APTI Course 427

Combustion Source Evaluation

Chapter 3:
Fuel Characteristics

Chapter Overview (outline)

- Fuel Characteristics and Usage Trends
- Fuel Analyses
- Fuel Properties (Gas, Oil, Coal)
- Other Solid Fuels

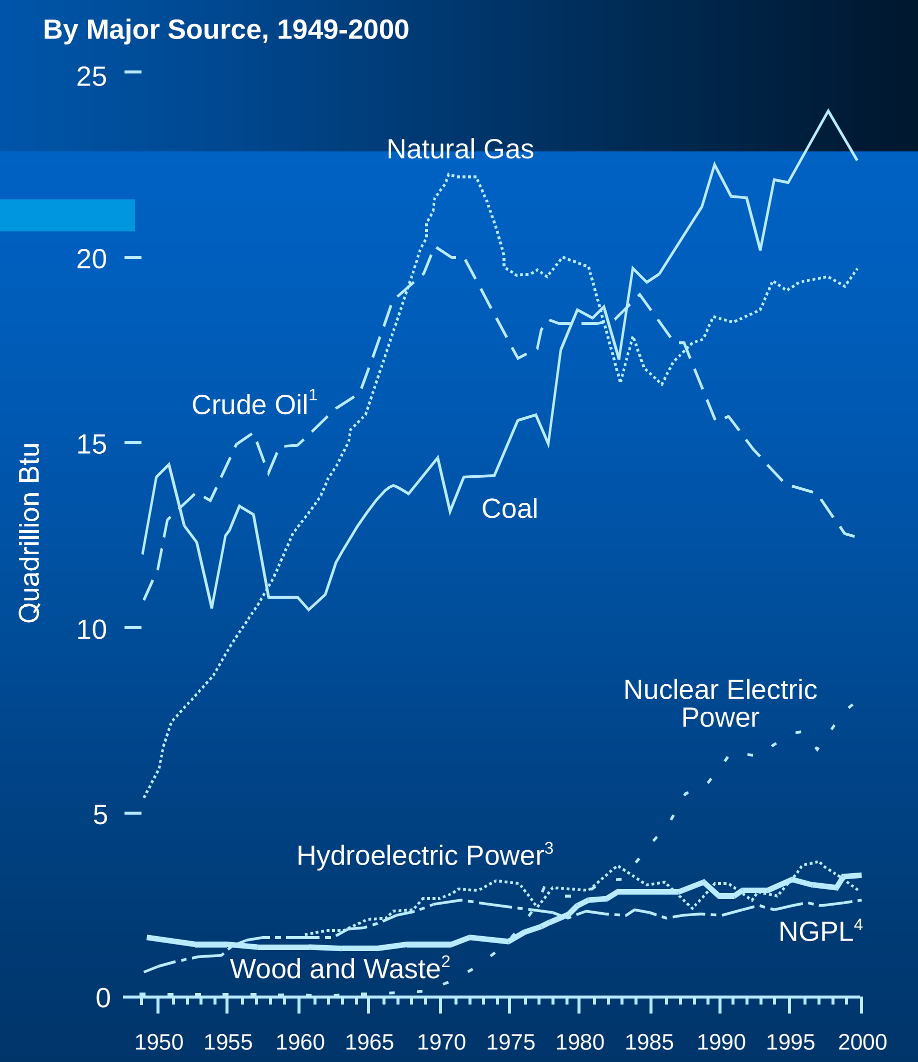
Some History

- Wood, the original fuel
- Coal, more abundant and efficient
- Oil, a cleaner ?? fuel
- Natural Gas, clean, cheap, abundant

Fuel Categories

Table 3-1. Fuels	
Fuel Category	***Examples***
Solids	Bituminous coal, sub-bituminous coal, lignite, peat, wood
Liquids	Kerosene, No. 2 oil, No. 6 oil, coal-water emulsions, oil-emulsion
Gaseous Fuels	Natural gas, propane, landfill and biological gases
Wastes	Municipal and medical wastes, hazardous wastes, sewage sludge, tires
Biomass	Wood and wood waste, bagasse, straw

US Energy Production Trends



[1] Includes lease condensate
[2] Includes ethanol blended into motor gasoline
[3] Conventional and pumped-storage hydroelectric power
[4] Natural gas plant liquids

Natural Gas Production

- A perceived shortage caused production to drop in the 70's
- Its availability has resulted in power plants that can only burn gas
- Distributed power generation may drive a continued increase in gas use.

Energy Consumption

Table 3-2. U.S. Energy Consumption, 1993-1997 Energy Use Expressed in Quadrillion BTU						
Energy Source	*Energy Type*	*1993*	*1994*	*1995*	*1996*	*1997*
Fossil Fuels	Coal	19.837	20.027	20.090	21.011	21.439
	Natural Gas	20.827	21.288	22.163	22.560	22.588
	Petroleum	33.841	34.735	34.663	35.864	36.314
Total Fossil Fuels		74.522	76.073	76.943	79.434	80.360
Renewable Fuels	Hydroelectric Power	3.147	2.996	3.472	3.914	3.932
	Geothermal Energy	0.393	0.395	0.339	0.352	0.322
	Biomass	2.784	2.838	2.846	2.938	2.723
	Solar Energy	0.071	0.072	0.073	0.075	0.074
	Wind Energy	0.031	0.036	0.033	0.035	0.035
Total Renewable Fuels		6.426	6.309	6.763	7.315	7.086

Source: DOE/EIA –0603(98)/1 Energy Information Administration [2]

Fuel Analyses (outline)

- Basis of Fuel Analysis
- Market Characteristics
- Ultimate Analysis
- Ash Composition Data
- Size Distribution of Solid Fuels

Basis of Fuel Analysis (outline)

- Purpose
- Examples
- Types
- Technique

Fuel Analysis - Concept

- Laboratory analysis of a fuel sample
- Original purpose – suitability for a particular combustor
  - Octane for a gasoline engine
  - #6 Oil viscosity
  - Coal ash melting temp for a PC boiler
- Purpose is expanded for environmental issues
  - Sulfur content

Examples of Fuel Analysis

- The analysis reports properties or % composition on different basis – such as:
  - As-received
  - Air-dried
  - Moisture free
  - Mineral and ash free

Types of Fuel Analysis (cont.)

Table 3-3. Fuel Analysis – Common Elements			
Type of Analysis	*Coal and Solid*	*Oil*	*Gas*
Market (Proximate)	▪ Heating value per lb. ▪ Moisture ▪ Sulfur ▪ Volatiles ▪ Fixed carbon ▪ Ash	▪ Heating value per gal. ▪ Density or API gravity ▪ Sulfur ▪ Viscosity ▪ Pour point ▪ Water & sediment	▪ Heating value per ft^3 ▪ Specific gravity
Ultimate (Chemical)	▪ C, H, S, N ▪ Oxygen by difference ▪ Moisture ▪ Ash	▪ C, H, S, N ▪ Oxygen by difference ▪ Moisture ▪ Ash	▪ CH_4, C_2H_6, C_3H_8, etc. ▪ CO_2, N_2, H_2O ▪ O_2
Ash or Trace Element	▪ SiO_2, Al_2O_3, TiO_2 ▪ Fe_2O_3, CaO, MgO ▪ K_2O, Na_2O, Cl, Hg ▪ Others by request	▪ V, Na, ▪ Others by request	▪ Others by request

Sample Acquisition

- Lab sample should be representative
- Oil & gas – easy but not fool proof
- Coal, wood, other solid fuels
- Municipal waste

Market Characteristics

- Proximate Analysis of coal
- Primary characteristics
  - Heating Value
  - Sulfur Content
- Secondary characteristics
  - Moisture Content
  - Ash or Mineral Content
  - Volatile Matter & Fixed Carbon
- Fuel Oil Secondary characteristics
  - Viscosity

Heating Value

- Fuel value is $/mmBTU

- Definitions
  - BTU
  - Higher Heating Value (HHV)
  - Lower Heating Value (LHV)

Heating Value Uses

- HHV – total energy (exhaust at ambient temp)
- LHV – HHV minus water vapor energy
- Difference is about 1030 BTU/lb of water

Higher and Lower Heating Values

Table 3-4. Fuel Heating Values - BTU/lb

Fuel	*HHV*	*LHV*
Natural Gas	22,200	20,000
No. 2 Oil	19,000	17,860
No. 6 Oil	18,200	17,300
Bituminous Coal	14,000	13,600
Doug Fir- Dry	9,000	8,400

HHV – LHV Issues

- Both HHV & LHV reported in BTU/lb
- Fuel suppliers and Utilities use HHV
- EPA and emissions reporting use HHV
- Engine manufacturers use LHV
- Calculations of fuel use or emission rates can err by 10% using the wrong units.

Example 1. Fuel Use Calculation

A combustion process operates at 10 mmBTU/hr. Fuel A has HHV=11,000 BTU/lb. Fuel B has HHV=12,750 BTU/lb.

What is the difference in amounts needed for alternatives A and B?

Solution:

$$\text{Fuel A} = \frac{H_T \text{ Release Rate}}{\text{Fuel HHV}} = \frac{10 \times 10^6}{11{,}000} = 909 \ {}^{lb}\!/_{hr}$$

$$\text{Fuel B} = \frac{H_T \text{ Release Rate}}{\text{Fuel HHV}} = \frac{10 \times 10^6}{12{,}750} = 784 \ {}^{lb}\!/_{hr}$$

Example 2. Ash Quantities

Both fuels from example 1 have an ash content of 10.5%. If the boiler operates 7000 hours per year, what change will occur in the total quantity of ash for disposal? Assume none of the ash escapes into the atmosphere.

Solution:

$$\text{Present Ash Quantity} = \frac{0.105}{12{,}750} \times 10 \times 10^6 \times 7{,}000 = 576{,}500\ ^{lb}\!/_{yr}$$

$$\text{Future Ash Quantity} = \frac{0.105}{11{,}000} \times 10 \times 10^6 \times 7{,}000 = 668{,}200\ ^{lb}\!/_{yr}$$

So the ash quantity will increase by 92,000 lb

Sulfur Content

- Why report? Typically air emission source permits limit fuel S to control SO_2 emissions

- Examples
  - Coal limited to 1% S
  - Oil limited to 0.5% S

Proximate Analysis Data

- Market analysis specific to coal
  - HHV
  - Sulfur
- ASTM D271
  - Ash
  - Fixed carbon
  - Volatile matter
  - Moisture (surface & inherent)

Moisture Content Impacts

- Amount of fuel required to fire a furnace
  - Water adds weight
  - Water absorbs energy converting to steam
- Water vapor in the flue gas effects
  - Emission measurement procedures
  - Performance of emission control equipment

Volatile Matter

- Organic compounds that vaporize when the fuel is heated
- Volatile matter supports ignition and rapid combustion – necessary for some combustors

Fixed Carbon

- Carbon remaining after heating (nonvolatile)
- Stoker furnace – fuel that will burn on the grate
- Burn rate - slow

Ash or Mineral Content

- Inorganic solids
- Furnace ash management
- Indicator of potential particulate emissions

Fuel Oil Market Properties

- HHV
- Density or Specific gravity
- Pour point
- Viscosity
- Water and sediment

Fuel Oil Density

- Oil is purchased by the gallon
- HHV is measured on a mass basis (BTU/lb)
- Density is used to report BTU/lb

$$Sp.gr@60^{o}F = 141.5/(API + 131.5)$$

Ultimate Analysis

- Elemental analysis by ASTM D3176
- Used primarily for emissions analysis
  - Needed to calculate F-factor
- Always totals to 100% (oxygen by difference)

Ultimate Analysis (cont.)

Table 3-5. Typical Ultimate Analysis for Coal and No. 6 Oil (% by wt.)			
Analyte	*Coal – As Received*	*Coal – Dry Basis*	*No. 6 Oil*
Moisture	3.03	0	nil
Carbon	60.68	62.58	85.78
Hydrogen	4.35	4.49	10.59
Nitrogen	1.12	1.16	0.03
Chlorine	0.12	0.12	
Sulfur	4.29	4.42	2.13
Ash	19.18	19.78	0.10
Oxygen (diff.)	7.23	7.45	1.37
Total	100.00	100.00	100.00

Ash Composition Data

- Solid material left after complete combustion
- Fate in a combustor
- Example: 150 tons of 10% coal leaves 15 tons of ash

Ash Composition Data (cont.)

Table 3-6. Example of Coal Ash Composition (%)		
Mineral	*Ash No. 1*	*Ash No. 2*
SiO_2	38.94	55.93
Al_2O_3	22.75	25.02
TiO_2	1.03	1.15
Fe_2O_3	30.97	9.73
CaO	1.59	0.81
MgO	0.94	1.07
K_2O	1.82	2.36
Na_2O	0.46	0.46
SO_3	0.31	0.85
P_2O_5	0.10	0.12
SrO	0.02	0.00
BaO	0.08	0.12
Mn_3O_4	0.10	0.02
Undetermined	0.89	2.36

Size Distribution of Solid Fuels

- Fuel particle size matters
  - Determines the burn rate
  - It usually governs carbon carry over
- Measuring Particle Fuel Size
- Stoker Fuel Sizes
- Pulverized Coal Size

Measuring Fuel Size

ASTM Sieves

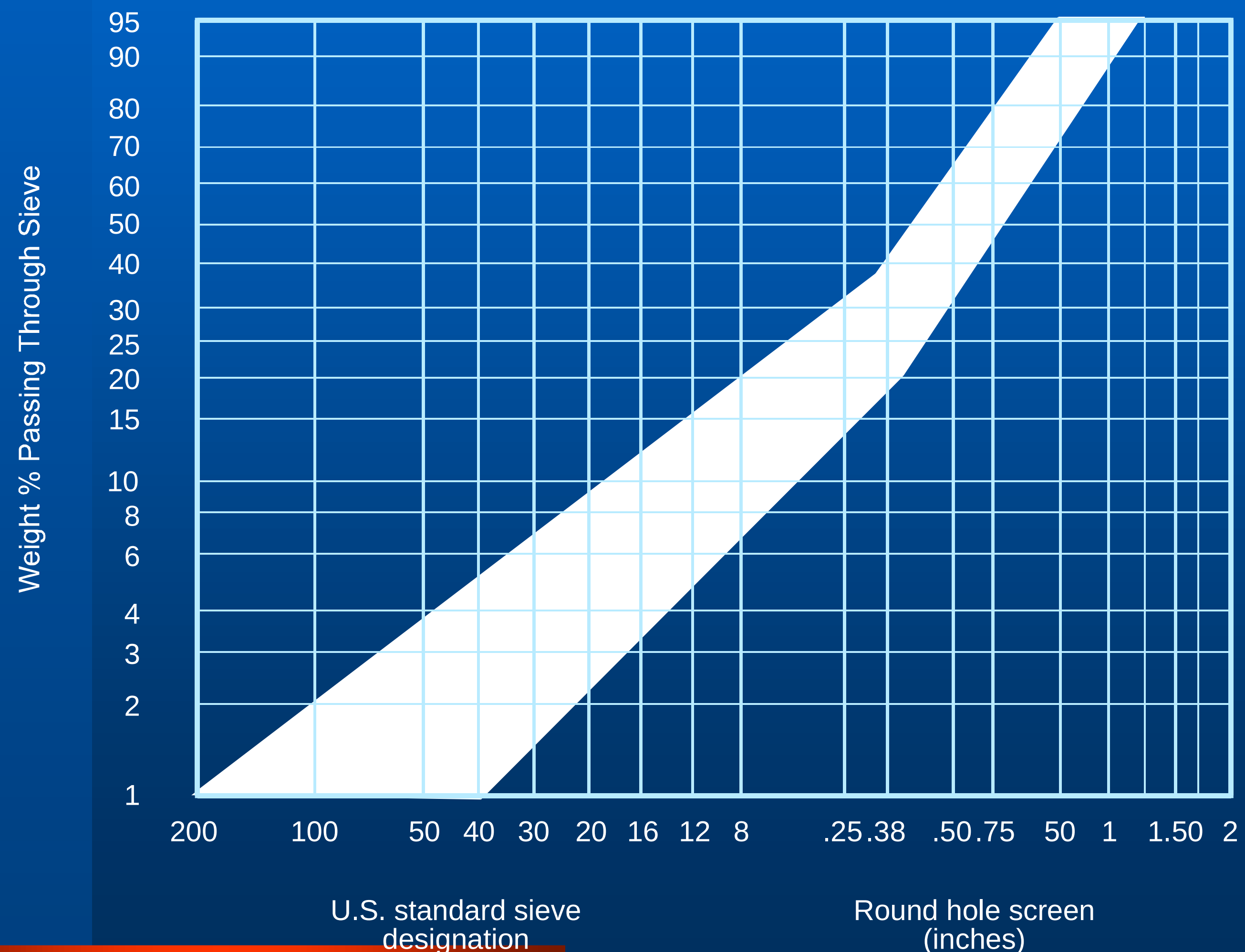
Measuring Fuel Size (cont.)

Table 3-7. Standard Sieve Size		
Mesh	***Size (mm)***	***Size (inch)***
200	0.075	0.003
100	0.15	0.006
50	0.30	0.012
35	0.50	0.020
18	1.00	0.039
10	2.00	0.079
8	2.36	0.093

Stoker Fuel Sizes

- The larger the particle the longer it takes to burn
- 0.5 Inch is typical
- Limits
  - Particles <2 mm can be blown out of the furnace
  - Particles >0.2 mm are too big to burn in suspension

Example Specification



Stoker Fuel Sizes (Cont.)

- Off spec coal is usually cheaper than the good stuff.
- Wood or wood waste
  - Little control over size. Adapt the system.
- Municipal and medical wastes
  - RDF

Example 3. Stoker coal sizing

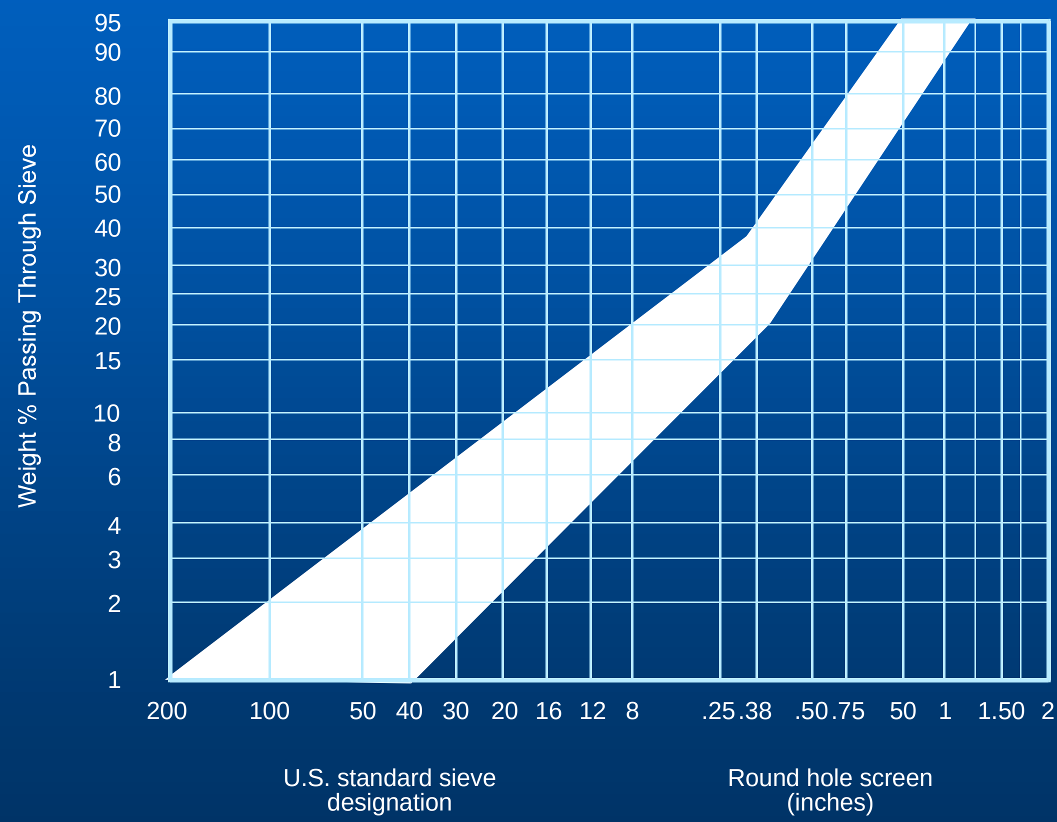
A coal supply to be used for a spreader stoker has a size distribution as indicated in the following table. Is this material appropriately sized for use in the boiler if the size curve shown in Figure 3-3 applies?

Coal Size Range	*Wt. % smaller*
< 3/8	80
< 1/8	25
<20 mesh	8
< 50 mesh	6

Note: Mesh sizes apply to standard ASTM sizing screens

Stoker Coal Example

- More coal req'd > 3/8"
  - 80% vs 18% – 40%
- 1/8" is close
  - 25% vs 8% – 22%
- 20 Mesh is OK
  - 8% vs 2% – 9%
- Too much <50 mesh
  - 6% vs <4%



Pulverized Coal Size

- (Powdered) coal burns in suspension
  - The finer the better
  - Fine size traded against grinding cost
- 50, 100, 200 Mesh screens
  - Generally 90% - 95% passes 200 mesh
  - >50 Mesh coal is too large for suspension firing

Fuel Properties (outline)

- Gas Fuels
- Fuel Oils
- Coal

Gas Fuels

- Advantages
  - Clean burning, clean handling
  - Mixes with air
- Constituents
  - Natural gas is mostly methane (CH_4)
- History
  - Original commercial gas made by heating coal
- Types
  - Natural Gas
  - Propane and Liquefied Petroleum Gas
  - Waste Biological Gases

Natural Gas

- Transportation
- Composition
  - See table 3-9
- Heating value

Natural Gas (cont.)

- Sour gas & Sweet gas
  - Refers to the amount of reduced sulfur compounds
- Lean gas
  - High methane content, meaning
  - Low heating value
- Wet gas
  - Contains condensable organic compounds

Propane and LPG

- Properties
  - Liquid at 15 psi → sold by the gallon
- Composition
  - Mostly (97%) propane (C_3H_8)
- Heating value – 2500 BTU/ft^3
- Used where natural gas is not available

Waste Biological Gases

- Generated in anaerobic conditions
  - Digestive tracts
  - Landfills
  - Sewage treatment
- Landfill formation rates vary
  - Water, oxygen exclusion required
- Biogas
  - Anaerobic digestion of sewage sludge

Fuel Oils

Fuel oil classification using ASTM standards.

Table 3-10. ASTM Fuel Oil Specifications						
Grade	*Flash Point, °F (°C) (EC)*	*Water and Sediment, (% by vol.)*	*Sulfur Content, (% by vol.)*	*Ash Content, (% by vol.)*	*Viscosity (centistokes)*	*Specific Gravity @60 °F*
	Min.	Max.	Max.	Max.	Min.	Max.
No. 1	100 or legal (38)	trace	0.5		2.2	0.85
No. 2	100 or legal (38)	0.10	0.5		3.6	0.85
No. 4	130 or legal (55)	0.50	–	0.10	26.4	
No. 5 (Light)	130 or legal (55)	1.00	–	0.15	65.0	
No. 5 (Hvy)	130 or legal (55)	1.00	–	0.15	194.0	
No. 6	140 or legal (60)	2.00			2,200.0	

Source: DOE/EIA –0603(98)/1 Energy Information Administration [2]

Distillate vs. Residual

- Refining crude oil
  - Distillate products
  - Residual (#6, Bunker C)
- Composition
  - Distillate is fairly clean
  - Residual concentrates most of the crude contaminants
- Residual fuel is cheaper to buy but more expensive to handle/use
- #6 Must be heated to pump or burn

Common Fuel Oils

Table 3-11. Typical Properties of Common Fuel Oils						
Grade	*Name*	*Color*	*Sulfur*	*Ash*	*BTU/Igallon*	*Comments*
No. 1	Kerosene	Light	0.0 – 0.5	Nil	137,000	
No. 2	Distillate	Amber	0.0 – 0.7	Nil	141,000	Home heating fuel
No. 4	Light Residual	Black	0.2 – 2.0	0.0 – 0.1	146,000	Fluid at ambient temperature
No. 6	Residual	Black	0.7 – 5.0	0.1 – 0.5	150,000	Heat required to pump or burn

Source: DOE/EIA –0603(98)/1 Energy Information Administration

Distillate fuel oil

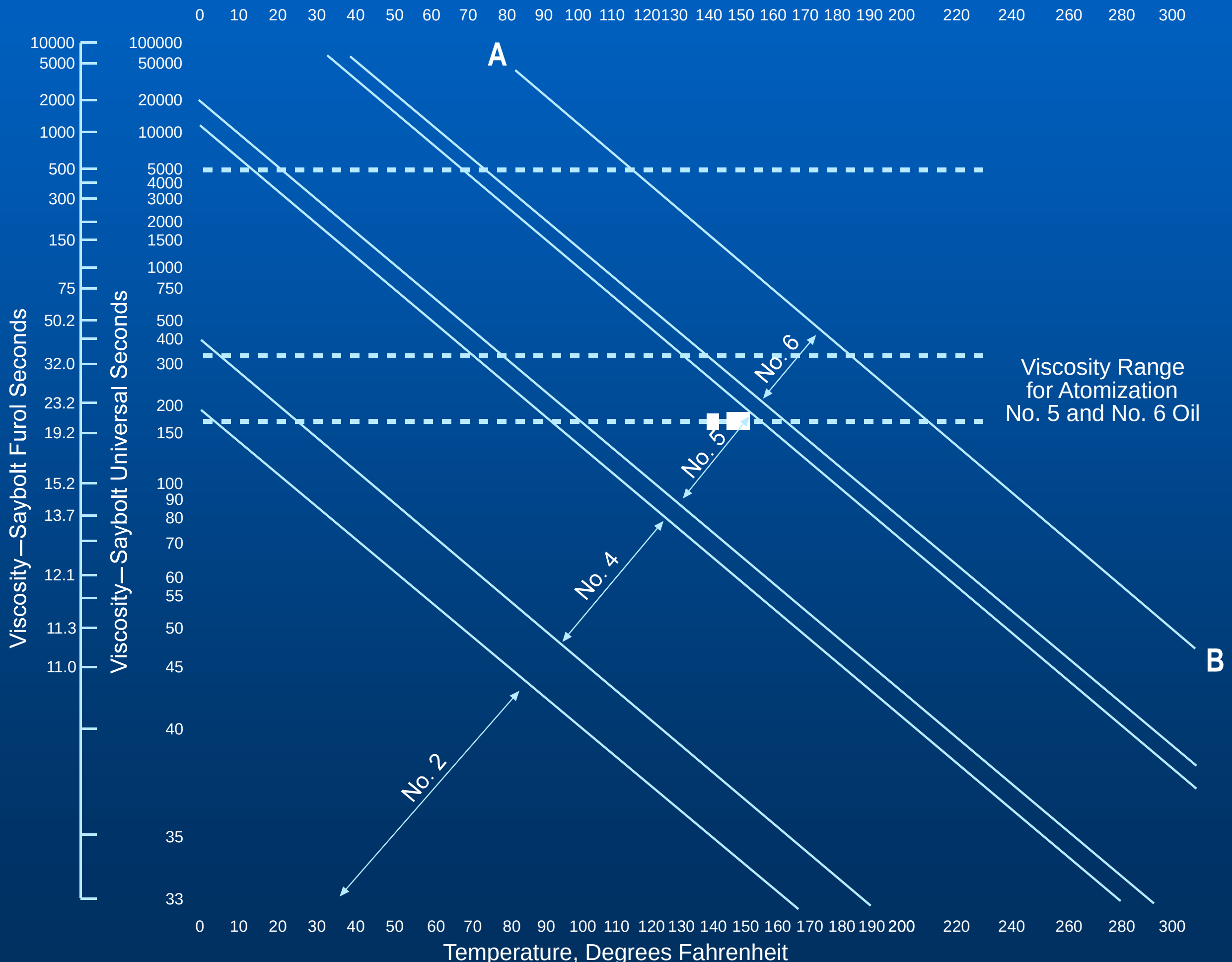
- #2 Oil, Diesel, Kerosene
- Viscosity can vary seasonally
- ASTM sulfur limit is 0.5%
  - Highway diesel limit is 0.05% (500 ppm)
  - Future diesel limit will be <100 ppm)

Residual Oil

- Residual properties are tailored to the market
- The ultimate residue is petroleum coke (solid)
- Marketable sulfur contents
  - 2.2% in the 1970's
  - Typically 1% or less today
- Residual oil has vanadium & other metals

- #4 Oil is thinner (more pumpable) than #6

Oil Viscosity-Temp Relationship



Emulsions (outline)

- Oil-water
- Coal- water

Oil Emulsions

- Oil-water mixtures
  - Very heavy oil becomes pumpable (Oremulsion)
- Combustion can be somewhat different
  - Substitute for poor atomization
  - Some NOx reduction

Coal-Water Emulsions

- Finely pulverized coal + water = liquid
  - Dispersant needed to keep coal in suspension
- Allows coal to be fired in an oil designed system – in theory
  - Coal ash content is 100 times oil ash
  - Furnace systems not designed for coal, can't easily use it.

Coal

- Primary fuel for electric power generation
- Classification (see Table 3-12)
  - Anthracite (high fixed carbon content)
  - Bituminous (higher volatile content)
  - Subbituminous (lower heating value)
  - Lignite (heating value < 8300 BTU/lb)
- Example properties (see Table 3-13)

Anthracite (hard coal)

- Source – mostly central Pennsylvania
  - A premium fuel
- Slow burning, not smokey → residential use
- Usually low sulfur

Bituminous

- Tend to form sticky “bitumen” when heated
- Volatile content 15% to 35% → fast burning
- Primary fuel for electric utility PC boilers
- Sulfur, ash & mercury content varies

Subbituminous

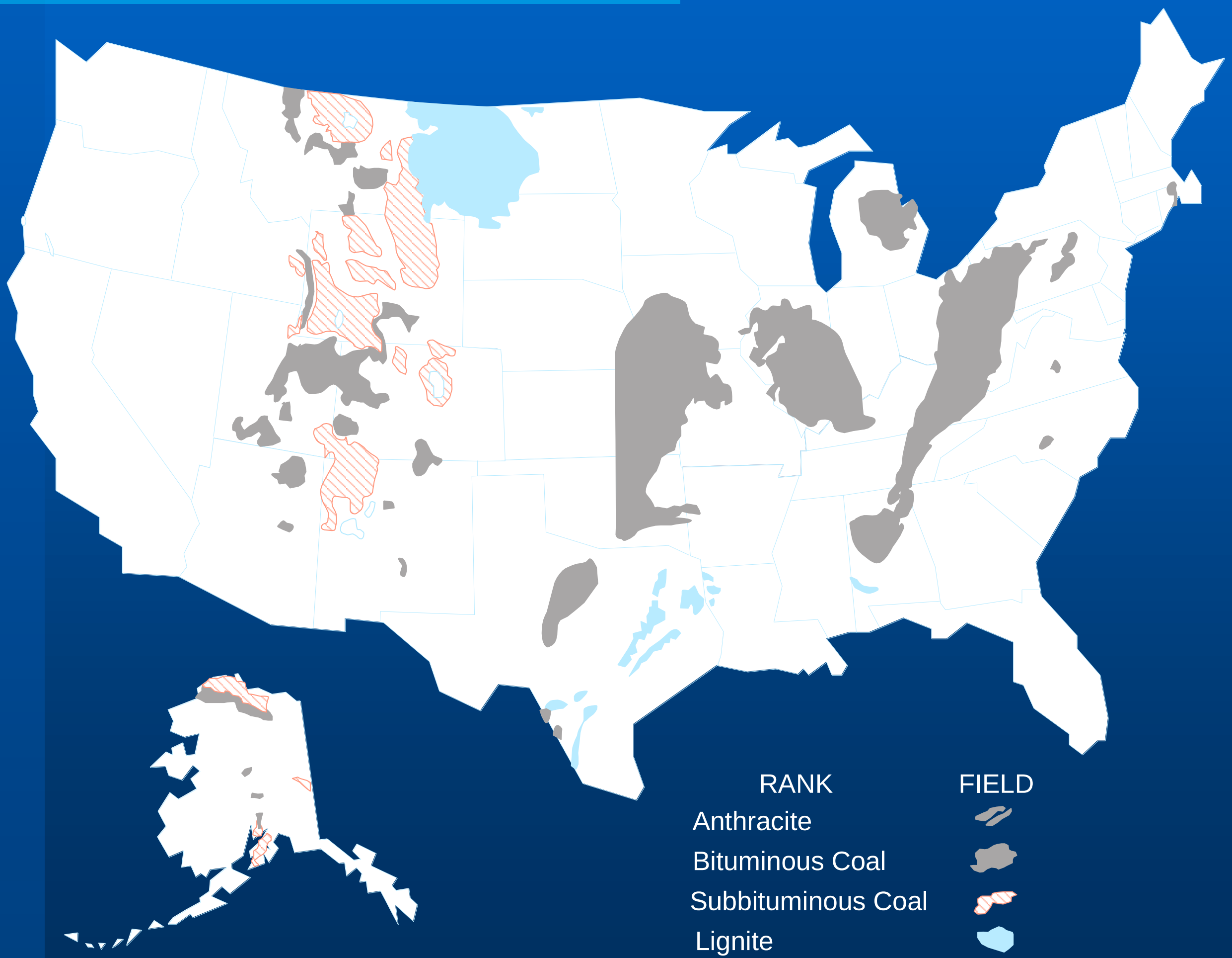
- Typically western coal

- Moisture content higher
- Sulfur content lower
- Ash content higher

Lignite

- Young coal, older than peat
- Very high moisture levels (30%)
- High volatile content
- Low heating value
- Susceptible to spontaneous combustion

Geographic Distribution of Coal



Coal Properties Related to Combustion (outline)

- Agglomerating /Caking Tendencies
- Ash Softening and Fusion Temperatures
- Stoker Fuel Size Distributions
- Coal Size Terminology
- Grindablity and Friability

Agglomerating/Caking Tendency

- Free Swelling Index by ASTM D720
  - Scale of 0 (free burning) to 9 (severe swelling)
- Tendency to fuse and swell when burning compromises stoker operation
- Coke from swelling coal is less dusty

Ash Softening and Fusion Temperatures

- Ash melting temperature affects accumulation in a PC boiler
- ASTM Procedure D1857-68
  - Initial deformation temperature
  - Softening temperature
  - Fluid temperature
- Ash chemistry determines temperature behavior.

Stoker Coal Size Distributions

- Most stoker coal is fired as purchased
  - Size distribution affects operation & emissions
- Spreader stoker distributes according to size
  - Too much fines accumulates below spreader
  - Too much oversize piles up elsewhere
- 0.2mm to 2mm fines in suspension cause carbon carryover

Coal Size Terminology

Table 3-14. Common Use Size Distribution Terms for Bituminous Coal		
Coal Category	*Size Description*	*Size Characteristics*
Bituminous	Run-of-mine	No size segregation
	Run-of-mine 8 inch	Lumps greater than 8 inches broken
	Lump	Larger than 5 inches
	Egg	Smaller than 5 inches and larger than 2 inches
	Nut	Smaller than 2 inches and larger than 1.25 inches
	Stoker	Coal smaller than 1.25 inches and larger than 0.75 inches
	Slack	Coal smaller than 0.75 inches

Source: DOE/EIA –0603(98)/1 Energy Information Administration

Grindability and Friability

- Grindability affects PC boiler operation
  - Hard grinding coal consumes more power or
  - Yields larger particle sizes
- Hardgrove grindability (ASTM D4090)

- Friability – How much dust is generated?
- Technique
  - Drop-shatter test
  - Tumbler test

Contaminants, Air Pollution, Cleaning (outline)

- Mercury
- Ash
- Sulfur
- Coal Cleaning

Mercury

- Forms – all are vapors
  - Elemental, oxide, chloride
- Fate – moves up the food chain
- Control – still evolving
- Levels (see Table 3-15)

Coal Ash

- Forms
  - Inherent
  - Incidental (rock & dirt)
- Cleaning can remove some incidental ash

Coal Sulfur

- Forms (ASTM D2492)
  - Pyritic sulfur
  - Organic sulfur
  - Sulfates

- Pyritic sulfur
  - Affects boiler slag
  - Causes SO_2 emissions from kilns

Coal Cleaning

- Purpose – remove rock & dirt
- Techniques
  - Hand sorting
  - Washing (flotation)
  - Froth flotation
- Cleaning may reduce ash by 25% - 50%

Other Solid Fuels (outline)

- Fossil Solid Fuels
- Wood
- Biomass Fuels
- Solid Wastes

Fossil Solid Fuels

- Peat
  - High moisture, low heating value
  - Rarely used commercially

Fossil Solid Fuels (2)

- Coke – carbon residue from heating coal
  - Main use is for steel making
- Metallurgical Coke
  - Ash is compatible with steel chemistry
- Petroleum Coke
  - High sulfur, low ash
- Coke breeze
  - Fines (<1/8”) generated during coke mfr
- Charcoal

Wood (outline)

- Green Wood (forest products)
- Mixed Wood Waste
- Dry Wood Waste (manufacturing)
- Sawdust and Sander Dust

Wood Chips (see Table 3-16)

Green Wood

- Common fuel and forest products mills
- Generated on site or purchased
  - Debarking & sawing operations
  - Chipping up trees too small to saw
  - Chipping up logging slash
- Green wood moisture usually >30%
  - Clean burning can be a challenge

Mixed Wood Waste

- Source
  - Construction & demolition, pallets
  - Can contain inorganic material
  - Usually dry, easy burning
- Processing
  - Shredded to facilitate conveyers & feeders
- Pollution impacts
  - Pressure treated wood burns clean, but is highly regulated.
  - Paint & dirt tend to increase particulate emissions

Dry Wood Waste

- Heating value can be 8000 to 10,000 BTU/lb
  - Dry wood burns easily, cleanly
- Sawdust, sander dust
  - May be blown directly from the source (no storage)
  - Typically burned in suspension
  - Fines >0.2 mm tend to create carbon carryover

Biomass Fuels

- Burned directly or converted to liquid fuel
- Fuel crops
  - Some wood fired boilers
  - Ethanol from corn
- Agricultural wastes

Biomass Fuels

Table 3-17. Bagasse Properties	
Analyses (as-fired), % by wt	*Value*
Proximate	
Moisture	52.0
Volatile Matter	40.2
Fixed Carbon	6.1
Ash	1.7
Analyses (as-fired), % by wt	*Value*
Ultimate	
Hydrogen, H_2	2.8
Carbon, C	23.4
Sulfur, S	trace to 0.6
Nitrogen, N_2	0.1
Oxygen, O_2	20.0
Moisture, H_2O	52.0
Ash	1.7
Heating Value	
Btu/lb.	4,000
kJ/kg	9,304

Solid Waste Fuels

- Waste-to-Energy
  - Facilities with no energy recovery are incinerators
- Municipal waste composition (Table 3-18)
  - Varies locally & seasonally
  - Not amenable to simple fuel analysis
- Problematic materials
  - Toxic: asbestos, batteries with mercury
  - Hazardous: fuel tanks, ammunition, compressed gas

Medical Waste (Table 3-19)

- Similar to MSW but
  - Moisture can be low
  - Heating value may be high
  - May have chloride from PVC plastic

- Regulated Medical Waste (some States)
  - Infectious, blood soaked, anatomical
- Small hospital incinerators have largely disappeared

Chapter Summary

- Fuel trends
- Sampling & analysis
- Heating values
- Contaminants
- Size distribution
- Natural gas constituents
- Fuel oil
- Coal properties
- Coal combustion
- Mercury levels
- Wood fuels
- Other solid waste fuel