Reinhold Environmental Ltd.

2008 APC Round Table & Expo Presentation

July 13-15, 2008, in Savannah, GA

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%

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]

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 Analysis

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

Atomic Ratios

- **H:C**
- **O:C**

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% 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

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

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
- 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

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/Al	2.19	2.13	2.15	1.79
Fe/Ca	5.92	3.85	0.35	0.26
Si/Ca	17.37	19.17	2.69	1.78
Si/Na	90.21	84.03	14.87	3.11
Dolomite %	15.87	21.37	69.09	59.32
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

Coal Mineral Types

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

Mineral type	Chemical formula[a]
Quartz	SiO_2
Al-silicate (kaolinite)	$Al_4Si_4O_{10}(OH)_8$
Fe-aluminosilicate	$Fe_xAl_ySi_z$
K-aluminosilicate (illite)	$K(Al, Fe)_4(Si, Al)_8O_{20}(OH)_4$
Ca-aluminosilicate	Ca_xAl_y, Si_x
Iron oxide	Fe_2O_3
Pyrite	FeS_2
Gypsum	$CaSO_4 \cdot 2H_2O$
Calcite	$CaCO_3$
Rutile	TiO_2
Barite	$BaSO_4$
Ankerite	$Ca(Mg, Fe, Mn)(CO_3)_2$
Siderite	$FeCO_3$
Crandallite	$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$
Dolomite	$CaMg(CO_3)_2$
Calcium aluminate	$Ca_3Al_2O_6$
Apatite	$Ca_5F(PO_4)_3$
Spinel	$(Fe, Al, Mg)O_4$
Calcium silicate	$CaSiO_3$
Pyrrhotite/iron sulfate	FeS
Ca-rich	—
Si-rich	—

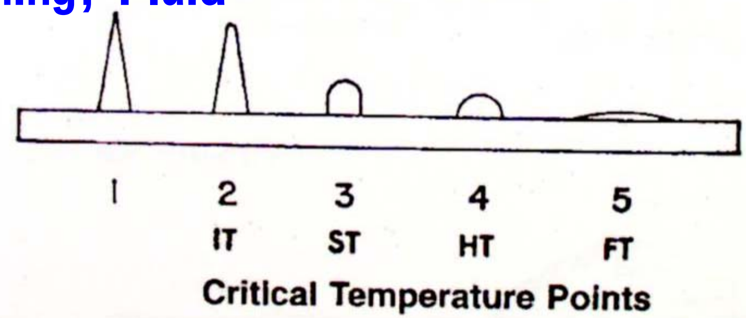
[a] Actual molar ratios will vary due to limits of the CCSEM technique.
Source: Zygarlicke *et al.* (1990a).

Ash Fusion Temperatures

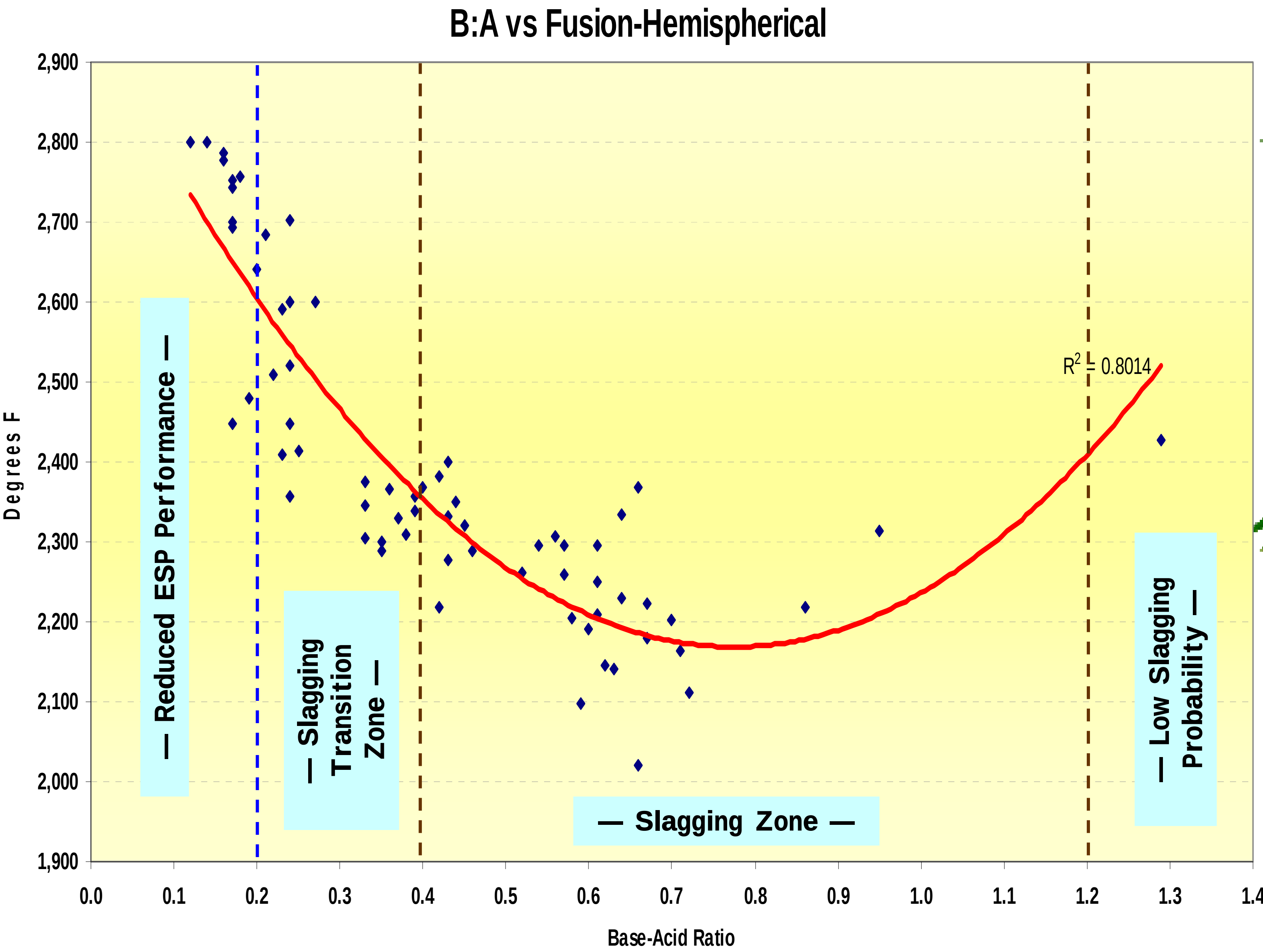
- Reducing & oxidizing atmospheres (CO/CO_2 vs. air)
  - **Initial, Spherical, Hemispherical, Fluid**
- Plastic range (**fusion box**)
  - Fluid – Initial
- Ash melting temperatures follows a hysteresis curve (lab vs. operating boiler)
- **Eutectics** in blends
- Need to correlate with unit operation
  - Compare relative changes
  - Cannot always use absolute values

Ash Fusion

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



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


B:A vs Fusion-Hemispherical
Degrees F
Base-Acid Ratio
— Reduced ESP Performance —
— Slagging Transition Zone —
— Slagging Zone —
— Low Slagging Probability —
R^2 = 0.8014
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

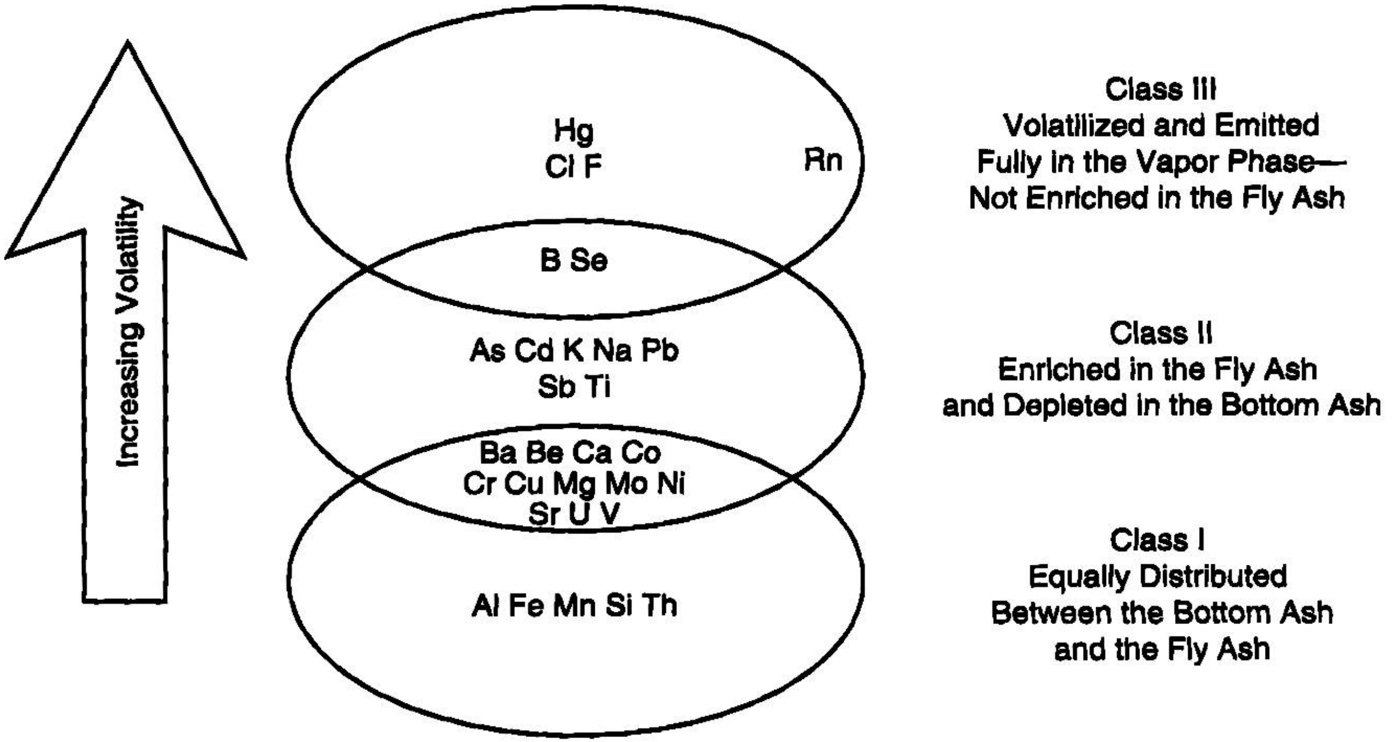
These values?

	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

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

Preferential Elemental Deposition in the Boiler



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].)

Size Consist

- **Raw vs. CROM vs. washed** *(or worsched?)*
  - Fully washed vs. partially washed
  - Roof, floor, slate, bone, sulfur balls, partings
  - Controlled by specific gravity & particle momentum
  - σ vs. mean (tighter for fully washed coals)

- **Pulverized**
  - 70% minus 200-mesh (75 µm)
  - 99% minus 50-mesh (300 µm)
    - With Low Rank Coals & Low NO_x burners, 99.5% minus 50-mesh is suggested

Mill Fineness

- Mill fineness and balance is one of the most important factors for proper combustion & burner line distribution; everything downstream is effected by coal particle size and particle distribution across the boiler
- Many negative environmental, combustion & performance factors can be traced back to mill performance
  - E.g., CO, NO_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

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?)

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 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 this becomes slag instead of fly ash

To Do the Above

You Must Control Your Processes

How Is This Done?

Define 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 hours burn**
- **Tons = total coal consumed in 1 hr**

Where:

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

Representative Sampling

&

Accurate Weighing

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

NOT

What number do you want?

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**

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 size sampled
    - Both tails of the normal distribution exist
- Causes of errors
  - Laboratory. 5%
  - Sample Preparation. 15%
  - Sampling. 80%

- **Sampling Techniques**
  - Stop-Belt (reference standard)
  - Mechanical (best commercial method)
  - Grab (continuous), Auger, Car-Top, Grab (one-time), Stockpile Core Drill, Stockpile Auger, Stockpile Manual
- **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