

REINHOLD ENVIRONMENTAL Ltd.



2010 APC Round Table & Expo Presentation

July 18-20, 2010, in Concord, NC / Hosted by Duke Energy

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Biomass 100% and Co-Firing Basics



*For Energy and
Environmental
Solutions*

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2010 APC Round Table

Charlotte, NC

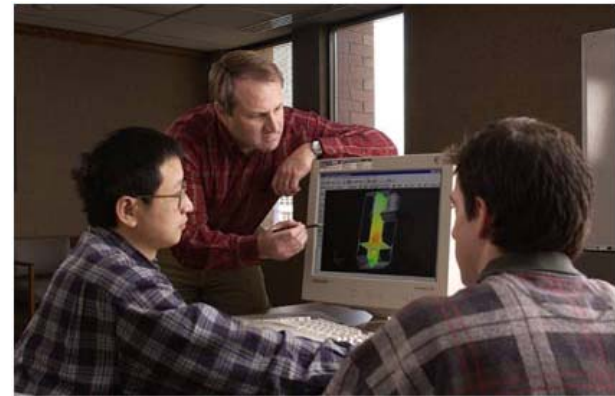
July 19&20, 2010



Reaction Engineering International

➔ Energy & Environmental Consulting Firm Specializing In:

- ◆ **System Design and Performance Analysis**
- ◆ **Complex CFD Simulations**
 - » Performance, Emissions, Operational Impacts
- ◆ **Customized Software**
- ◆ **Specialized Equipment**
- ◆ **Proof-of-Concept Testing**



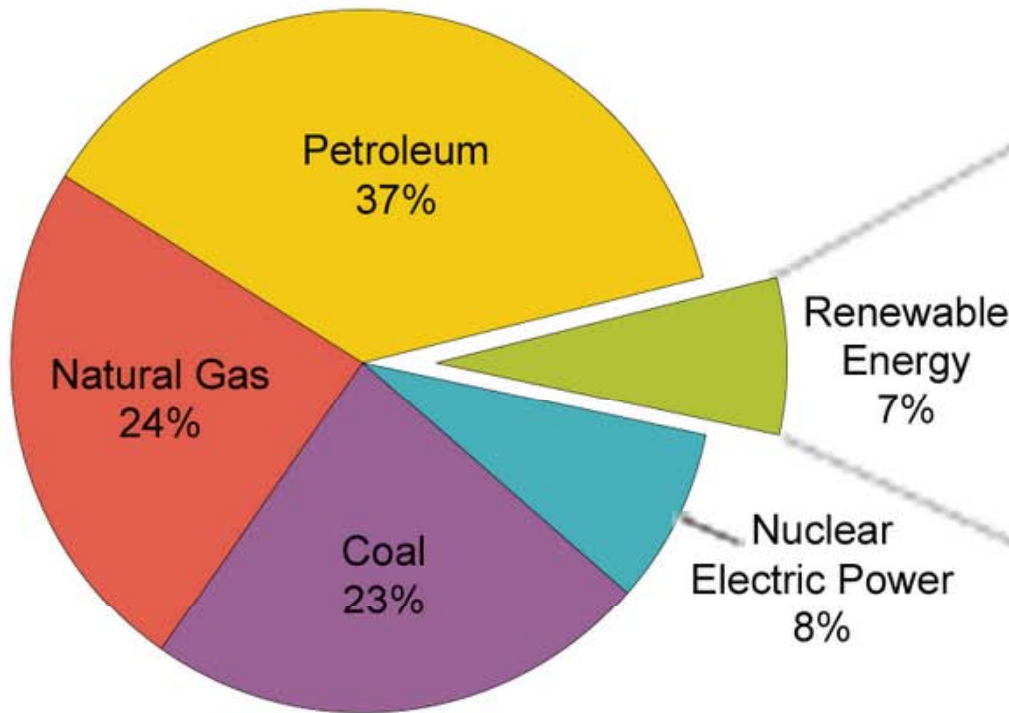
➔ **Founded 1990, ~20 Full-Time Employees**

➔ **Strong University Affiliations**

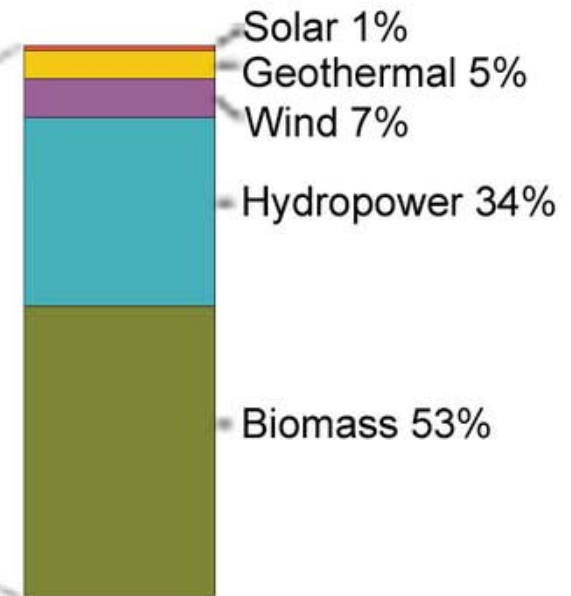
➔ **Commercial Affiliates in Taiwan and Germany**

U.S. Energy Contributions

Total = 99.304 Quadrillion Btu



Total = 7.300 Quadrillion Btu

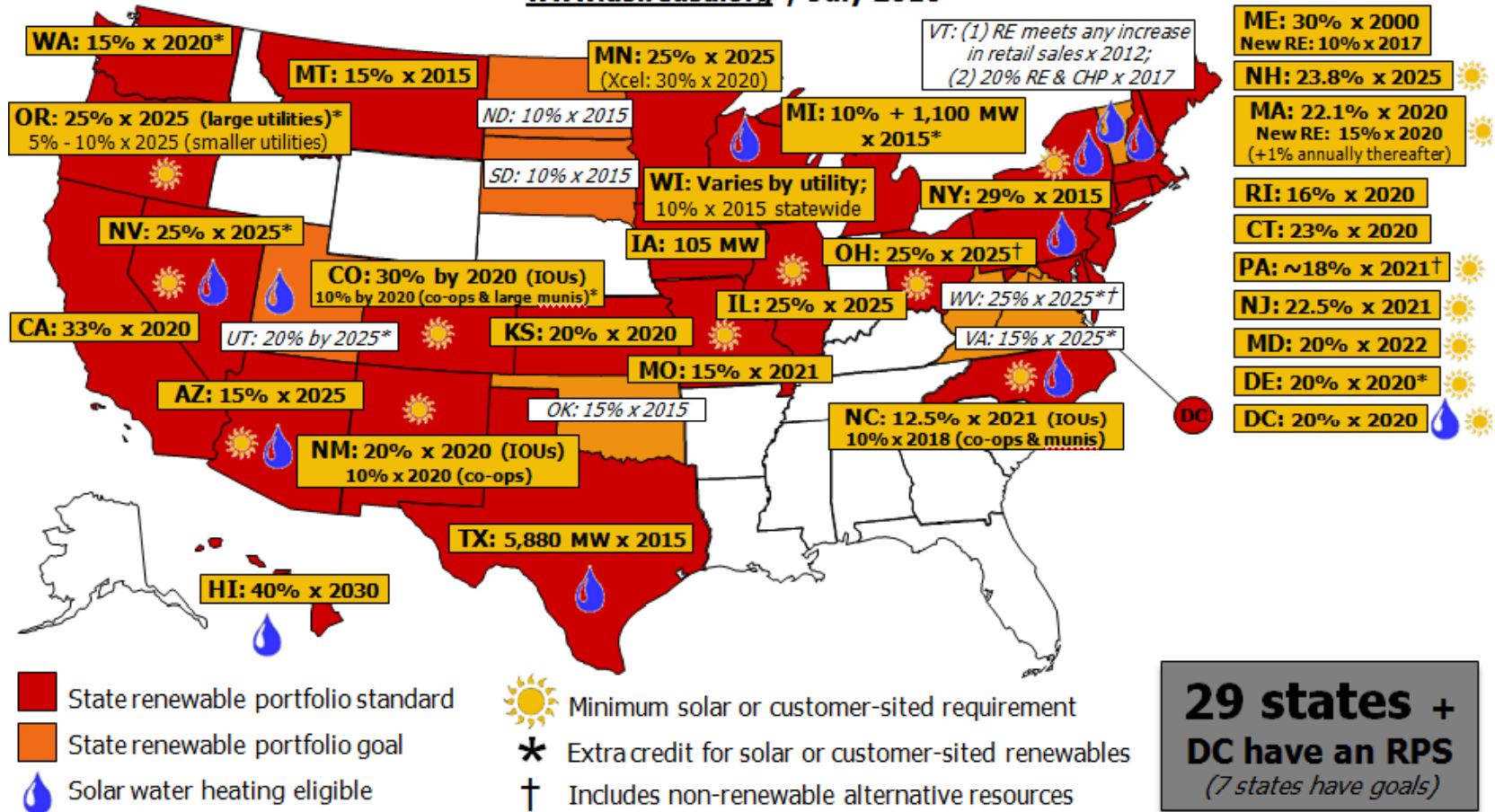


Note: Sum of components may not equal 100% due to independent rounding.

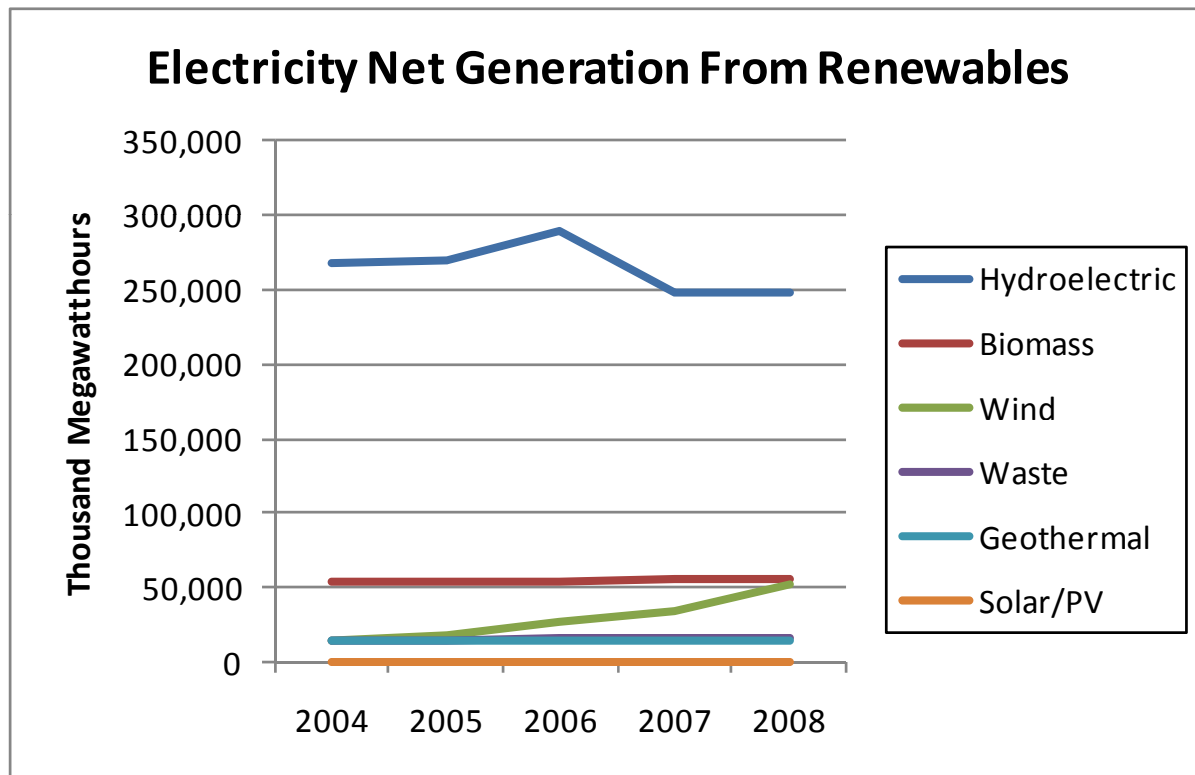
Source: U.S. Energy Information Administration, *Annual Energy Review 2008*, Table 1.3, Primary Energy Consumption by Energy Source, 1949-2008 (June 2009).

Legislative Driving Force

www.dsireusa.org / July 2010



Renewable Power Generation



Biomass (2008)

➔ 55,875 GWhr total

- ◆ 38,789 wood and wood wastes
- ◆ 2,036 agricultural residues, sludge
- ◆ 8,460 MW MSW
- ◆ 6,590 landfill gas

➔ **Classes:**

- ◆ **Dedicated**
- ◆ **Co-fired**
 - » Blended
 - » Separate injection

Dedicated Firing of Biomass

→ Grate-fired units

- ◆ Increasing numbers industrial applications
- ◆ Proposed Mitchell repowering

→ Fluidized bed combustion/gasification

- ◆ Increasing numbers for industrial applications
- ◆ Schiller – 50MW Fluidized Bed – wood

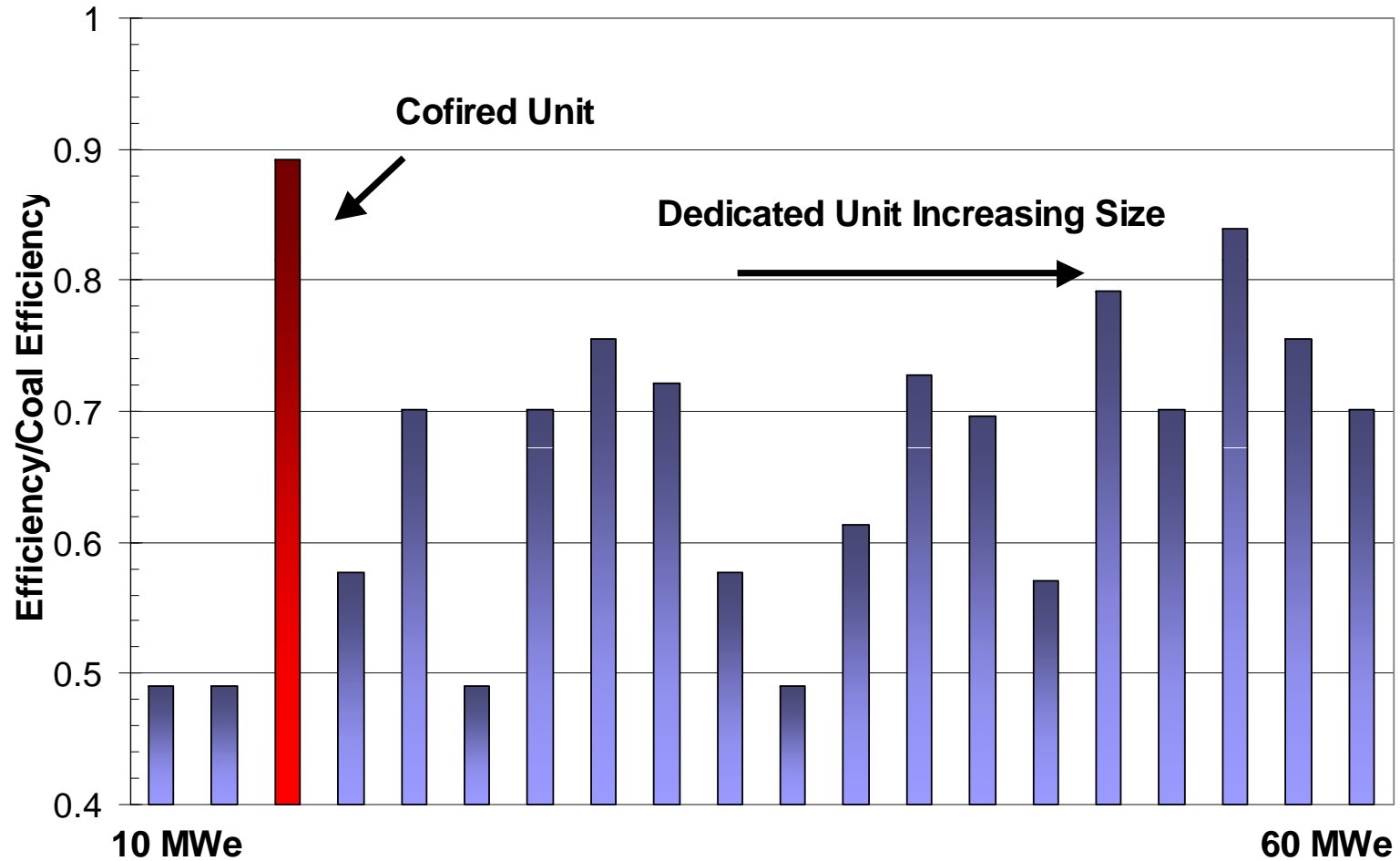
→ Fixed bed gasifiers



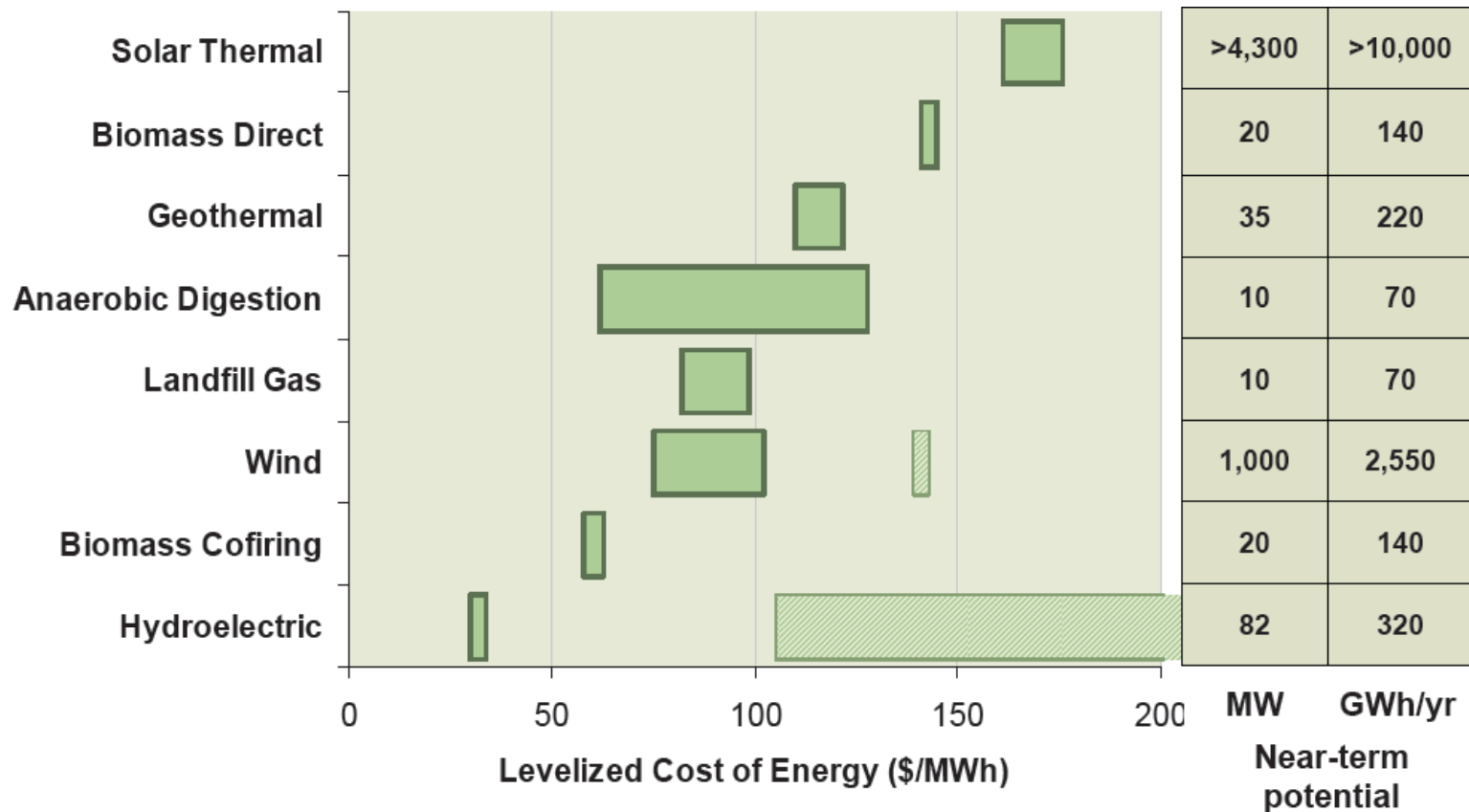
If Plant Mitchell's biomass conversion proceeds, trucks of wood waste would unload at a whole-truck tipper, similar to the one at right. The offload area, foreground in the above rendering, would feed the wood chips to fuel storage that will replace Mitchell's current coal pile.



Efficiency of Biomass-fired Boilers



Cost of Energy: Renewables



Black & Veatch, EUEC 2008.

Utility-scale Co-firing

Pulverized Coal

Utility, Plant Name, Location	Co-fired Fuels	Total (Net) Plant Size *	Boiler Technology
GPU Genco Shawville Station Johnstown, Pennsylvania	Coal/wood residues	130 MW _e and 190 MW _e	Pulverized Coal
IES Utilities Inc. Sixth Street (1) and Ottumwa (2) Stations Marshalltown, Iowa	(1) Coal/agricultural residues	(1) 3 Units, 6-15 MW _e	(1) Pulverized Coal
	(2) Coal/switchgrass	(2) 714 MW _e	(2) Pulverized Coal
Madison Gas & Electric Blount Street Station Madison, Wisconsin	Coal/switchgrass	50 MW _e	Pulverized Coal
New York State Electric & Gas Greenidge Station Dresden, New York	Coal/wood residues and coal/energy crops (willow)	108 MW _e	Pulverized Coal
Niagara Mohawk Power Corp. Dunkirk Station Dunkirk, New York	Coal/wood residues and coal/energy crops (willow)	91 MW _e	Pulverized Coal
Tennessee Valley Authority (1) Kingston and (2) Colbert Fossil Plants	(1) Coal/wood residues	(1) 190 MW _e	(1) Pulverized Coal
	(2) Coal/wood residues	(2) 190 MW _e	(2) Pulverized Coal
EPON Centrale Gelderland Netherlands	Coal/wood residues (demolition)	602 MW _e	Pulverized Coal
I/S Midkraft Energy Co. Studstrupvaeket, Denmark	Coal/straw	150 MW _e	Pulverized Coal
Uppsala Energi AB Uppsala, Sweden	Coal (peat)/ wood chips	200 MW _e and 320 MW _e	Pulverized Coal

Other

Utility, Plant Name, Location	Co-fired Fuels	Total (Net) Plant Size *	Boiler Technology
Northern States Power Allen S. King Station Minneapolis, Minnesota	Coal/wood residues (lumber)	560 MW _e	Cyclone
Otter Tail Power Co. Big Stone City, South Dakota	Coal/refuse-derived-fuel (RDF)/tires/waste oil/ag. refuse	440 MW _e	Cyclone
Tennessee Valley Authority Allen Fossil Plant Memphis, Tennessee	Coal/wood residues and coal/wood/tires	272 MW _e	Cyclone
I/S Midkraft Energy Co. Grenaa Co-Generation Plant Grenaa, Denmark	Coal/straw	150 MW _e	Circulating Fluidized Bed
Tacoma Public Utilities -- Light Division Steam Plant No. 2 Tacoma, Washington	Coal/RDF/wood residues	2 x 25 MW _e	Bubbling Fluidized Bed
New York State Electric & Gas Hickling (1) and Jennison (2) Stations Big Flats and Bainbridge, New York	Coal/wood residues and coal/tires	(1) 37.5 MW _e	(1) Stoker
		(2) 37.5 MW _e	(2) Stoker
Northern States Power Bay Front Station Ashland, Wisconsin	Coal/wood residues (forest)	2 x 17 MW _e	Stoker

<http://www.p2pays.org/ref/36/35394.pdf>

Fuel Properties

Parameter	Wood Waste		Corn Stover		Switchgrass		Eastern Bituminous Coal	
	Dry Basis	As Rec'd	Dry Basis	As Rec'd	Dry Basis	As Rec'd	Dry Basis	As Rec'd
Proximate Analysis								
Total Moisture	--	45.54	--	5.25	--	14.23	--	6.53
Ash	3.14	1.71	13.73	13.01	2.25	1.93	17.28	16.15
Volatile Matter	77.99	42.48	70.32	66.63	80.88	69.37	30.40	28.42
Fixed Carbon	18.87	10.28	15.95	15.12	16.87	14.47	52.32	48.90
Total	100.00	100	100.00	100	100.00	100.00	100.00	100.00
Ultimate Analysis								
Carbon	50.42	27.46	43.68	41.39	49.09	42.10	72.19	67.48
Hydrogen	6.78	3.69	6.71	6.36	6.86	5.88	5.13	4.80
Nitrogen	0.30	0.17	3.73	3.54	0.21	0.18	1.33	1.24
Sulfur	0.06	0.03	1.42	1.35	0.09	0.08	0.74	0.69
Oxygen	39.30	21.40	30.72	29.11	41.50	35.59	3.33	3.11
Ash	3.14	1.71	13.73	13.01	2.25	1.93	17.28	16.15
Total Moisture	--	45.54	--	5.25	--	14.23	--	6.53
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Higher Heating Value (Btu/lb)	10,766	5,863	7,224	6,845	8,149	6,989	12,020	11,235

Duong et al, 2010

Fuel Preparation

- ➔ Sizing/milling
- ➔ Drying
- ➔ Pelletization
- ➔ Torrefaction
- ➔ Pyrolysis
- ➔ Gasification
- ➔ Liquifaction



Issues to Consider

- ➔ Fuel collection, storage, processing and handling
- ➔ Combustion
 - ◆ Combustion stability
 - ◆ Burnout
 - ◆ Temperature / Heat transfer
 - ◆ Efficiency
- ➔ Emissions
 - ◆ Carbon Dioxide
 - ◆ Sulfur Oxides
 - ◆ Mercury
 - ◆ Fine Particles
 - ◆ Nitrogen Oxides



- ➔ Operational Impacts
 - ◆ Slagging / Fouling
 - ◆ Catalyst deactivation
 - ◆ Fly-ash properties
 - ◆ Corrosion
- ➔ Economics
- ➔ Regulatory

Biomass Combustion

→ Combustion impacted by:

- ◆ Particle drying and heat-up
- ◆ Volatile yield
- ◆ Devolatilization rate
- ◆ Char oxidation rate

→ Relative to coal, woody biomass typically has:

- ◆ Larger and less spherical particles
- ◆ More moisture
- ◆ Less ash
- ◆ More volatile matter/less fixed carbon (char)
- ◆ Lower heating value
- ◆ Higher variability in ash content and composition



Combustion Impacts



→ For suspension firing:

- ◆ If mingled or burner injected, flame stability controlled by injection design
- ◆ Burnout is a function of biomass particle size, shape and residence time; generally slower than coal
- ◆ Lower adiabatic flame temperature than coal (not necessarily lower flue gas temperature)
- ◆ Slightly lower boiler efficiency (~1% per 10 wt% co-fired)
- ◆ Significance of impacts depends on amount fired

→ Application should be addressed on case-by-case basis due to variability of biomass and firing systems

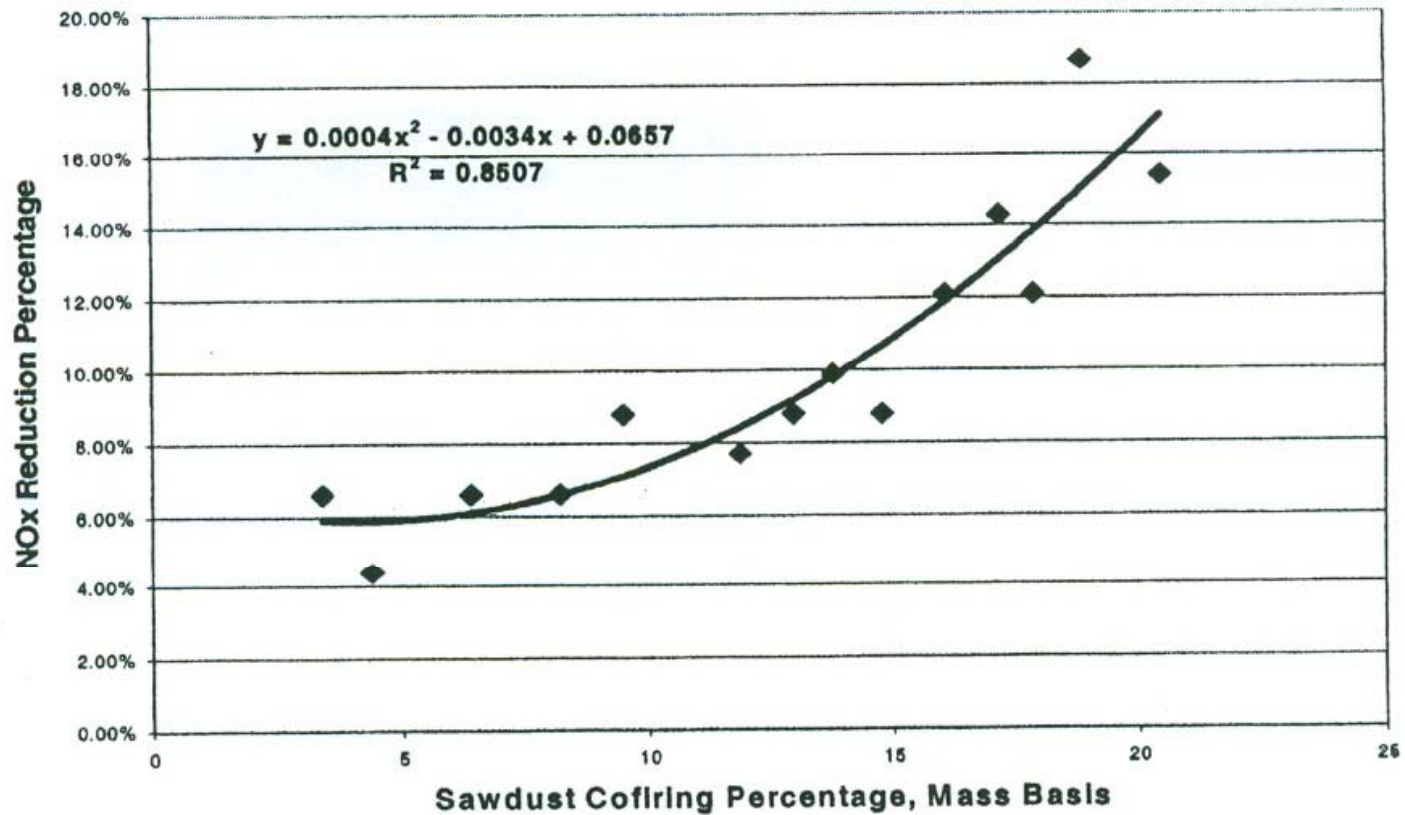
Biomass Emissions



- Emission reductions are greatest potential benefit of biomass co-firing
 - ◆ CO_2 – consider net zero emissions
 - ◆ SO_2 – lower because biomass is a very low sulfur fuel
 - ◆ Hg – lower because biomass is a very low mercury fuel
 - ◆ Fine particulates – co-firing tests have shown minimal impact
 - ◆ NO_x – complex process, but reductions can be significant

NOx Reduction: Seward Co-firing

Tillman and Harding (2004)



Operational Impacts

→ Slagging and Fouling

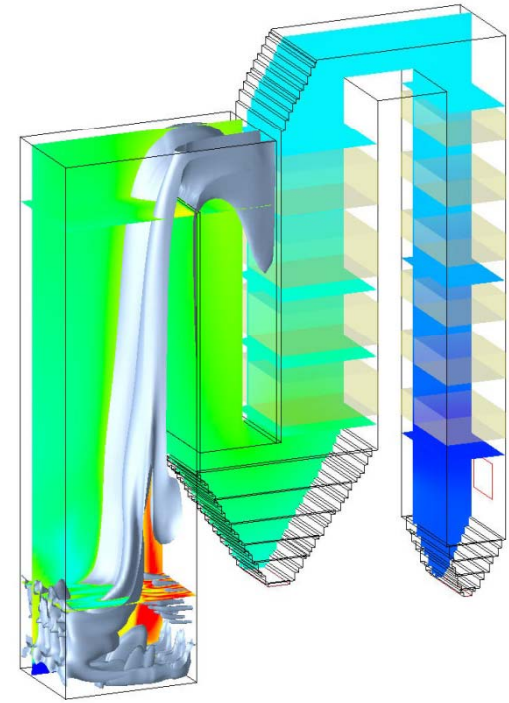
- ◆ Depends on deposition rates and ash chemistry (CaO , K_2O , SiO_2)
- ◆ 100% biomass systems more susceptible
- ◆ Co-firing less susceptible (minimal impacts with <10 wt%)
- ◆ Urban wood waste has higher slagging/fouling potential than naturally grown or wood products

→ Potential for corrosion and SCR catalyst impacts with 100% firing; lower ash with co-firing can mitigate impacts



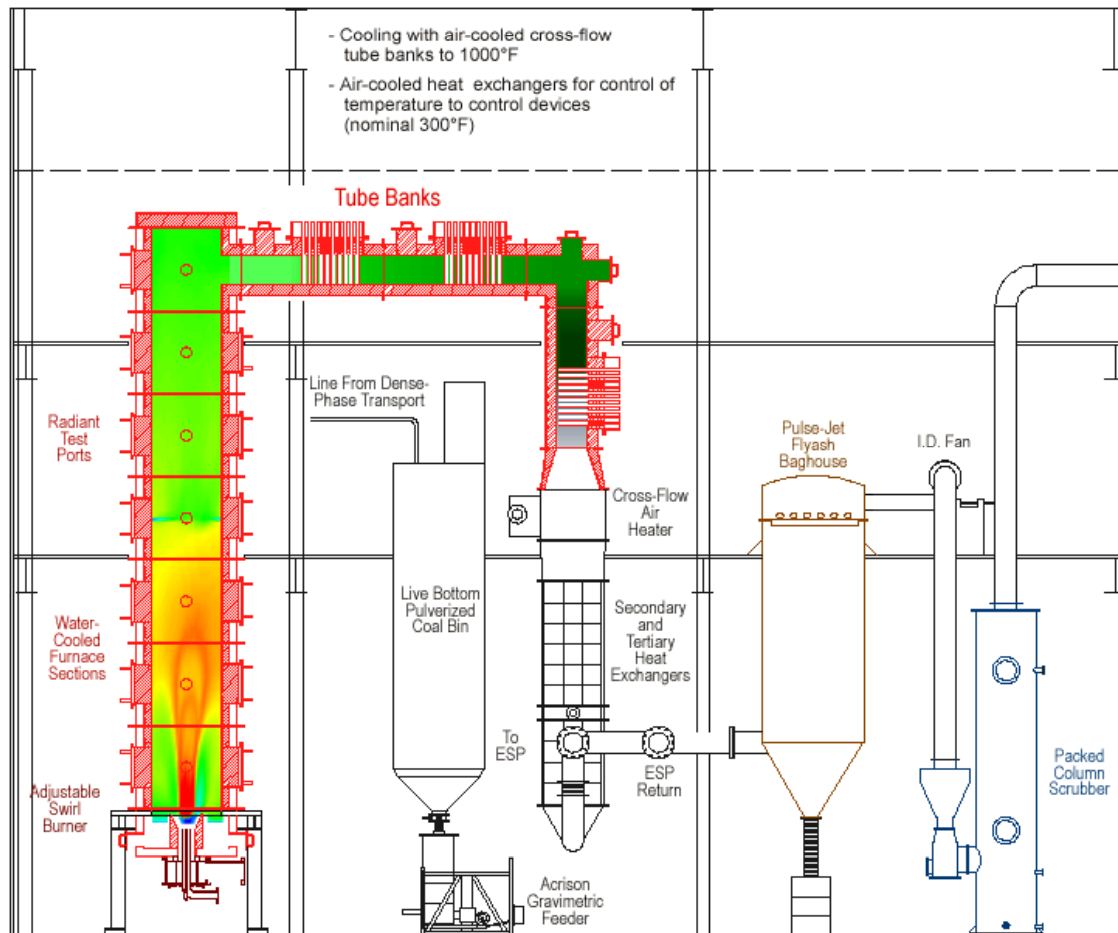
Predictive Technical Assessment

- ➔ Application of co-firing should be assessed on a case-by-case basis
 - ◆ Characterization of combustion system
 - ◆ Characterization of biomass fuel
 - ◆ Appropriate modeling of biomass firing



- ➔ Combustion (CFD) modeling can be used to:
 - ◆ Characterize current system
 - ◆ Assess different biomass injection strategies and fuels
 - ◆ Track dispersion, reaction, deposition of coal and biomass
 - ◆ Predict combustion, emissions, and slagging/fouling

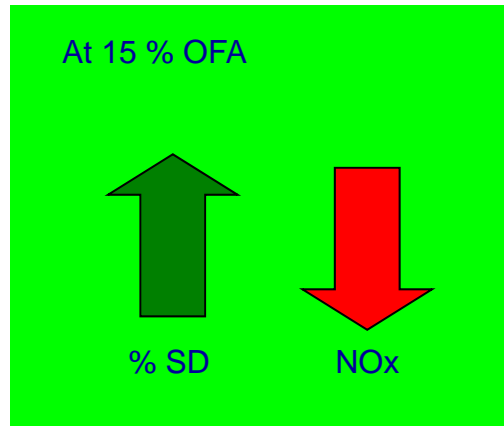
Biomass Injection Strategies



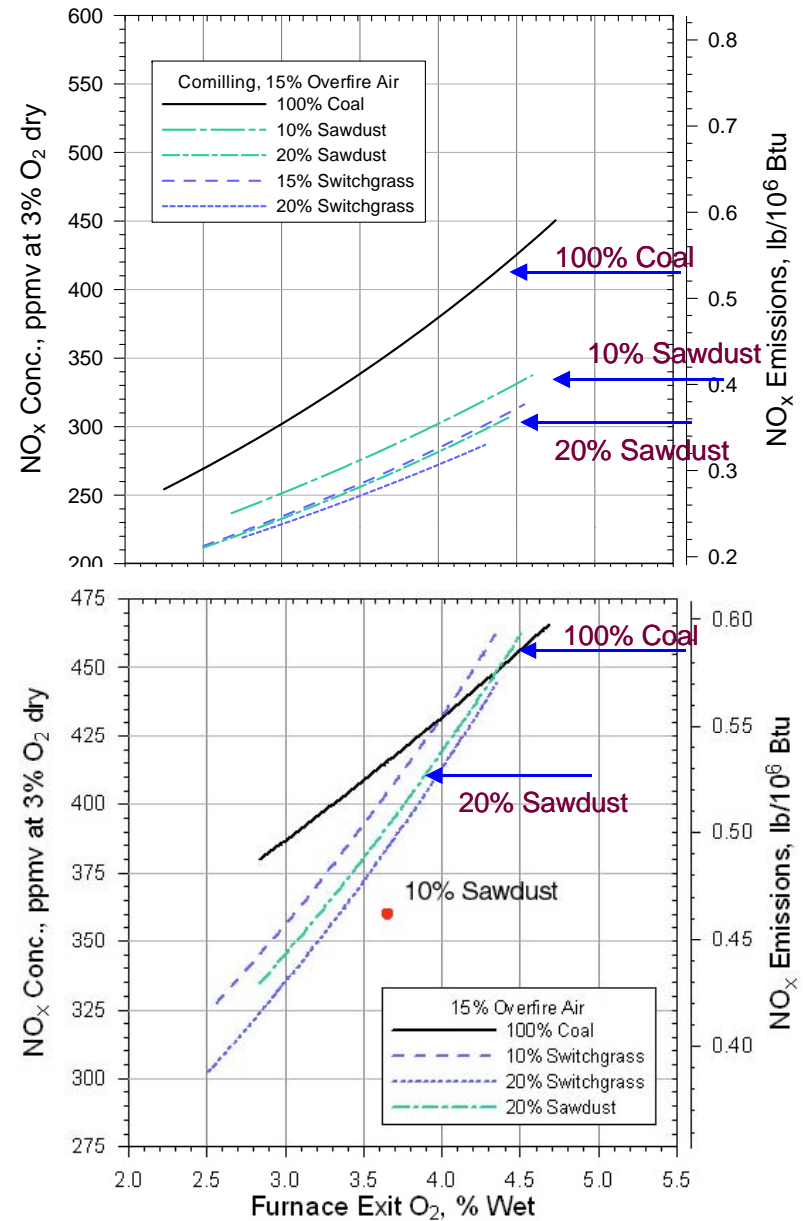
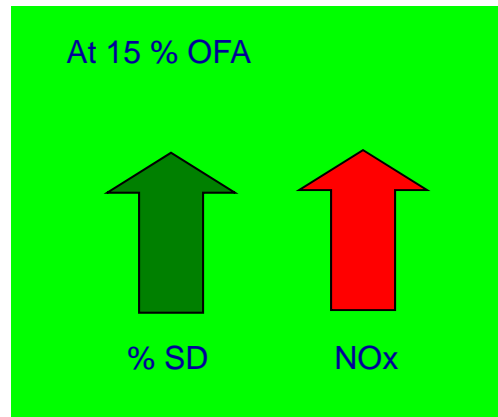
- ➔ Southern Research Institute facility designed to reproduce pc boiler conditions
- ➔ Assess NO_x impacts for different injection strategies
 - ◆ Co-milled
 - ◆ Separate center injection
- ➔ Detailed CFD modeling with biomass-specific sub-models

NO_x Measurements During Testing

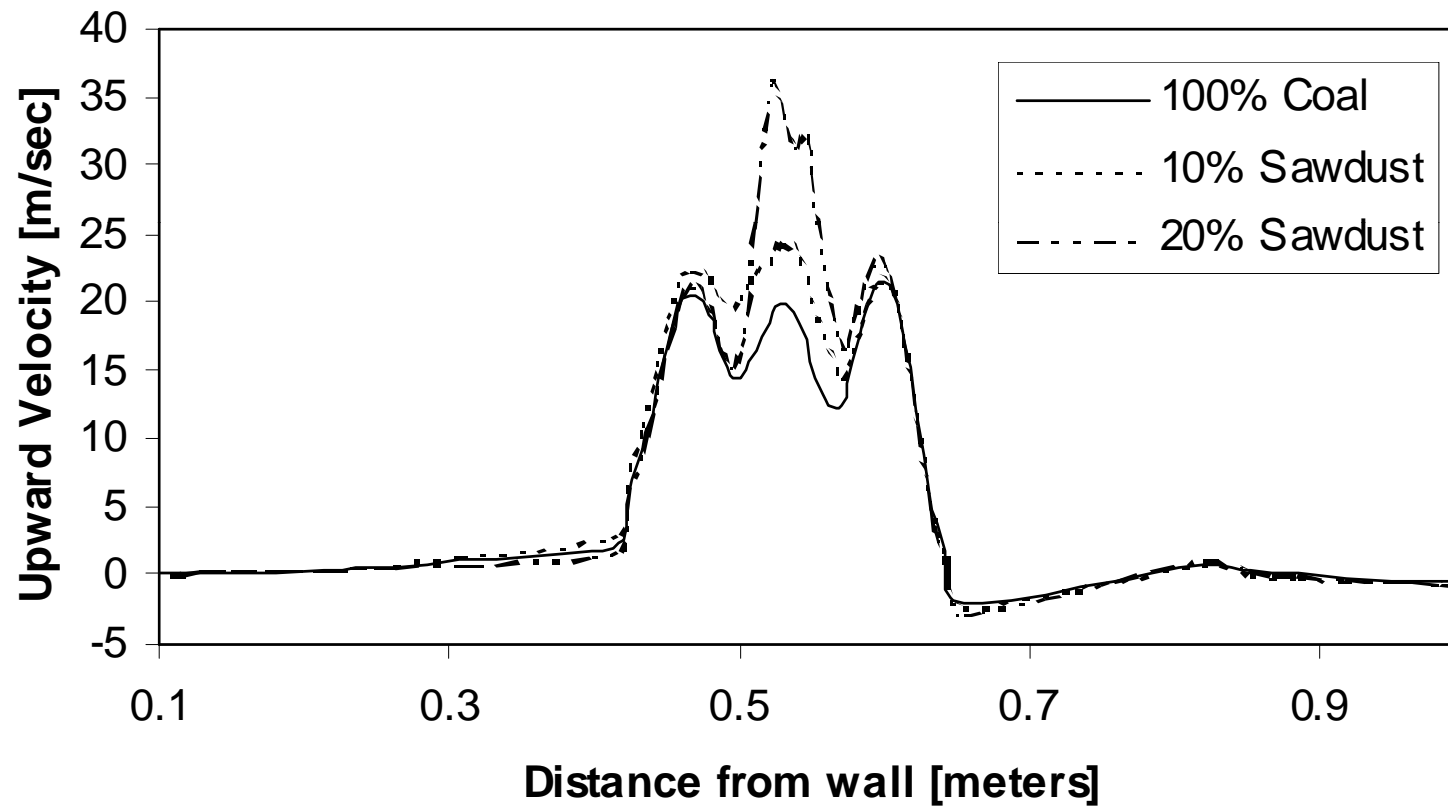
Co-milled



Center Injection

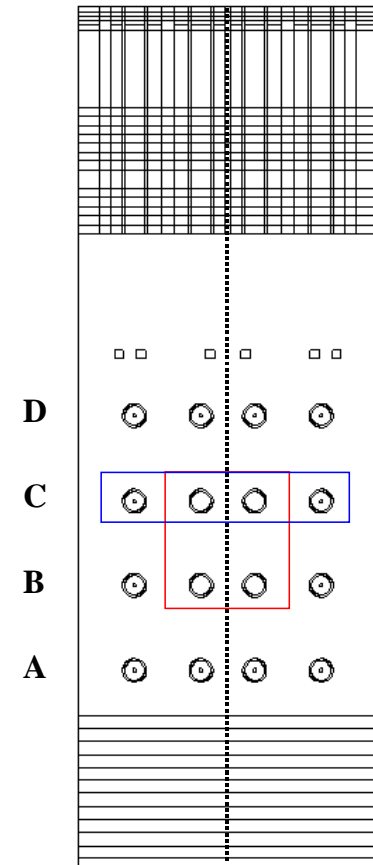


Near Burner Velocity Profile



Full-scale NO_x Application

- ➔ 150 MW front wall-fired boiler
- ➔ 16 Low NO_x burners in 4 elevations and OFA
- ➔ Co-firing scenarios
 - ◆ 7% Green Wood Chips based on heat input
 - ◆ Separate center injection
 - » Multi-fuel burners in "C" row.
 - » Multi-fuel burners at center 2 locations in B & C rows
- ➔ Determine impacts on
 - ◆ NO_x reduction
 - ◆ Unburned carbon-in-flyash
 - ◆ CO



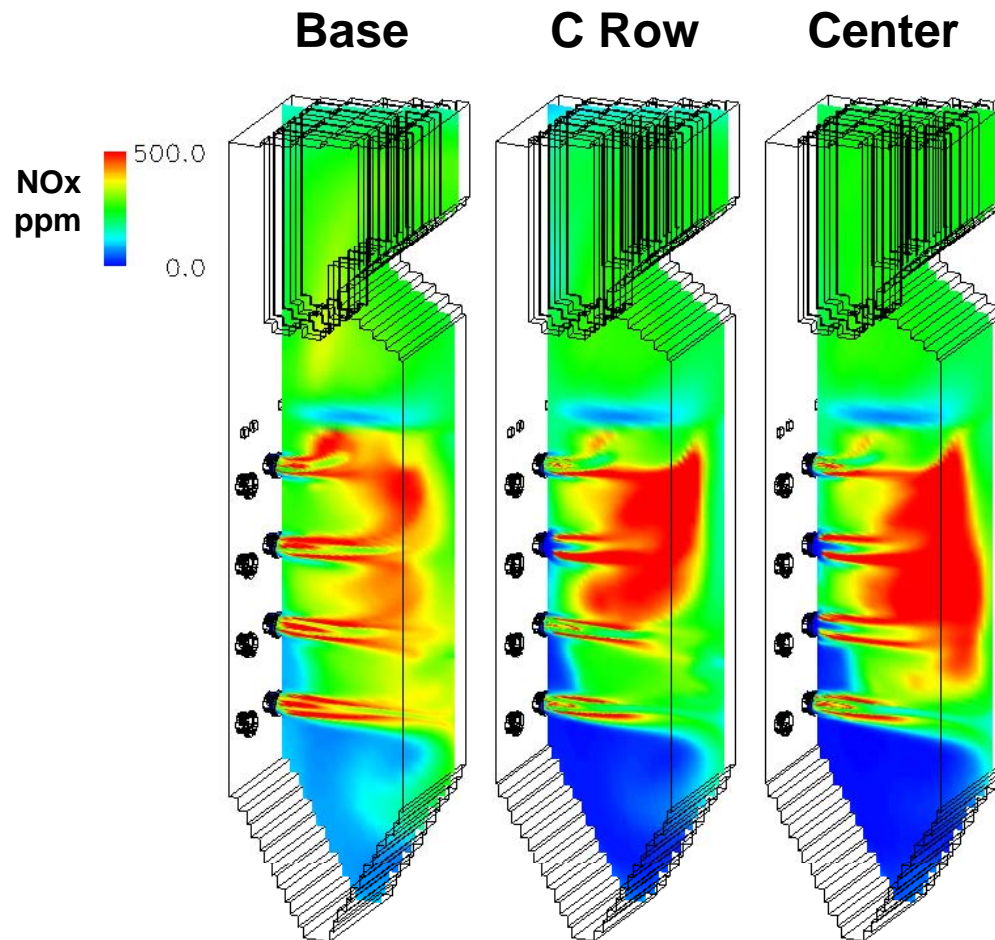
Modeling Results

<u>Proximate Analysis</u>	<u>Coal</u>	<u>Biomass</u>
Volatiles	35.70%	48.47%
Fixed Carbon	51.69%	7.68%
Moisture	6.04%	43.47%
Ash	6.57%	0.39%
HHV (Btu/lb)	132701	4667

<u>Ultimate Analysis</u>		
C	72.80%	28.12%
H	5.69%	3.52%
O	6.10%	24.37%
N	1.50%	0.07%
S	1.30%	0.06%
Moisture	6.04%	43.47%
Ash	6.57%	0.39%

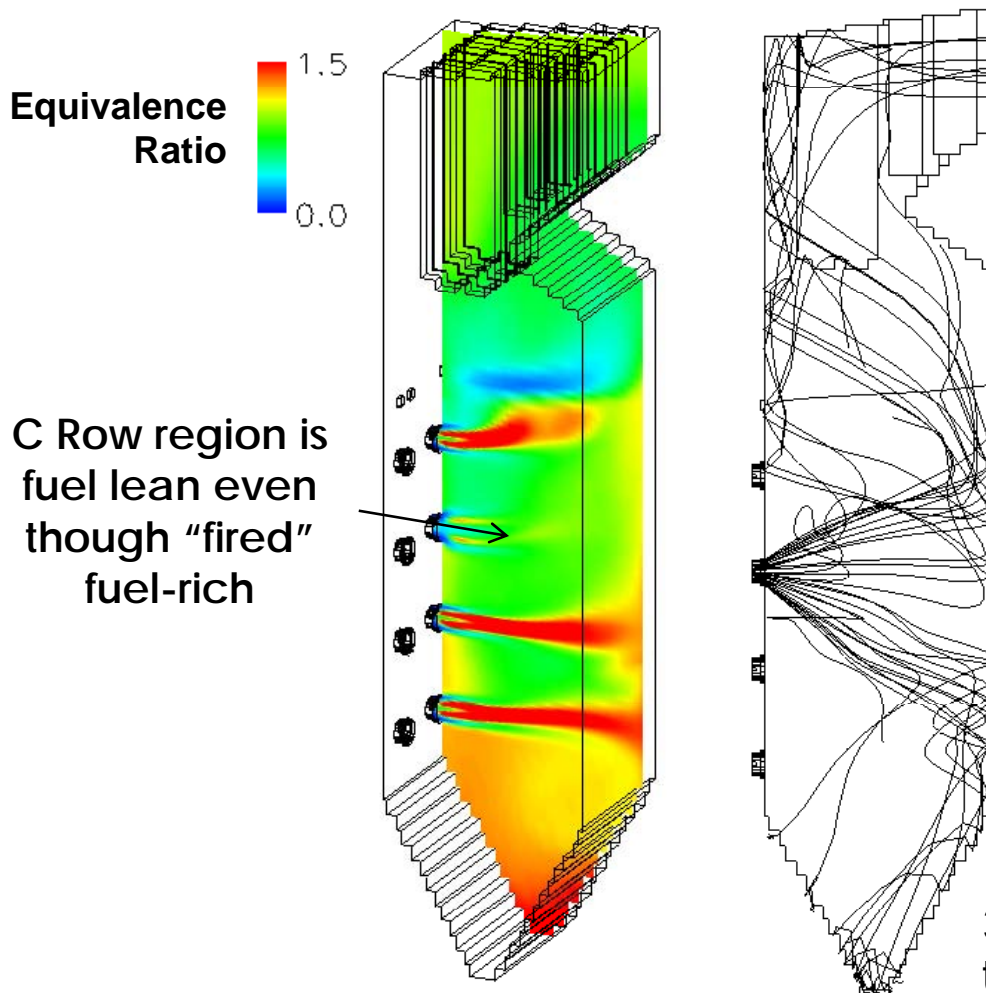
	Location	Temp. (°F)	O2 (%)	CO (ppm)	%Carbon-in-flyash	NOx (ppm)
Plant Estimates	Nose	2300	n/a	1500	n/a	n/a
	Economizer Exit	n/a	3.5	n/a	n/a	300
Baseline	Nose	2250	3.9	2930		297
	Furnace Exit	1920	3.7	340	16	292
"C" Row Biomass	Nose	2240	4.0	3370		269
	Furnace Exit	1940	3.8	140	10	264
Center 4 Biomass	Nose	2260	3.9	2020		264
	Furnace Exit	1940	3.7	110	12	267

NOx Concentration



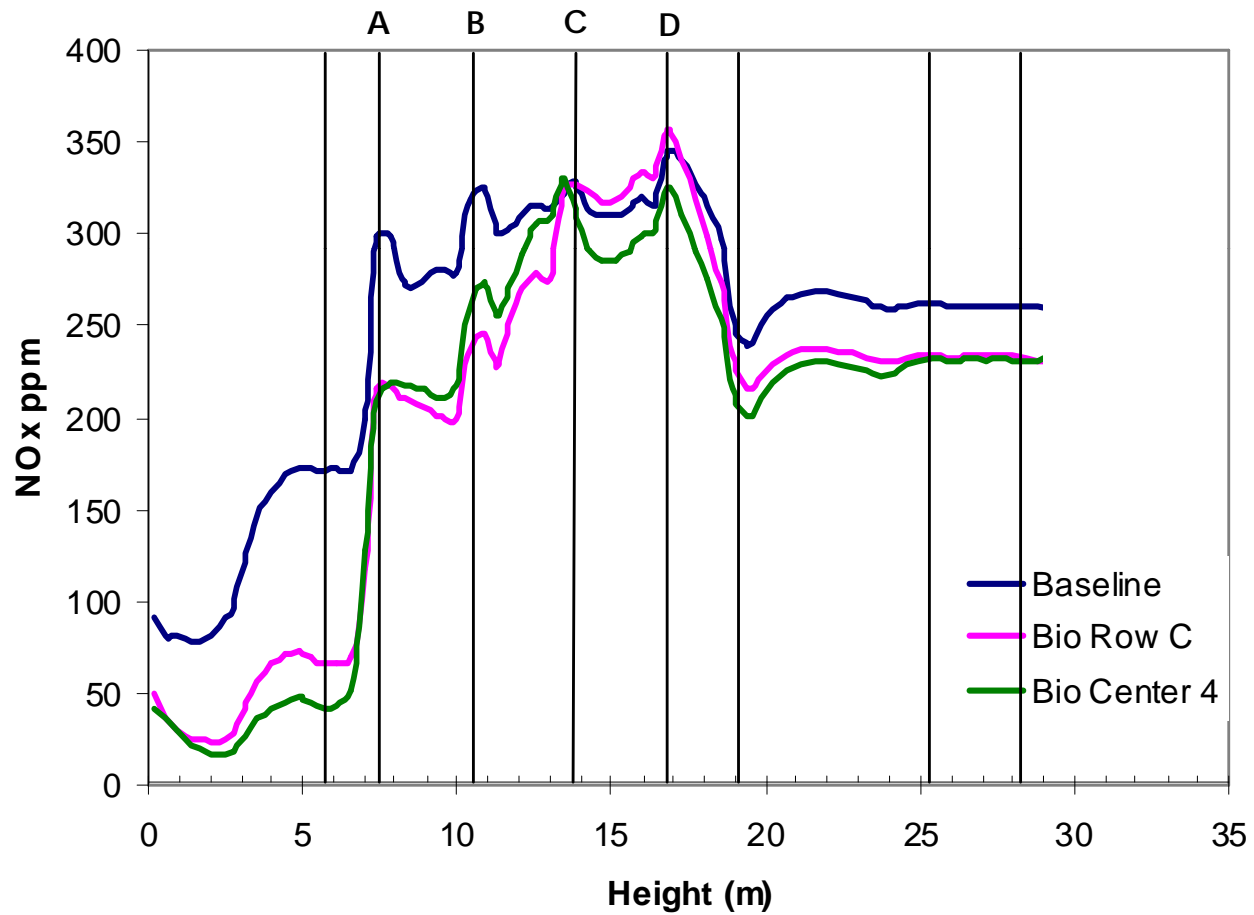
- Co-fired burners actually produced more NOx
- Why did NOx go down?

Wood Particle Paths



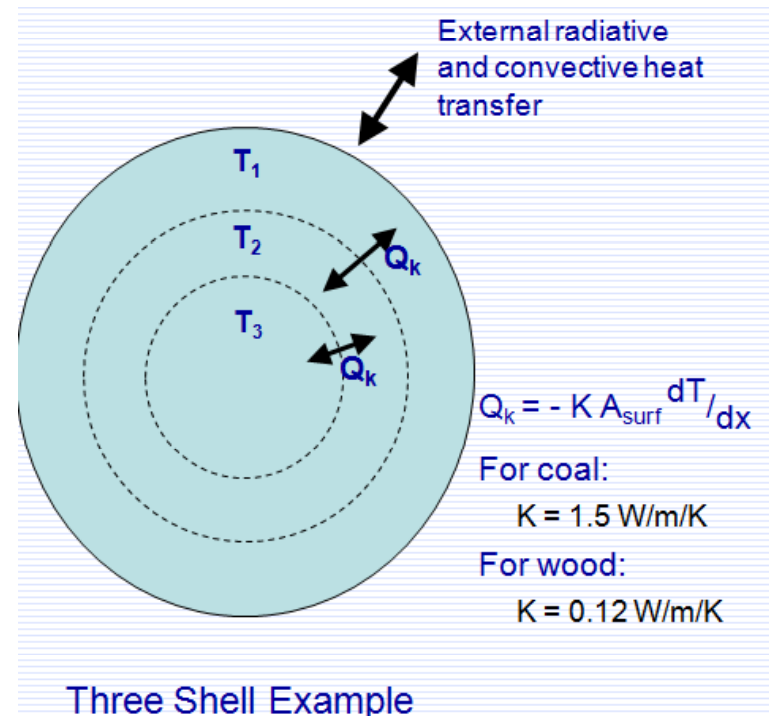
- Large, green (wet) wood chips delayed volatile release, creating:
 - ◆ Fuel-lean upper burner zone which increased NO_x
 - ◆ Fuel-rich lower furnace which reduced NO_x from coal-fired burners
- Modeling non-spherical, wet particles with wood kinetics important

NOx Distribution

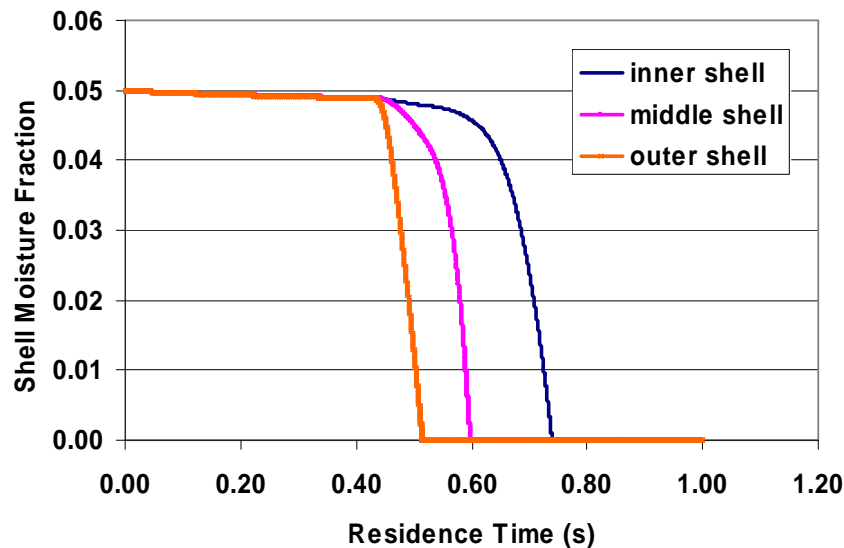
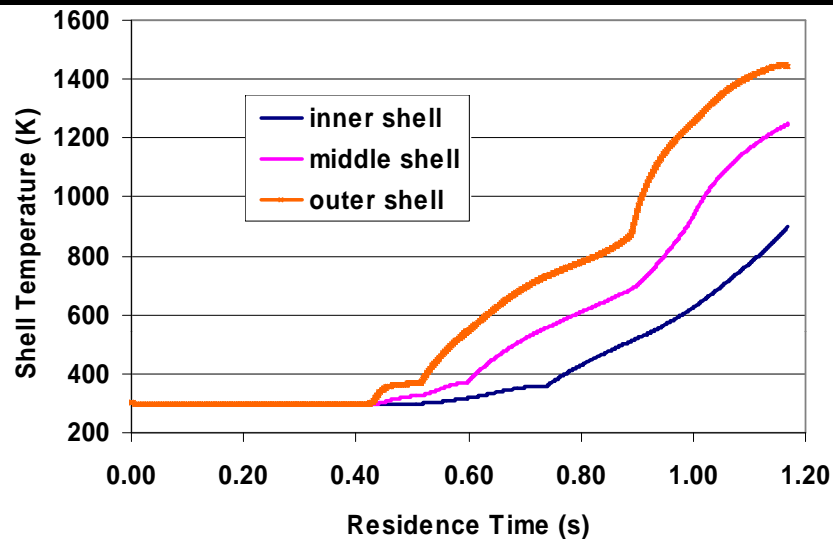


Biomass Particle Combustion (Cyclones & Stokers)

- Large particles are modeled as a series of concentric spherical shells of equal mass
- The number of shells is dependent on the particle diameter
- External radiative and convective heat transfer are only to the outermost shell
- Conductive heat transfer occurs between each shell and the shells immediately adjacent



Drop Tube Shell Model Example



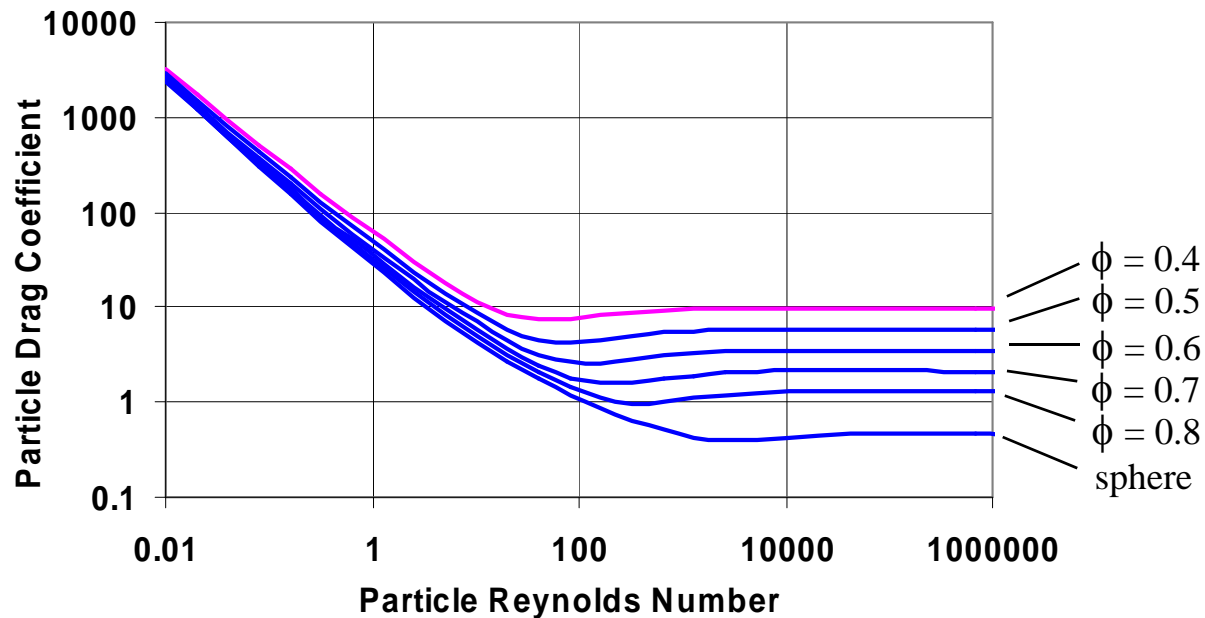
- ➔ Temperature increase and drying of outer shell occurs most rapidly; inner shell most slowly
- ➔ While moisture is present in a shell, the temperature of that shell is limited to boiling temperature (373 K)
- ➔ The temperature of the outer shell is well above the boiling temperature while moisture is still present in the inner shell

Three shell example
with $K = 0.12 \text{ W/m/K}$
(wood conductivity)

Drag on Non-Spherical Particles

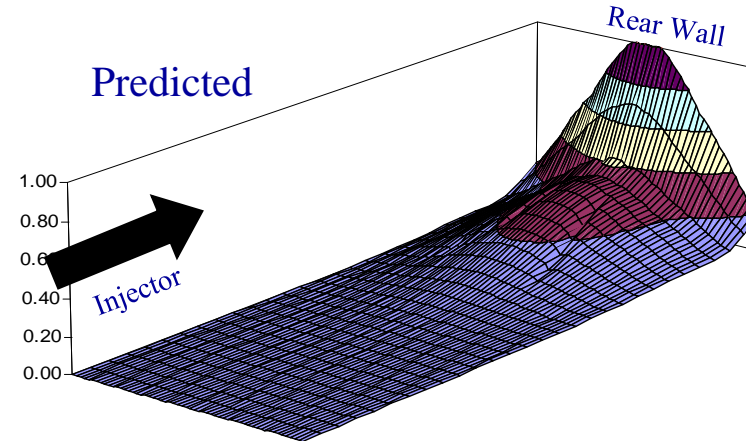
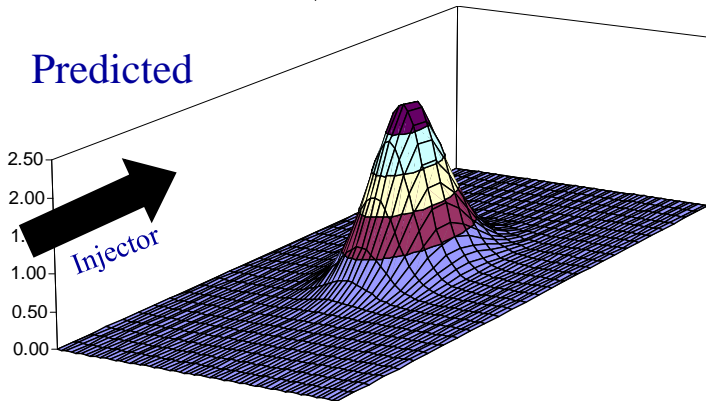
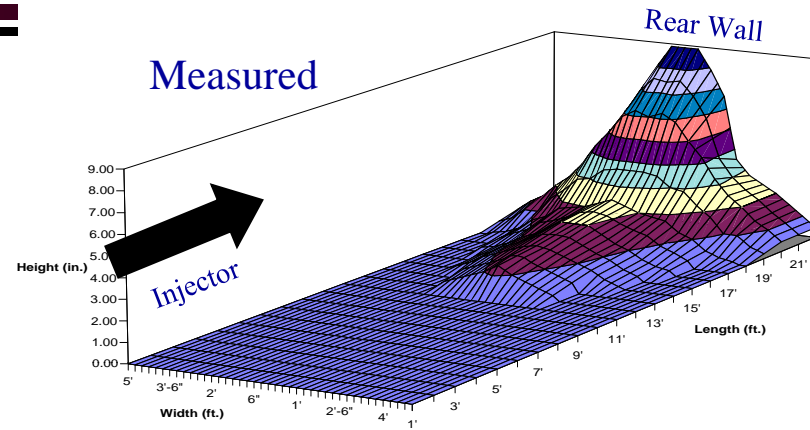
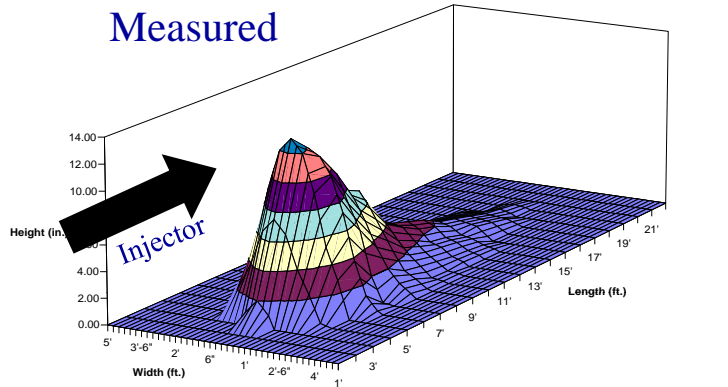
Particle drag is calculated in terms of a shape factor ϕ (Haider and Levenspiel, *Powder Technology*, 58 (1989), pp63-70).

$$\phi = \frac{\text{Surface area of sphere of same volume}}{\text{Surface area of particle}}$$



Particle drag increases with increasing deviation from spherical shape

Non-Spherical Drag Model Verification



Low air velocity

High air velocity

Wood chip spread from an air blast spreader

Cyclone Barrel Inputs

	Coal Only	5% Wood Co-Fire	10% Wood Co-Fire	15% Wood Co-Fire
Barrel Stoichiometry	0.74	0.74	0.74	0.74
Total Air	219,850 lb/hr	220,507 lb/hr	221,085 lb/hr	221,664 lb/hr
Primary Air	30,780 lb/hr	30,871 lb/hr	30,952 lb/hr	31,033 lb/hr
% of Total	14%	14%	14%	14%
Secondary Air	189,070 lb/hr	189,636 lb/hr	190,133 lb/hr	190,631 lb/hr
% of Total	86%	86%	86%	86%
Air Temperature	492° F.	492° F.	492° F.	492° F.
<u>Fuel Mass Input</u>				
Coal	30,835 lb/hr	29,294 lb/hr	27,752 lb/hr	26,210 lb/hr
Wood	-	4,607 lb/hr	9,214 lb/hr	13,820 lb/hr
Total	30,835 lb/hr	33,900 lb/hr	36,966 lb/hr	40,031 lb/hr
% Biomass	-	13.6%	24.9%	34.5%
<u>Fuel Thermal Input</u>				
Coal	430 MBtu/hr	408.5 MBtu/hr	387.0 MBtu/hr	365.5 MBtu/hr
Wood	-	21.5 MBtu/hr	43.0 MBtu/hr	64.5 MBtu/hr
Total	430 MBtu/hr	430 MBtu/hr	430 MBtu/hr	430 MBtu/hr
% Biomass	-	5.0%	10.0%	15.0%

→ In the coal / biomass co-fire simulations, 5%, 10%, or 15% of the coal thermal input is replaced by wood

Fuel Properties

Blend Fuel Composition

	Coal	Wood	5% Co-Fire	10% Co-Fire	15% Co-Fire
C	70.70%	28.12%	64.91%	60.09%	56.00%
H	4.71%	3.52%	4.55%	4.41%	4.30%
O	5.39%	24.37%	7.97%	10.12%	11.94%
N	1.31%	0.07%	1.14%	1.00%	0.88%
S	2.65%	0.06%	2.29%	2.00%	1.75%
ash	7.74%	0.39%	6.74%	5.91%	5.20%
H ₂ O	7.50%	43.47%	12.39%	16.47%	19.92%
HHV	13,945 Btu/lb	4,667 Btu/lb	12,684 Btu/lb	11,632 Btu/lb	10,742 Btu/lb

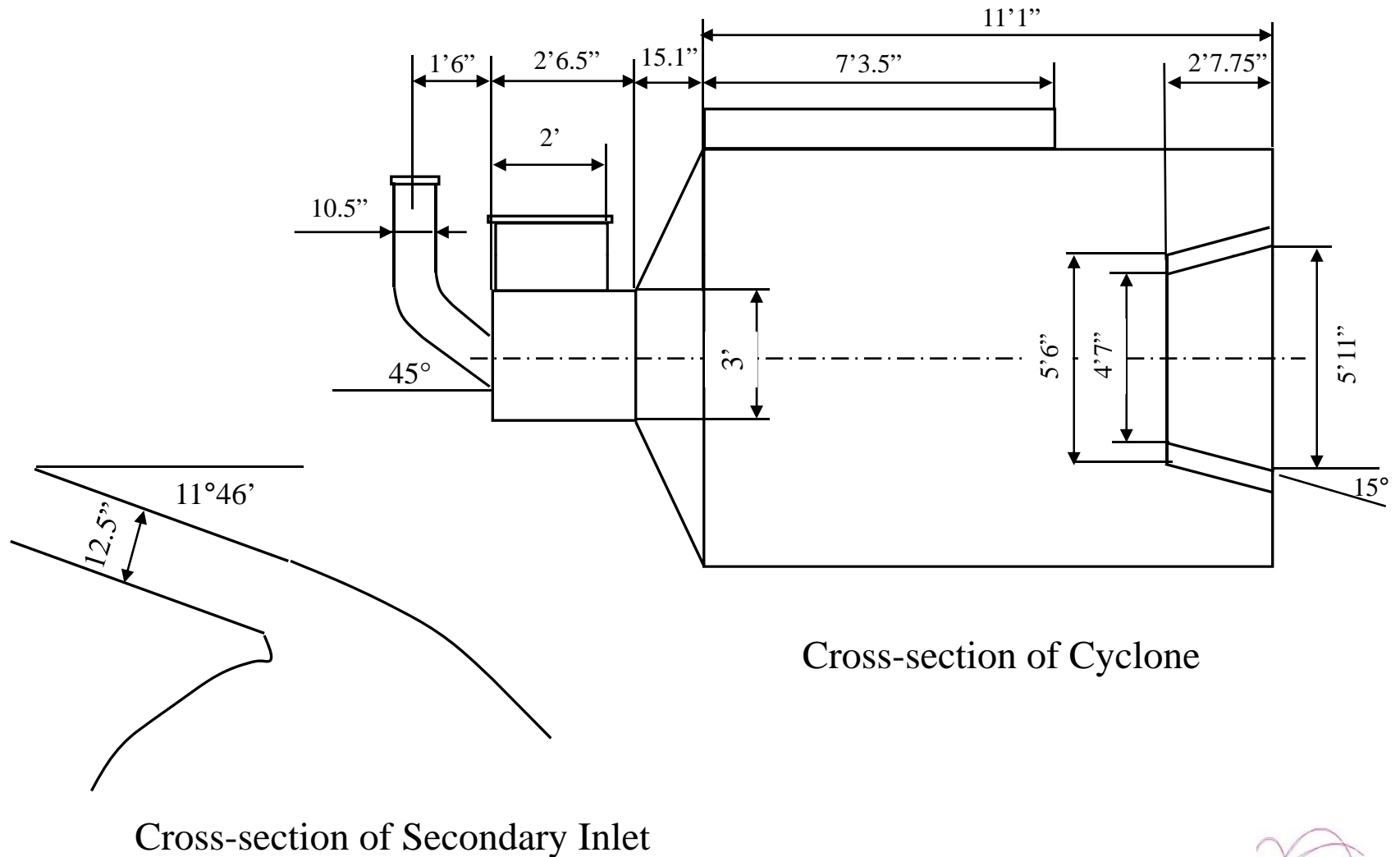
	Coal	Wood
Volatile Yield	36.6%	48.5%
Fixed Carbon	48.3%	7.7%
Density	84 lb/ft ³	18 lb/ft ³

Coal Ash Fusion Temperatures

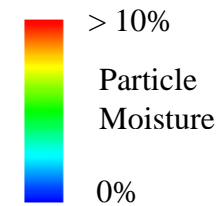
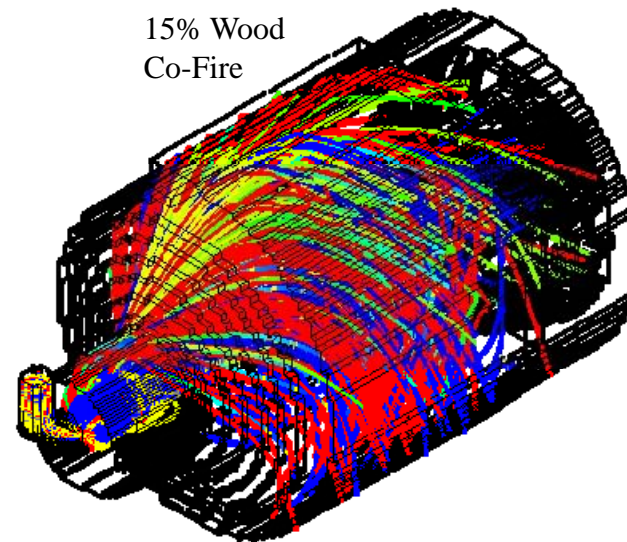
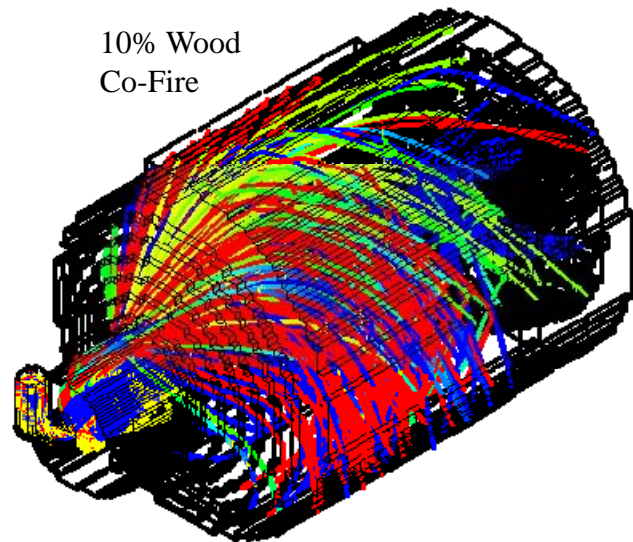
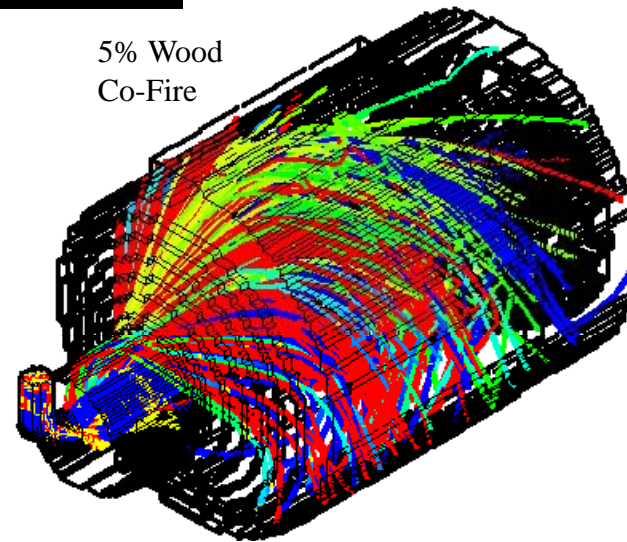
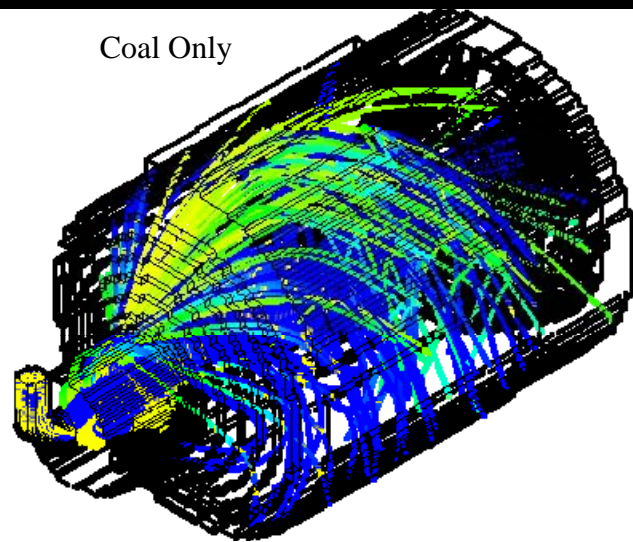
T_{250} 2350°F
 T_{80} 2500°F

Green wood devolatilization and oxidation kinetic rates are used for wood particles.

Cyclone Barrel Geometry



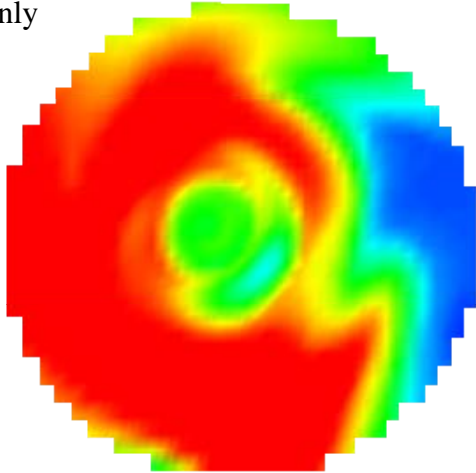
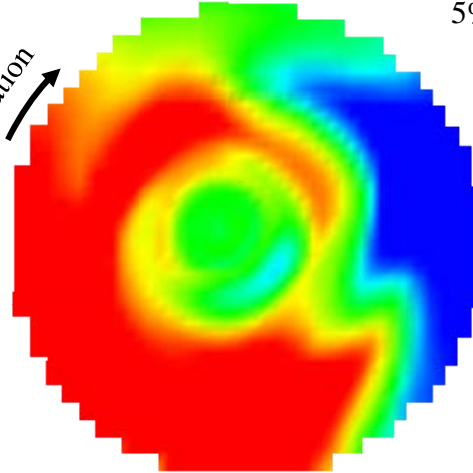
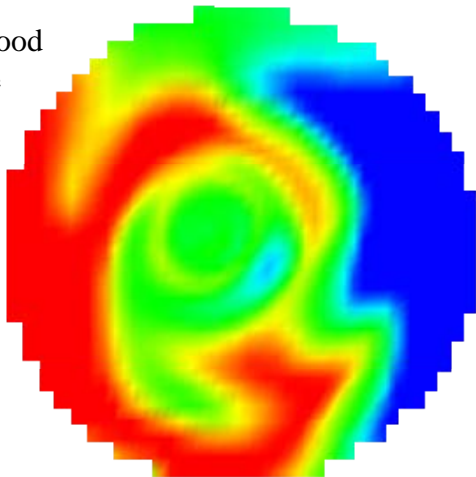
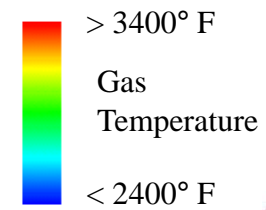
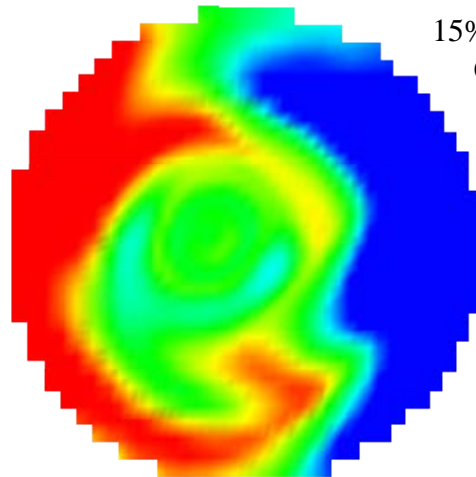
Particle Trajectories



Mass Weighted
Average of All Shell
Moisture Contents

Barrel Exit Temperature

Coal Only

5% Wood
Co-Firerotation
10% Wood
Co-Fire15% Wood
Co-Fire

Barrel Exit Results

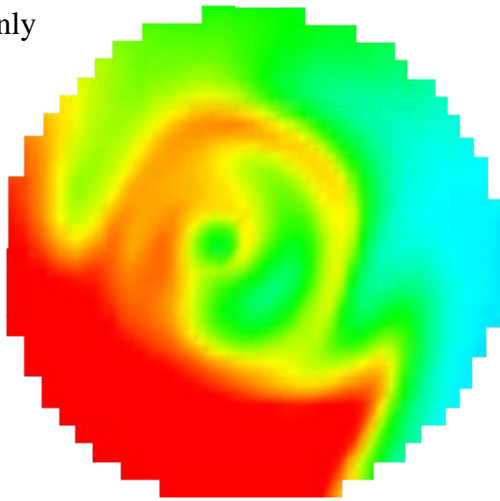
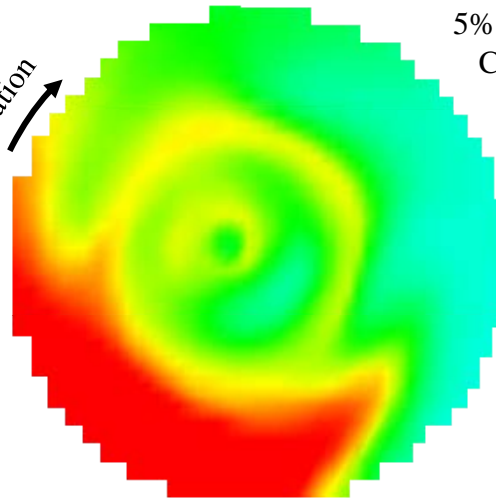
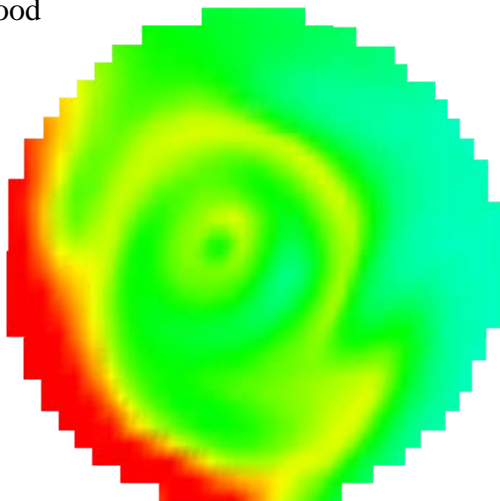
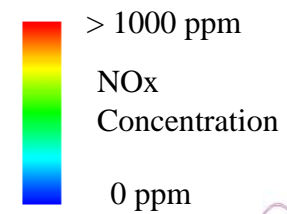
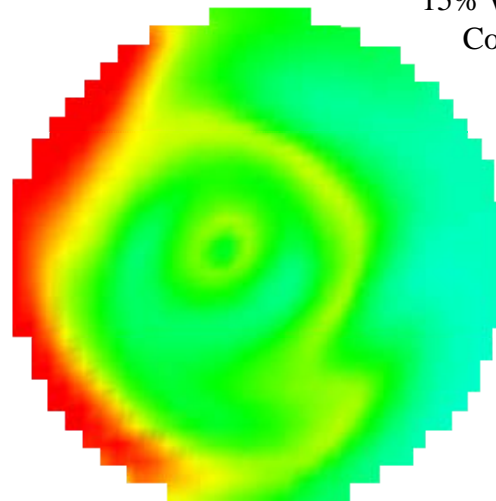
Barrel Model Predicted Exit Conditions

	Coal Only	5% Wood Co-Fire	10% Wood Co-Fire	15% Wood Co-Fire
Temperature	3223° F.	3108° F.	2958° F.	2801° F.
CO Concentration	94,644 ppm	93,637 ppm	92,285 ppm	92,104 ppm
O ₂ Concentration	2.81%	3.19%	3.54%	3.74%
NO _x Concentration	726 ppm	634 ppm	557 ppm	518 ppm
Burnout	90.6%	91.3%	90.3%	92.4%
Ash Escaping	20.2%	26.2%	27.2%	28.0%

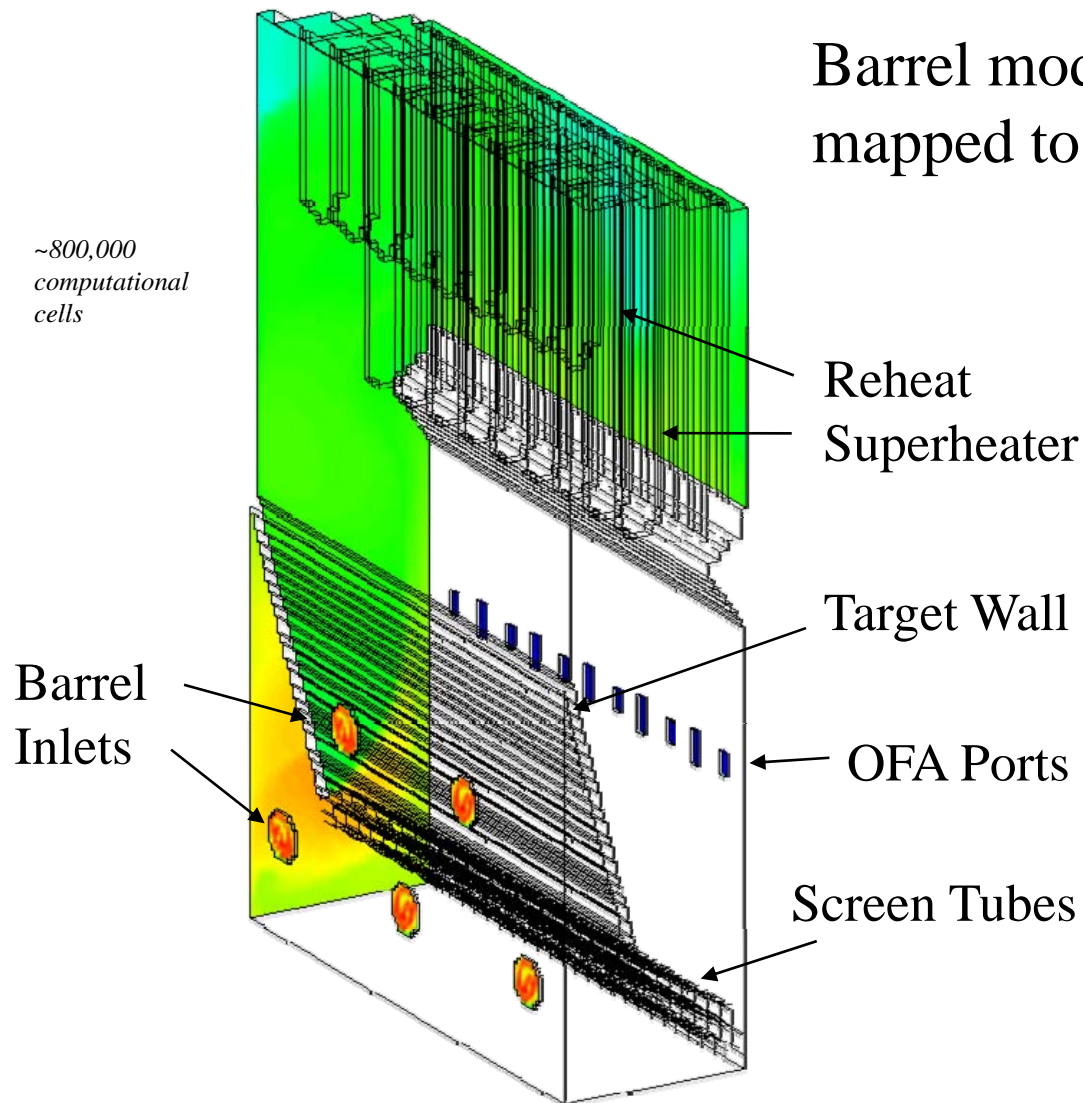
- Replacing coal with wood decreases barrel exit temperature, CO concentration, and NO_x concentration
- Higher barrel exit O₂ with increasing fraction of wood co-firing indicates the presence of higher levels of unoxidized species other than CO (OH, hydrocarbon radicals, etc.)
- Replacing some coal with wood increases the fraction of ash escaping the barrel and tends to increase burnout

Barrel Exit NOx Concentration

Coal Only

5% Wood
Co-Firerotation
10% Wood
Co-Fire15% Wood
Co-Fire

Furnace Model Configuration



Barrel model throat results are mapped to furnace barrel inlets

Furnace dimensions:

Height: 73'-9"

Width: 48'

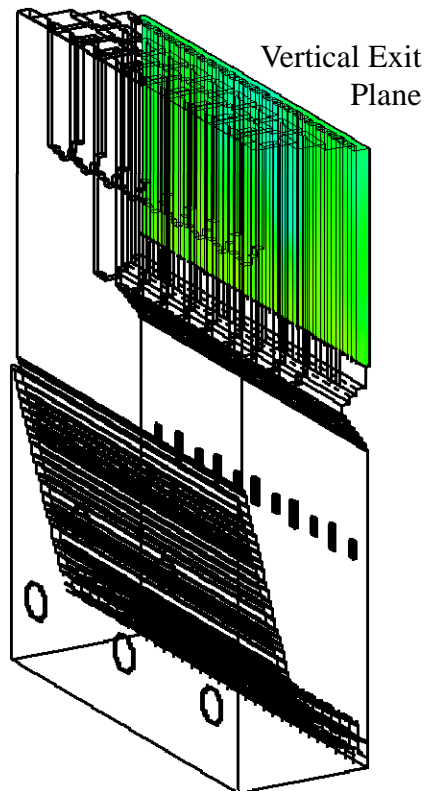
Depth: 16'

Barrel elevations:

Upper row: 663' 1"

Lower row: 651' 7"

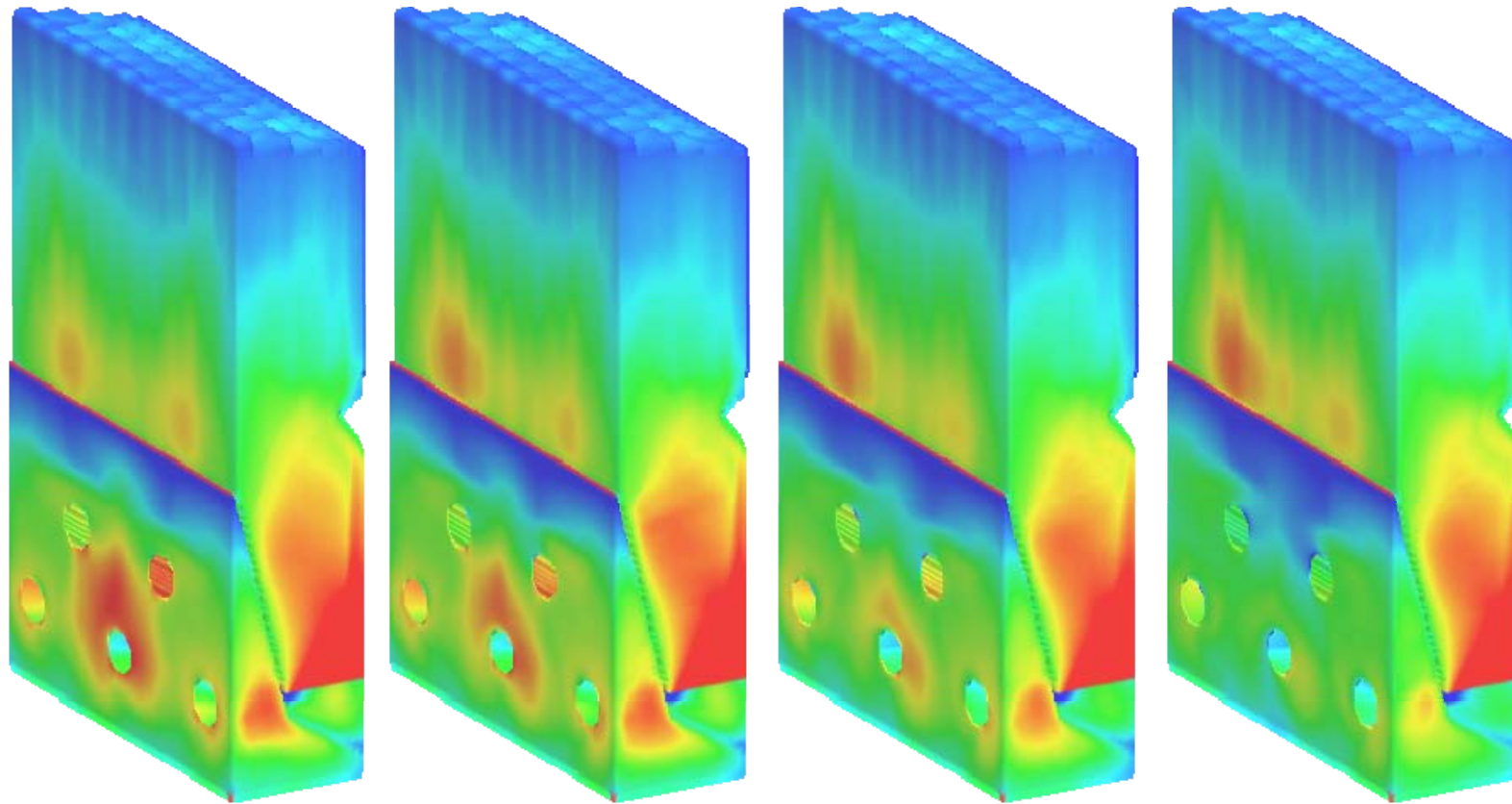
Furnace Exit Predictions



	Coal Only	5% Wood Co-Fire	10% Wood Co-Fire	15% Wood Co-Fire
Temperature	2332° F.	2355° F.	2354° F.	2363° F.
CO Concentration	3761 ppm	4876 ppm	4951 ppm	5373 ppm
O ₂ Concentration	3.48%	3.41%	3.48%	3.40%
NO _x	0.41 MBtu/hr	0.41 MBtu/hr	0.40 MBtu/hr	0.38 MBtu/hr
Carbon in Fly Ash	69%	62%	58%	56%
Fraction Ash Escaping	15%	17%	20%	20%
Total Wall Heat Transfer	694,741 Btu/hr	694,659 Btu/hr	669,966 Btu/hr	639,127 Btu/hr

- Predicted furnace exit NO_x and carbon in fly ash decrease with wood co-firing
- The fraction of ash escaping the furnace, CO concentration, and temperature increase with wood co-firing
- Wall heat transfer decreases with increasing fraction of wood co-firing (the decreased sooting propensity of wood vs. coal results in less radiative heat transfer to the walls)

Furnace Wall Heat Flux



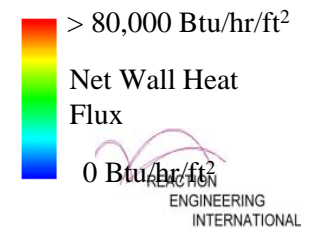
Coal Only

5% Wood Co-Fire

10% Wood Co-Fire

15% Wood Co-Fire

- In the region in front of the target wall, net wall heat transfer decreases with increasing biomass fraction due to lower soot levels and lower gas temperatures.



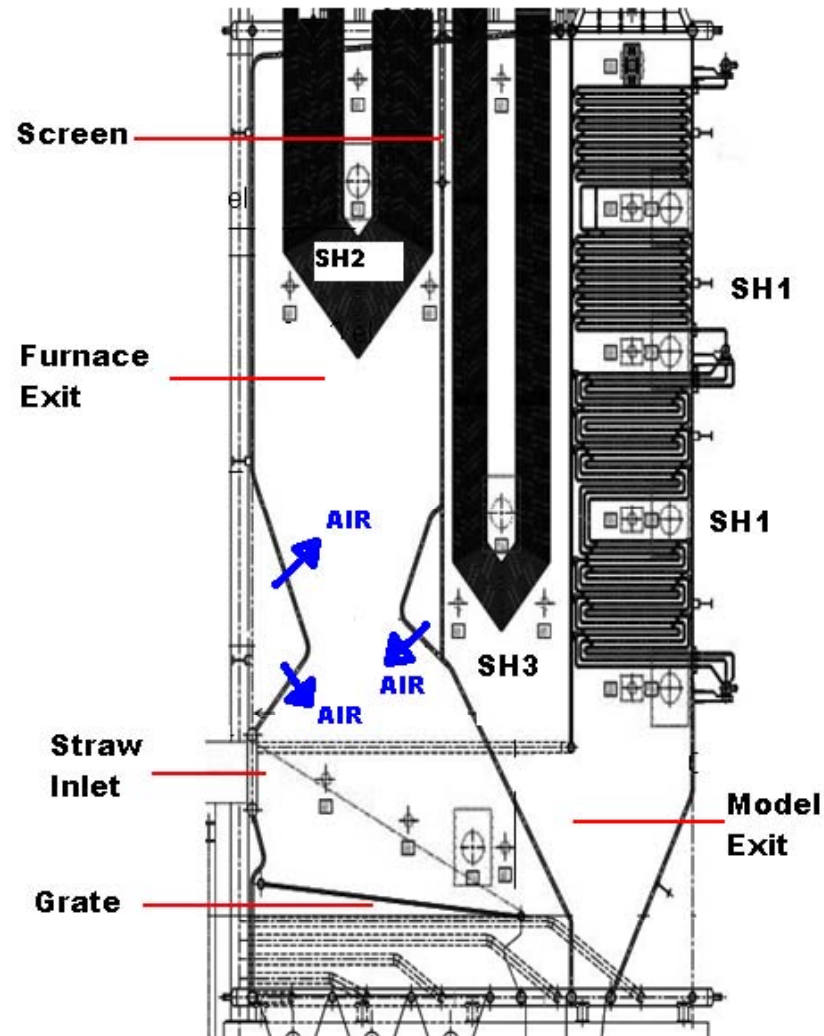
Straw Combustion in a Mass Burn Stoker

- High K & Cl results in low melting, corrosive ash.
- Pendent super heaters are generously spaced to avoid plugging



*Fenger, L.D., The use of Straw as Energy Source-example
Denmark, Proceedings of European Biomass Conference, Graz,
2008*

Conventional Design



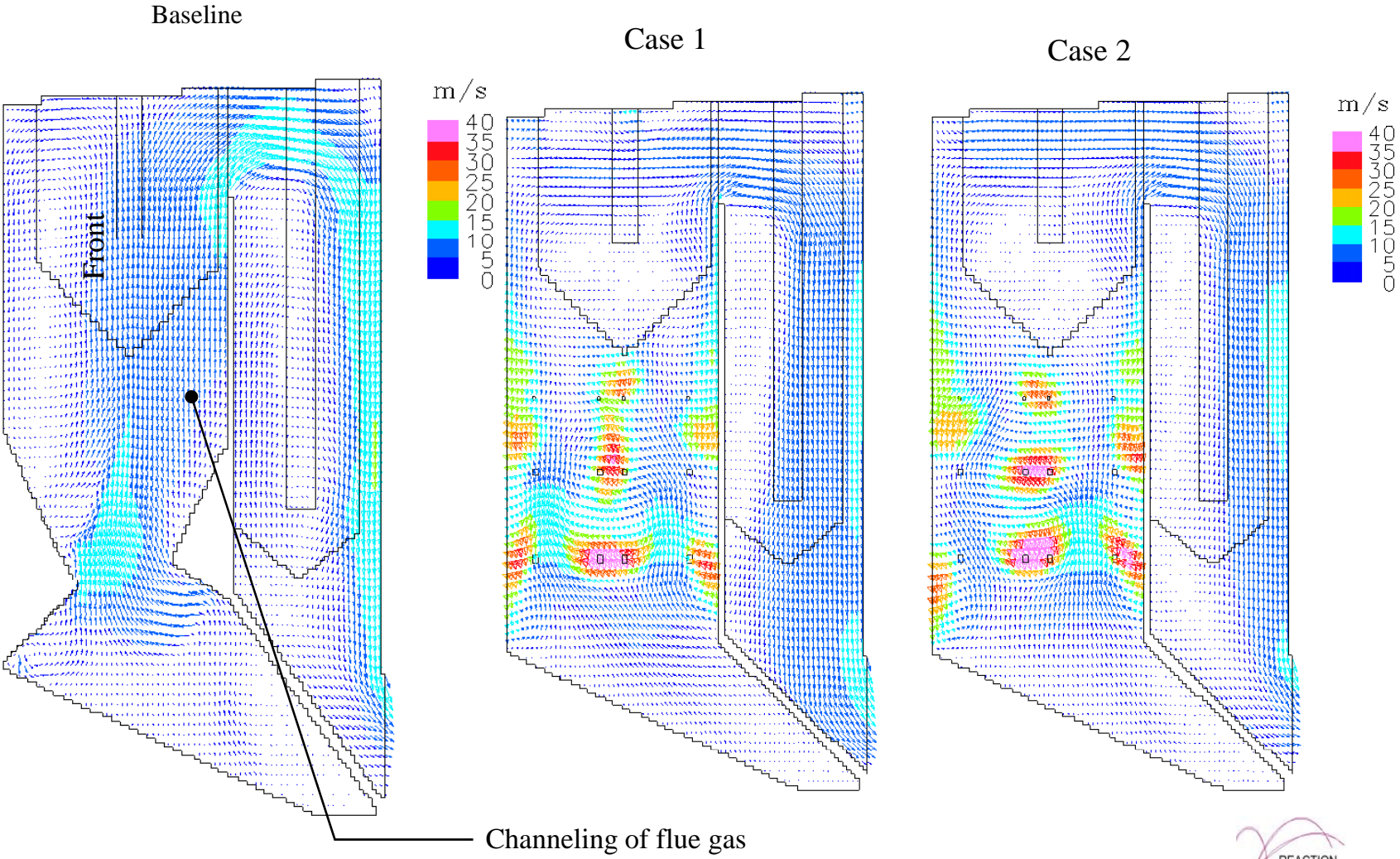
Straw Fuels Analysis

C	39.48%
H	5.31%
N (0.96% max)	0.52%
S	0.07%
O	35.79%
Cl (1.19% max)	0.36%
Ash	4.47%
Moisture	14.00%
TOTAL	100%
LHV(MJ/kg)	14.43

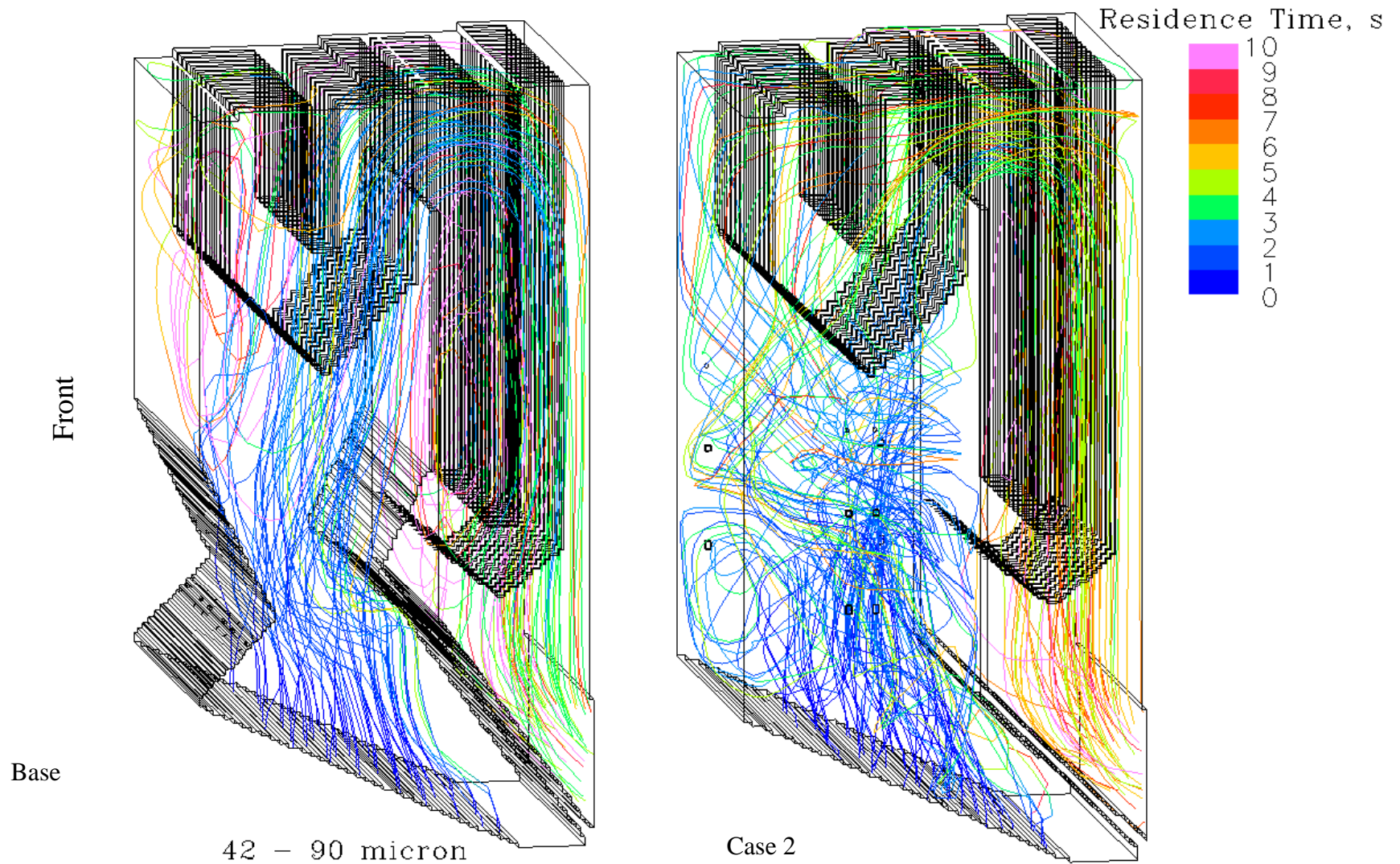
Proximate Analysis	Mean	Min.	Max
Moisture	14%	9%	30%
Volatile(dry)	76.1%	71.9%	80.9%
Fixed C(dry)	18.7%	16.5%	21.5%
Ash(dry)	5.2%	2.6%	11.5%

Ash Analysis	Mean	Min.	Max.
Al ₂ O ₃	2.1%	0.2%	9.1%
CaO	13.3%	7.8%	22.0%
K₂O	19.6%	11.0%	31.5%

Gas Velocity

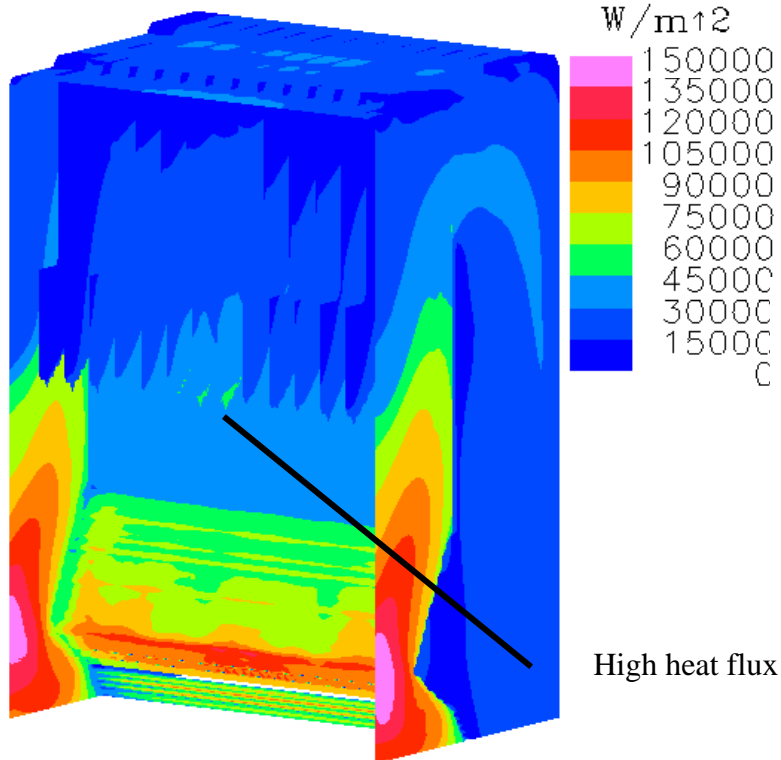


Ash Trajectories



Heat Flux

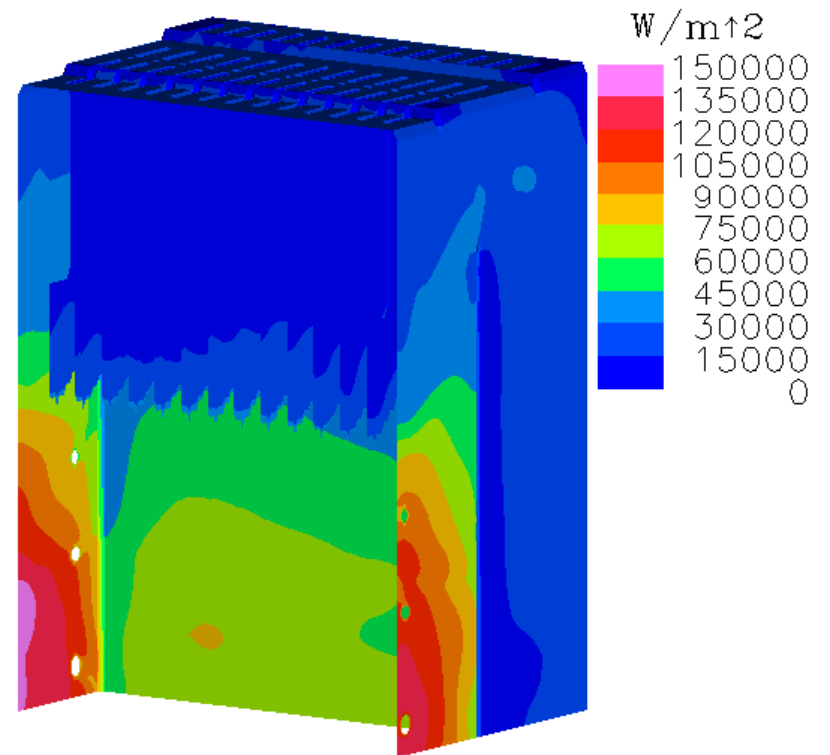
Base



Cut away to show rear wall arch and SH

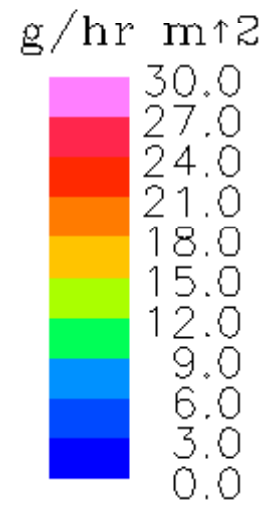
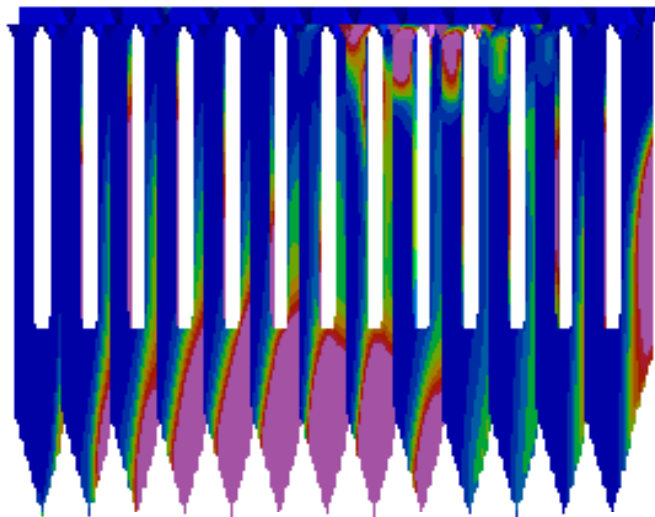


Case 2

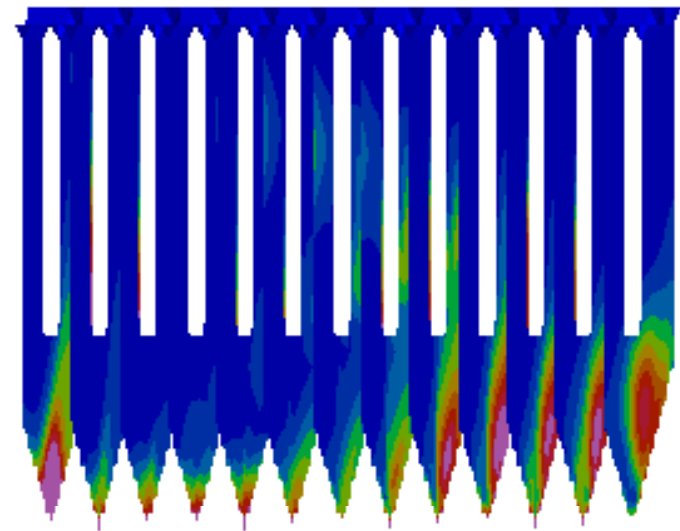


Ash Deposition

Baseline



Case 2



Cut away to show SH

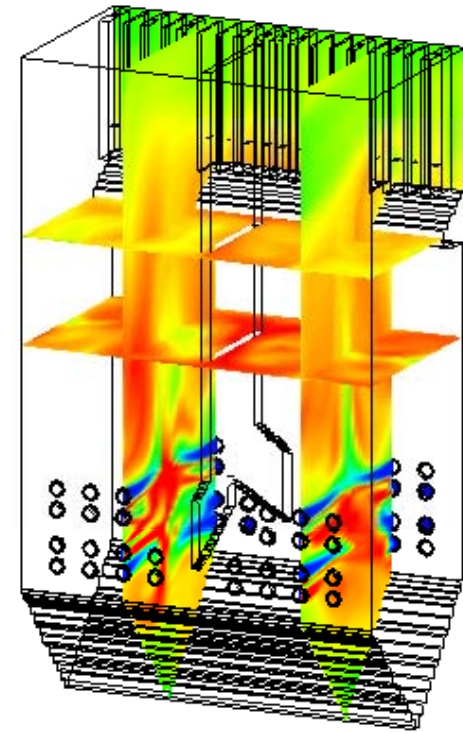
Deposition & Slagging of Complex Fuel Blends

→ Predict deposition impacts w/ CFD

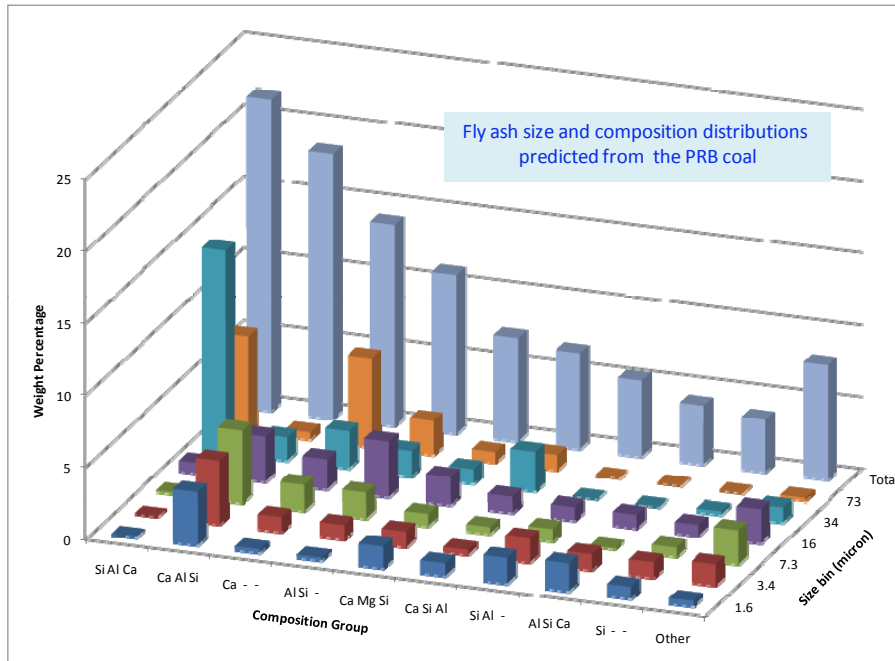
- ◆ Deposition patterns and rates
- ◆ Size, shape, composition of fly ash
- ◆ Fly ash viscosity = $f(\text{composition, temperature, local stoichiometry})$
- ◆ Deposit sintering = $f(\text{deposit mass, composition, temperature})$

→ Example

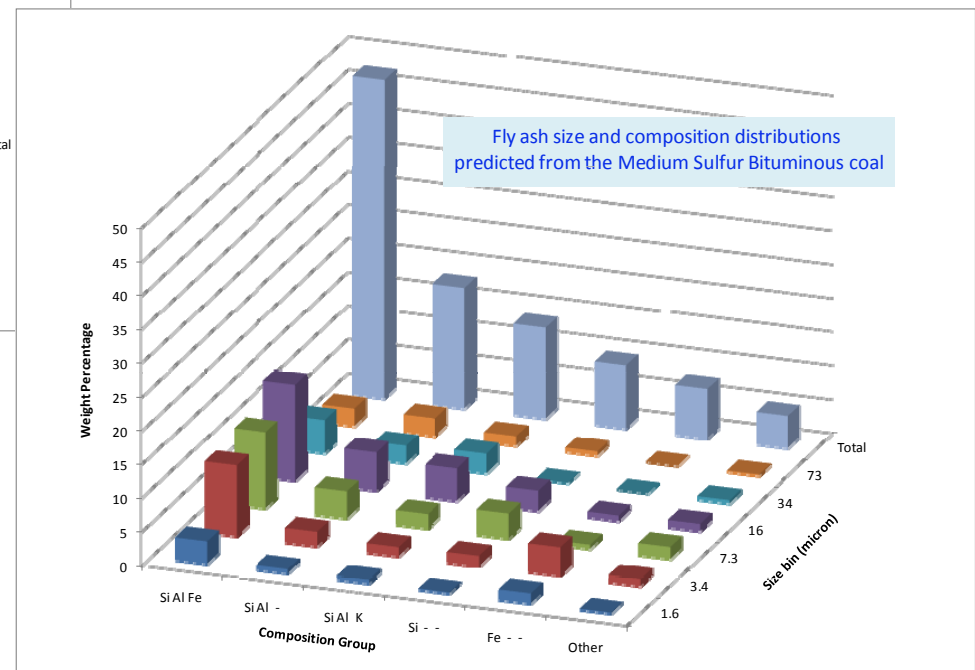
- ◆ 800 MW opposed wall-fired unit
- ◆ 56 burners firing 55/45% PRB/MSB coal blend



Fly Ash Size and Composition



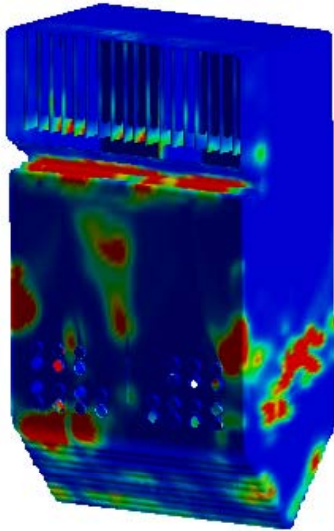
- Track properties separately (size, composition, trajectory)
- ◆ PRB has mostly Si-Al-Ca group
 - ◆ MSB has mostly Si-Al-Fe group



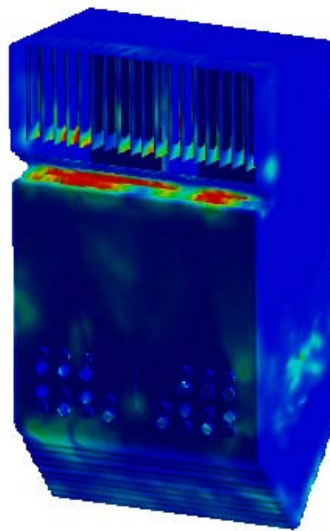
Predicted Deposition Impacts

- 6-hours after build-up
- Deposits change performance

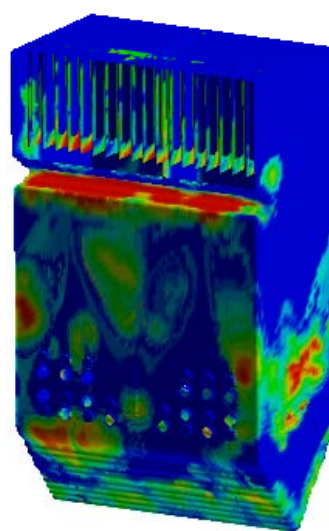
Deposition rate



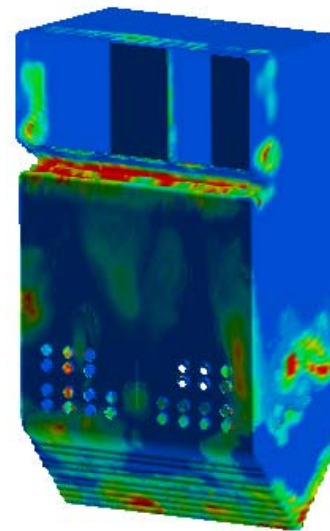
Deposit thickness



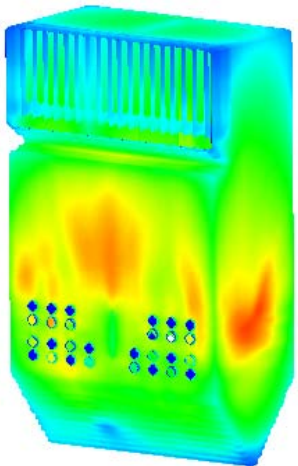
Deposit sintering



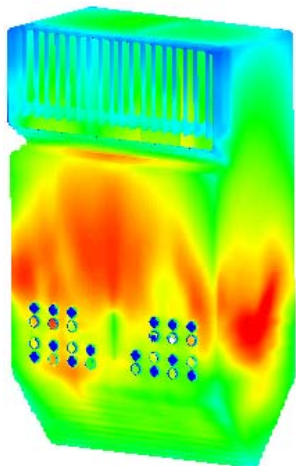
Deposit resistance



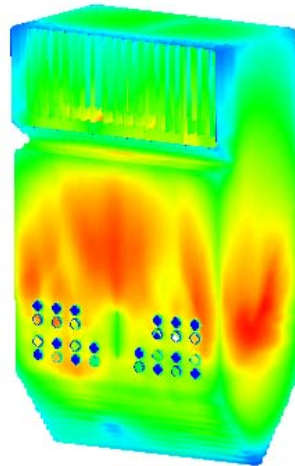
Initial incident heat flux



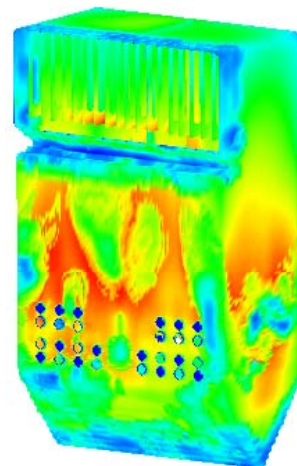
6-hr incident heat flux



Initial net heat flux



6-hr net heat flux



T_{exit} up 80 °F
NOx up 18%

Summary

- ➔ Key fundamental issues to consider in incorporating biomass into a renewable portfolio include:
 - ◆ Fuel processing and handling
 - ◆ Combustion impacts
 - ◆ Emissions
 - ◆ Operational impacts
- ➔ Characterization of combustion system, fuel and injection strategies must be performed on a case-by-case basis