Performance Engineering for Coal-Fired Power Plants
(Advanced Coal Quality & Combustion)
by Rod Hatt

Class Outline

Introduction of Attendees and Instructors

Review of Basic Coal Quality

It is important to understand the results and meaning of the following coal tests. These are all covered in our **"Basic Coal Quality and Combustion Class"**

Proximate

> Originally
> Moisture
> Ash
> Volatile
> Fixed Carbon

> Short Prox
> Sulfur
> Heating value (HHV, LHV)

> Uses
> Rank determination - Reactivity
> Ash loading
> SO2
> Air Dry moisture

Ultimate

> Carbon
> Hydrogen
> Nitrogen
> Oxygen

Forms of Sulfur

Look for Pyrite, Sulfate = oxidized

Ash Fusion Temperatures

This is a physical test with variable atmospheric conditions.

Best used as an indication of what combustion conditions do to slag viscosity.

High variability lab to lab.

Major and Minor Ash Chemistry

More consistent lab to lab?
Try to infer slag viscosity and fouling potential.
Elemental loading
ESP Performance

Hardgrove Grindability Index

Variable with low and mid ranked coals due to moisture influences.

Equilibrium moisture

Coals are dustier if they fall below the equilibrium moisture level, even if it is just the surface of large pieces.

Combustion Tune-up Procedures

Air Flow and Balancing

Oxygen (O2) Readings
    Short history of Bailey Combustion Controls
    In situ Probes

Verifying O2 Readings
    How much leakage
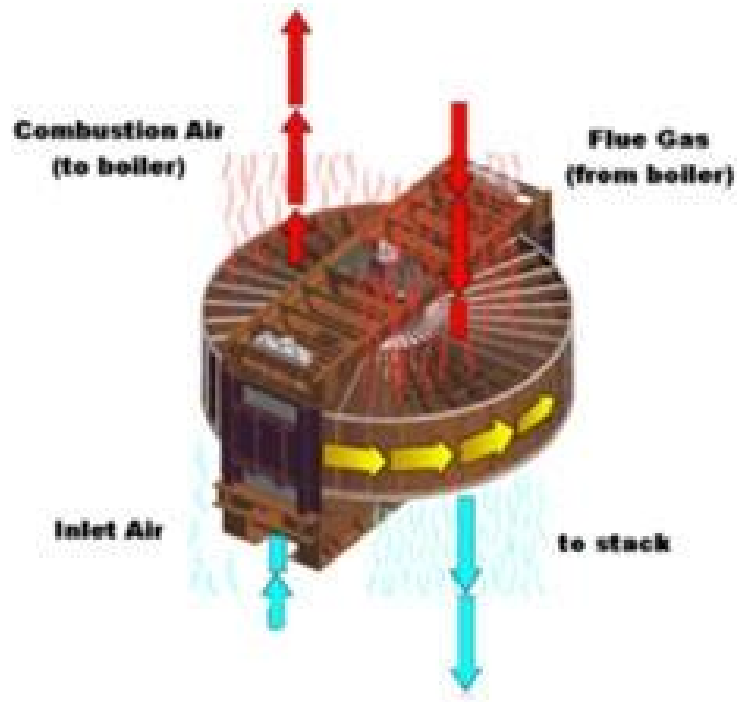   Induced draft fans

Comparing O2 to air flow measurements

Excess air = 20.9/(20.9-O2)

Look up design air flows
Calculate air flow and compare to measured flow

Air Heater Leakage

= 90 x ((O2 leaving – O2 Entering) / (21 – O2 Leaving)
    or perform both excess air and take difference.

Other Leakage

Is the leakage before the ESP

Balancing

O2 levels
Temperature
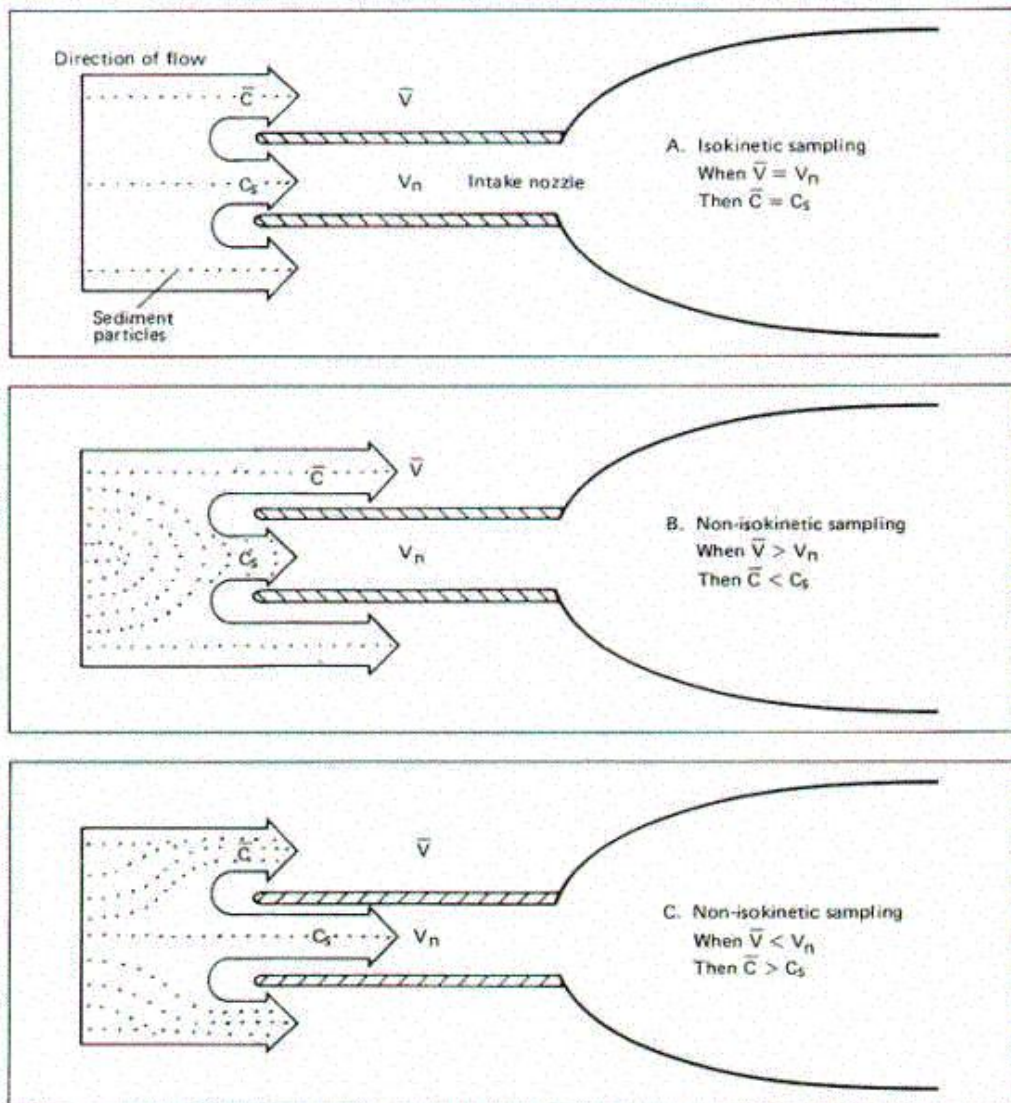Flows
Opacity
NOx

Coal Sizing
Hard work
Sampling is critical
ASTM, ASME, Dick Storm, Rotoprobe
Screening, - worn screens, QCQA
Rosin Rambler

200 mesh for capacity
50 mesh for LOI

Direction of flow

$\bar{C}$ $\bar{V}$

C_s V_n Intake nozzle

A. Isokinetic sampling
When $\bar{V} = V_n$
Then $\bar{C} = C_s$

Sediment particles

$\bar{C}$ $\bar{V}$

C_s V_n

B. Non-isokinetic sampling
When $\bar{V} > V_n$
Then $\bar{C} < C_s$

$\bar{C}$ $\bar{V}$

C_s V_n

C. Non-isokinetic sampling
When $\bar{V} < V_n$
Then $\bar{C} > C_s$

Air and Fuel Flow
    Plugged pipes
    Plugged riffles

Clean and Dirty Coal Pipe Measurements
    Error in measurements
    Both important
    Combine with iso-kinetic sampling for mass balance.

Pyrite Rejects
    These are a sample of the rocks and minerals in a coal

    Consider tuning this aspect of mill for coal cleaning

Primary Air Flow
    Moves coal though pipes
    Minimum velocities to avoid settling out of dust
    Temperature control
    Impacts flame front

Look for coal settling out on air inlet ducts

Adjustments include:
    Roller and journal pressure, alignment, air flow,
    Classifiers, temperature, ball charge, ball size,

LOI Testing and Combustion Verification

LOI Test
    Loss on Ignition
    Includes drying step

Carbon in Ash
    More expensive

HHV of Ash
    Done by standard additive method

Sampling Location
      ESP Hoppers
      Dust silo
      Ductwork

Sampling Methods
      Bucket
      Pipe
      Corn thief
      Street elbow
      Iso kinetic
      Grid-work of points
      EPA Method 17
      EPA Method 5

Operator Feedback
      Don't wait for test results if it is black
      Calibrated jars
      Take data and discuss operations with operator while
      sample is being collected

CO Analyses
      Use with O2 and NOx

NOx Analyses

Results Engineering

<u>Boiler Efficiency Testing</u>

Output/Input

Eff. = Heat in Steam/Btus of Coal

Heat Loss Method

Start with 100% and then remove

Moisture in Air
Moisture in Fuel
Moisture from Hydrogen
Unburnt Carbon
Heat in Flue gas
Radiation
Unknown and fudge

L I N E	Table 12　　Combustion Calculations Based on quantities per 10,000 Btu fuel input			L I N E
1	Fuel—*Bituminous Coal, Virginia*	**Conditions** by test or specification	Date	a
2	Analysis As Fired			
3	Ultimate, % by Wt　　Proximate, % by Wt	Total air　　　　　　　　　　　　%	120	b
4	C　80.31　　Moisture　2.90	Air temperature to heater　　　　F	80	c
5	H_2　4.47　　Volatile　22.05	Air temperature from heater　　　F	350	d
6	S　1.54　　Fixed carbon　68.50	Flue gas temperature leaving unit　F	280	e
7	O_2　2.85　　Ash　6.55	H_2O per lb dry air　　　　　　lb	0.013	f
8	N_2　1.38　　100.00			g
9	H_2O　2.90	Unburned fuel loss　　　　　　%	0.4	h
10	Ash　6.55	Unaccounted loss　　　　　　　%	1.5	i
11	100.00	Radiation loss (ABMA), Fig. 27, Chapter 4　%	0.8	j
12	Btu per lb, as fired, *14,100*			k
13	**Quantities per 10,000 Btu Fuel Input**			13
14	Fuel burned, [100 (100 — line 10) ÷ line 12] — .007 × line h　　　lb		0.66	14
15	Dry air, line b [(value from Fig. 4, Table 11 or Eq. 6) — .08 × line h]　lb		9.11	15
16	H_2O in air, line 15 × line f = 9.11 × 0.013　　　lb		0.12	16
17	Wet gas, total, lines (14 + 15 + 16)　　　lb		9.89	17
18	H_2O in fuel, 100 (8.94 × line 5 + line 9) ÷ line 12, or Table 11　lb		0.30	18
19	H_2O in flue gas, total, line 16 + line 18　　　lb		0.42	19
20	H_2O in flue gas, total, in percent, (line 19 ÷ line 17) × 100　%		4.31	20
21	Dry gas, total, line 17 — line 19　　　lb		9.47	21
22	**Losses per 10,000 Btu Fuel Input**			22
23	Unburned fuel, 10,000 × line h ÷ 100　　　Btu		40	23
24	Unaccounted, 10,000 × line i ÷ 100　　　Btu		150	24
25	Radiation, 10,000 × line j ÷ 100　　　Btu		80	25
26	Latent Heat, H_2O in fuel, 1040 × line 18　　　Btu		312	26
27	Sensible heat, flue gas, line 17 × Btu from Fig. 1 @ line e and line 20 = 9.89 × 50　Btu		495	27
28	Total losses, lines (23 + 24 + 25 + 26 + 27)　　　Btu		1077	28
29	Total losses in percent, (line 28 ÷ 10,000) × 100　%		10.8	29
30	Efficiency, by difference, 100 — line 29　%		89.2	30
31	**Quantities per 10,000 Btu Fuel Input** Combustion temperature, adiabatic			31
32	Heat input from fuel　　　Btu		10,000	32
33	Heat input from air, lines (15 + 16) × Btu from Fig. 8 @ line d temp　Btu		612	33
34	Heat input, total, lines 32 + 33　　　Btu		10,612	34
35	Less latent heat loss, H_2O in fuel, line 26　　　Btu		−312	35
36	Heat available, maximum　　　Btu		10,300	36
37	Less (lines 24 + 25) × 0.5*　　　Btu		−115	37
38	Heat available, line 36 — line 37　　　Btu		10,185	38
39	Heat available per lb of flue gas, line 38 ÷ line 17　　Btu	1021		39
40	Adiabatic temperature, from Fig. 1 for lines 20 & 39　　F	3513		40

*Note: It is customary to reduce the maximum heat available, line 36, by from ⅓ to ½ of the unaccounted plus radiation losses, on the assumption that a portion of these losses occurs in the combustion zone.

Problem areas

      Hard work
      Still need coal and ash samples
      Use theory rather than measure

Improving Boiler Efficiency

      Improving Combustion

            Low LOI
            Low excess air

      Optimizing Combustion

            O2 verse Boiler Efficiency

      Optimizing NOx
            May require higher CO and or higher LOI
            Small sizing critical

<u>Unit Heat Rate</u>

      Input/Output

      Heat rate = Btus input / kilowatts output

      Coal Sampling and Testing Results are Critical

            Concerns and Opportunities
                Piss in the bucket or dont let the sample dry out

            Gross and net differ due to the auxiliary power that the plant uses itself

      Performance Diagrams
            Feed water heaters and turbine cycle
                ONE SHOT ITTERATION

Ash Deposits . Slagging verse Fouling

Slag is Molten, Fouling is Sulfate Salts

TABLE I - Major Causes of Ash Deposits

Fuel Related	**Large pyrite particles that impact the furnace wall before they completely combust**
	Clay minerals that contain significant amounts of iron, calcium, sodium or potassium causing them to have low melting temperatures
	Interaction of pyrite, clays and alkalis with alumino silicates to form low viscosity melts
	Extremely fine or organically bound alkalis
Equipment Related	**Soot blowers not in operation or used improperly**
	Poor pulverization of fuel
	Improper air to fuel ratio
	Burners damaged or improperly adjusted
	Changes in operation of boiler or other equipment
Design Related	**Furnace size too small for fuel**
	Tube material and/or spacing inadequate
	Soot blowing coverage inadequate
	No means provided to observe slag buildup

Most Slag begins on the Furnace walls and the proceeds up the furnace

Basic Analytical Procedures

Ash Fusion Temperatures

Spread between ID and FT
Spread between Oxidizing and Reducing
Spread Between Laboratories
Impact of Combustion
Cross Plotting between other Coal Characteristics

Major and Minor Ash Elements

ASTM designates the reporting of ash elements in their fully oxidize form. This is due to the assumption that the elements are found in the ash, and ash is produced in an oxidizing atmosphere at high temperature. These elements may or may not be in the fully oxidizes form in actual power plant ash, and certainly not all in the oxidized form in the original coal. The challenge in interpreting ash analyses is to understand the actual minerals in the coal and the mineral transformations. An additional complication is that some elements can be bound to the actual coal material and are not in a mineral form. This is particularly true for calcium and sodium in low rank coals. The high oxygen content of these coals provides places for these elements to slick to the coal due to ground water movement.

One other element that causes confusion in ASTM analyses is sulfur. It is reported as SO_3 . sulfur trioxide . which is a gas commonly found in flue gas. The SO_3 reported in ASTM analyses is truly sulfur in the sulfite or sulfate form. A reaction takes place during the ashing of the coal between the calcium and the sulfur gases forming calcium sulfate. This reaction takes place at temperatures in the 1500° . 1800° F. range. The same reaction is used in fluidized bed combustors to capture sulfur using

limestone. The laboratory ashing furnace has a temperature of 1300° - 1400° F and of course the burning coal raises this locally. The SO3 reported in <u>coal</u> ash analyses is usually much higher than that found in the fly and bottom ash, due to their formation at much higher temperatures where the calcium and sulfur gases can not react. The main fouling reaction is this same reaction and will be discussed in detail in a following section.

Acid Oxides or Glass Formers

SiO2 . Silicon dioxide - Silica . Represents elemental silicon found in the   mineral Quartz, and the aluminosilicate rocks Shale, Slate, and Clays

Al2O3 . Aluminum oxide - Alumina . Represents the aluminum found in the aluminosilicate rocks and minerals, not the mineral corundum (Al2O3) which is an industrial abrasive and also the gems rubies and sapphires

TiO2 . Titanium dioxide . Titania . Seams to always be about one to two percent

Basic Oxides or Fluxing agents or Gluing Elements

Fe2O3 . Iron oxide . hematite . Represents the elemental iron in its fully oxidized form. Iron in coal is in pyritic and carbonate forms, iron in ash can be in elemental, reduced and oxidized form. This element is **one of the most important** in influencing slagging behavior

CaO . Calcium oxide . lime . represents both mineral (calcite, limestone) and organically bound calcium. The oxidation state of this element is basically fixed to CaO. There is less impact of the oxidizing conditions on the fusion temperatures of high calcium coal ash. This element is also **one of the most important** in slag and fouling deposits

MgO . Magnesium oxide . generally lower, (less than six percent) than the calcium, but follows calcium levels as the mineral dolomite.

K2O . Potassium oxide . typically found in clays and other aluminosilicates

Na2O . Sodium oxide . found in several forms depending on coal rank and depositional environment, Organically bound form common in low rank coals and NaCl found in coals saturated with sea or briny water. Sodium is also **one of the three important elements** in slag and fouling deposits.

SO3 . Sulfur trioxide . actually in the solid form of sulfates combined with calcium and other basic elements. Not commonly found in high levels in fly and bottom ash. It is found in fouling deposits held together by calcium sulfate.

Basic Slagging factors

B/A . Base to acid ratio, sum of total bases divided by sum of all acid elements

$$B/A = \frac{Fe2O3 + CaO + MgO + K2O + Na2O}{SiO2 + Al2O3 + TiO2}$$

Since most of the basic elements are troublesome the B/A is an indication of the level of fluxing agents.

Slagging Factor . Dry sulfur times the B/A provides a result that is similar to an iron squared term $(Fe2O3)^2$, this is due to Fe2O3 being a base and a significant portion of the sulfur being in the pyritic form, FeS2.

Ash and Elemental Loading . ash and important elements reported in pounds per million Btus. We all ready use $/MBtu to evaluate the price of coal and report sulfur dioxide SO2 levels in Lbs./MBtu. These calculations report the ash and elemental

Lb. Ash/MBtu = %Ash/(Btu/lb./10,000)

Elemental loading = Ash Load x Element %/100

Example . Which coal has more iron?

	Coal 1	Coal 2
Ash	=9.0%	14.0%
Btu/lb	=12,300	11,200
Fe2O3	=12.0%	9.0%

<u>Coal 1</u>

Lb. Ash/MBtu = 9/(12,300/10,000) = 9/1.23 = **7.3**

Lbs Fe2O3 = 7.3 x 12.0/100 = 7.3 x 0.12 = **0.88**

<u>Coal 2</u>

Lb. Ash/MBtu = 14/(11,200/10,000) = 14/1.12 = **12.5**

Lbs Fe2O3 = 12.5 x 9.0/100 = 7.3 x 0.09 = **1.13**

Percent iron that Coal 2 has more than Coal1 =

1.13/.88 = 28 % more iron in Coal 2

This example illustrates the importance of data manipulation rather than just using the straight ASTM levels reported by the laboratories.

Advanced Methods for Slag

Mineral and Elemental Analyses of Coal

Computer Controlled Scanning Electron Microscopy (CCSEM)

Uses Energy Dispersive X-ray Analyses (EDAX) to size and quantify elemental composition.

Low Temperature Ashing

Microscopically identify minerals present

Chemical Fractionation

Provides information on Organically Bound elements

Elemental Analyses of float sink and/or size fractions

Can be performed by ASTM coal laboratories

Pounds of iron per million Btu

Pounds calcium, sodium, and other elements

Ash Deposit Analyses

Sampling Procedure for Ash Deposits

Polarized Light and Scanning Electron Microscopy

Look for the glue holding the material together
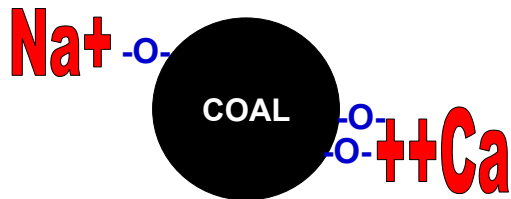Look for signs of combustion conditions

Forms of Iron by chemical fractionation

Mossbauer spectroscopy

Fouling Deposit Formation

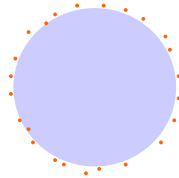Organic calcium and sodium elements vaporize during combustion
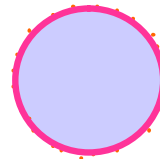
Organically Bound Alkalis

The calcium reacts with sulfur gases to form calcium sulfate.

Sodium can condense onto aluminosilicate flyash particles and melt the surface

Sodium Condenses on Surface

Causing a Molten Layer on Surface

Electrostatic Precipitators

Basic Operation Principles

High Voltage DC . Transformer Rectifier Sets

Voltage Control . Controlling the wave from and sparking rate

Sizing ESP . Plate area (fixed) and Flue gas volume
(operational variable?)

Migration Velocity or why the particle goes to the plate

Ash Resistivity concerns

Gas Velocity . impacts ESP size and treatment time

Rapping . important equipment that can be high maintenance

Hopper Evacuation . useful for determining ash partitioning
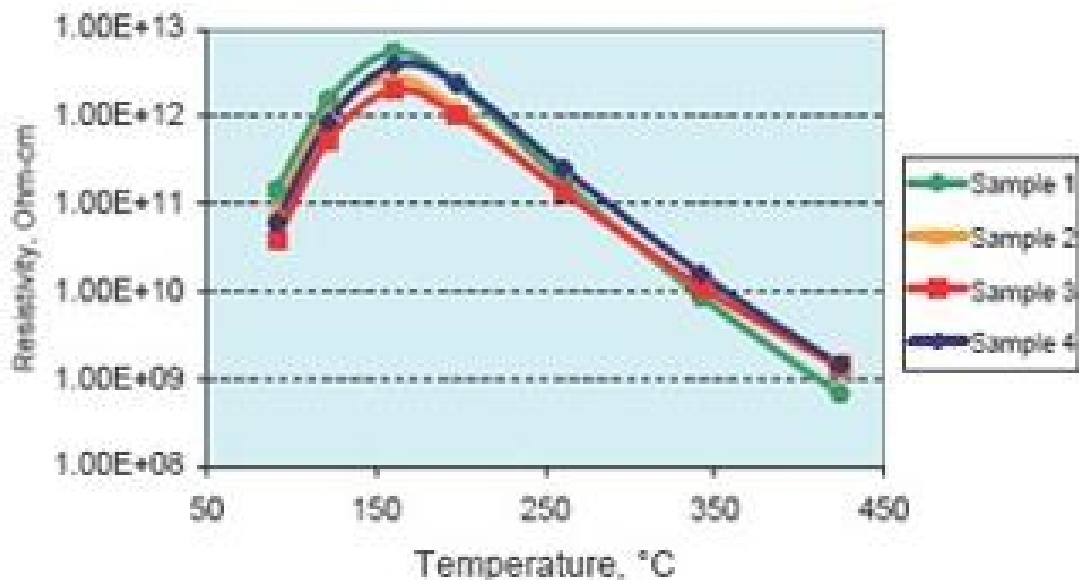
Dust Collection and Storage

Figure 3   Variation of Resistivity vs Temperature of typical Indian fly ash samples.

Advanced ESP Methods and Tune-up

Combustion Influences

ESP is meant to collect ash, not carbon from incomplete combustion

Resistivity, volume of material, and potential fires all point towards spending time on combustion

Air in leakage and air heater leakage can significantly impact ESP performance

Balancing furnace and flue gas flows

What do you balance, flow, temperature, excess air?

Calculating and Measuring Fly Ash Resistivity

Calculation Methods

Laboratory Measurements

In situ Measurements

Cup Collection Method

Point to Plane Resistivity Probe

Correlating and making sense of resistivity data

Rappers

Adjustment and different thoughts on rapping sequencing

Inspections and Maintenance

Measuring rapper force

High Voltage controls

    Spark rate theories

    Ramp rate, hold and setback settings

Measuring gas flows and particular loadings

    EPA Methods 5 and 17

    Hotwire anemometer

ESP Inspections

    Learn form your inspector

    Mechanical and Electrical
Tune-up Procedures

    Good Combustion
    Furnace conditions and temperatures
    Air Leakage
    Rapper Performance
    Balancing
    Voltage controls