB (Na<4)	PRB (Na>4)
SiO_2	53.31	51.57	38.34	35.96
Al_2O_3	24.98	23.58	17.83	20.08
TiO_2	1.04	0.95	1.29	1.67
Fe_2O_3	11.84	15.95	5.03	5.20
CaO	3.07	2.69	14.23	20.19
MgO	0.86	0.80	4.63	4.89
K_2O	2.01	1.98	0.82	0.42
Na_2O	0.61	0.57	2.58	**11.58**
% Acid	81.18	77.58	67.80	57.71
% Base	18.82	22.42	32.20	42.29
Base / Acid	0.23	0.29	0.47	0.73
Slagging Type	Low	Severe	High	High
Fouling Type	Low	Low	Low-Medium	Severe

Coal Comparisons

Ash Mineral	Pitt (S<1.7)	Pitt (S>1.7)	PRB (Na<4)	PRB (Na>4)
Si Ratio	73	77	62	54
Si/Al	2.19	2.13	2.15	1.79
Fe/Ca	5.92	3.85	0.35	0.26
Si/Na	90.21	84.03	14.87	3.11
Dolomite %	15.87	21.37	69.09	59.32
Fe + Ca	18.65	14.91	19.26	25.40
Fe Load	0.81	0.61	0.22	0.20
Ca Load	0.14	0.16	0.63	0.76
Na Load	0.03	0.03	0.11	0.44
"Sticky" Alkali Load	0.21	0.23	0.95	1.39
ESP Index	75	78	54	56

Ash Fusion

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

Sulfur Forms, EQ Moisture, HGI

	Pitt (S<1.7)	Pitt (S>1.7)	PRB (Na<4)	PRB (Na>4)
Sulfur Forms				
Organic S	0.80	1.10	0.27	0.29
Pyritic S	0.70	1.02	0.08	0.05
Sulfate	0.01	0.03	0.01	0.01
Equilibrium Moisture				
EQ Moisture	4.0	3.7	23.5	23.1
Hardgrove Grindability Index				
HGI	51	53	47	51
@ Moisture	1.52	1.64	11.10	11.60

Our Problem

Our answers and remedies

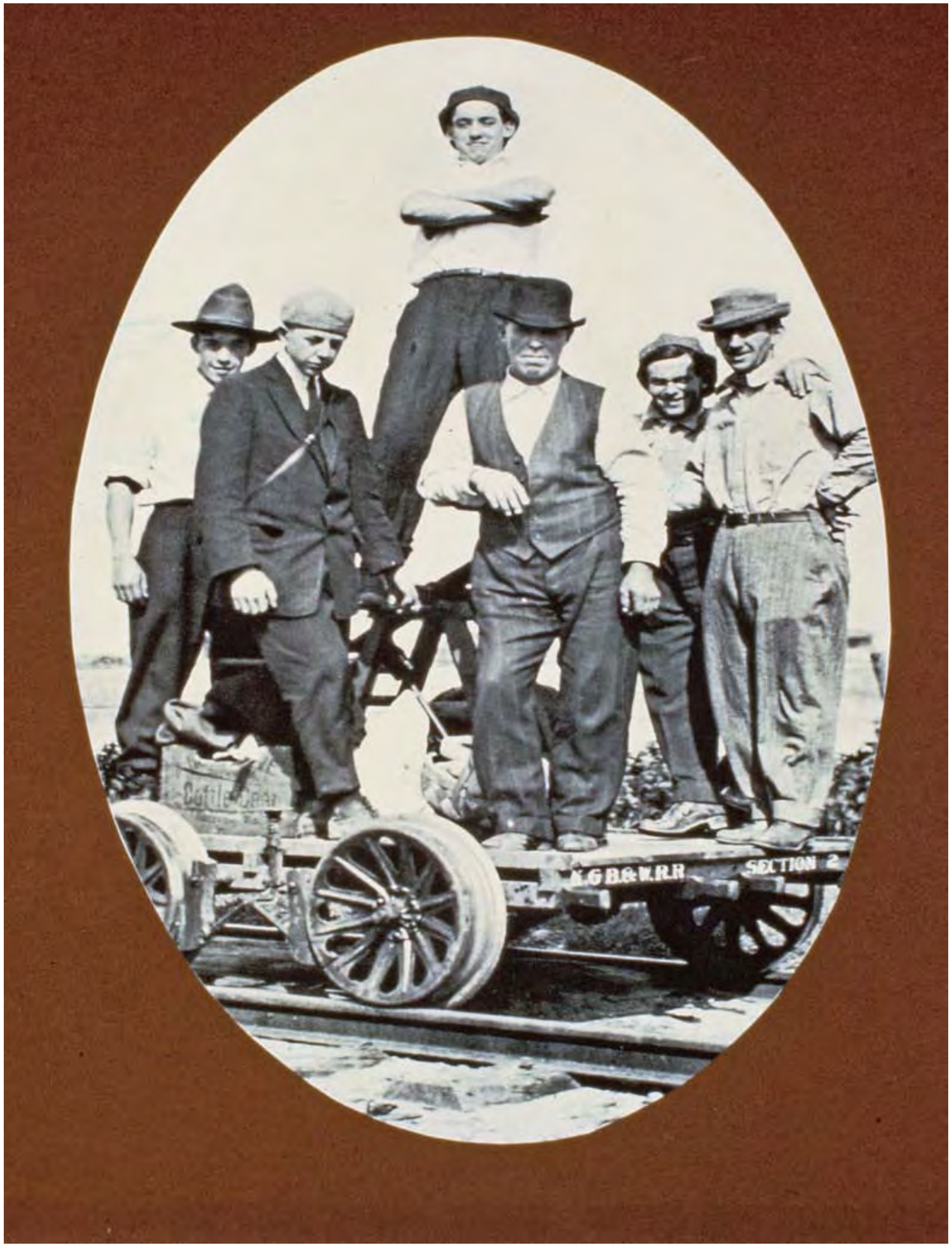
Coal 1:

- Subbituminous PRB from Montana
- Increased Ca
- Increased Na
- Remedy: Tell mine operator to reduce sodium (yeeeah!)

Coal 2:

- Bituminous NApp from Pittsburgh seam
- S increased
- Therefore, Fe increased
- Fe is a flux and depressed reducing atmosphere fusion temperatures
- Remedy: Tell preparation plant operator to reduce iron (yeeeah! At what cost?)

Thank You!



Enjoy the Rest of the Meeting

Be Safe, Have Fun!