REINHOLD ENVIRONMENTAL Ltd.

# 2017 NOx-Combustion-CCR Round Table Presentation

February 27 & 28, 2017, in Cleveland, OH / Hosted by FirstEnergy

# Biomass for Power Generation

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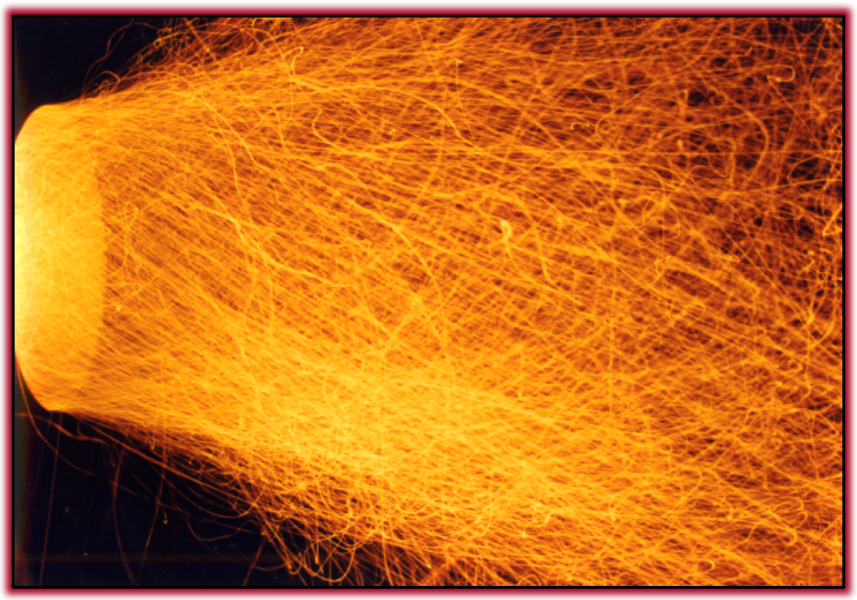
REACTION ENGINEERING INTERNATIONAL

NOx-Combustion-CCR Round Table
Hosted by FirstEnergy
Renaissance Cleveland Hotel, Cleveland, OH
February 27-28, 2017

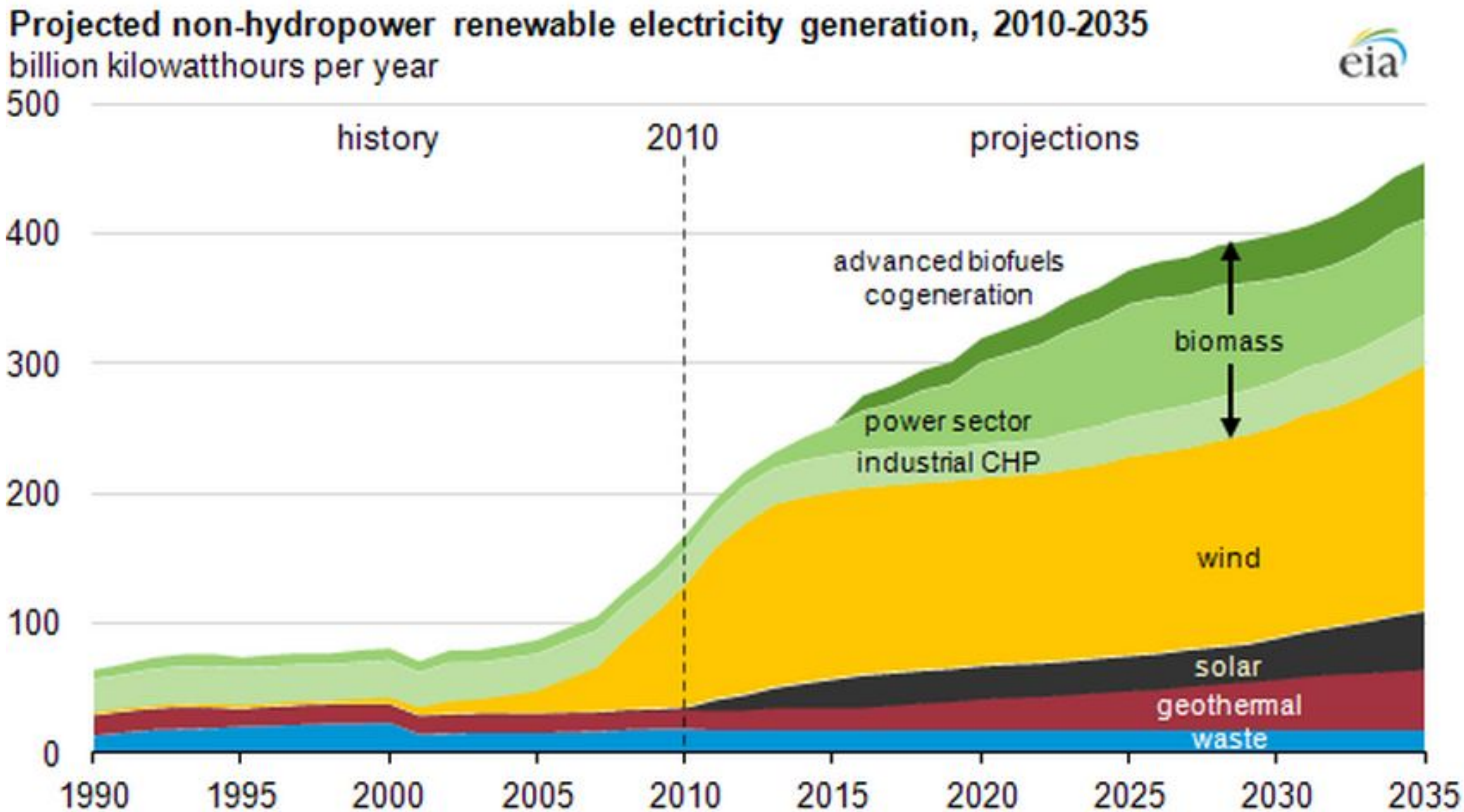
# Reaction Engineering International

*Privately held consulting firm recognized for independent analysis and evaluations involving a range of industrial combustion applications*



- Technical focus on multi-phase, chemically reacting flows
- Serving the utility industry since 1990
- Affiliates in Asia and Europe
- Established capabilities include advanced modeling, process evaluation and testing

# Biomass – Past & Future of Renewable Power?

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# Pros / Cons of Biomass vs Coal

- **Pros:**
  - **Reduced emissions**
  - **Replacement of coal with locally produced crops and/or waste**
  - **Benefits to local employment**
  - **Reduction of landfill pressures**
- **Cons:**
  - **Problematic fuel supply and consistency**
  - **Low energy density**
  - **Fuel properties complicate utilization in coal boilers (heat balance and ash management)**

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# Biomass Emissions

**Emission reductions are greatest potential benefit of biomass co-firing**

- $CO_2$ – significant reduction below that of coal or natural gas under appropriate conditions
- $SO_2$ – very low sulfur fuel
- Hg – very low mercury fuel
- Ash – although variable, typically lower than coal
- NOx – complex but reductions can be significant

# Dedicated Firing of Biomass

- ➔ **100% replacement in traditional coal units**
- ➔ **Grate-fired units**
  - Increasing numbers for industrial application
  - Co-gen potential
  - IB MACT regulatory advantages
- ➔ **Fluidized bed combustion/gasification**
  - Increasing numbers for industrial applications
  - Co-gen potential
  - Fuel flexible

http://www.syracuse.com/news/index.ssf/2014/11/fort_drum_renewable_energy_wood-burning_power_plant.html

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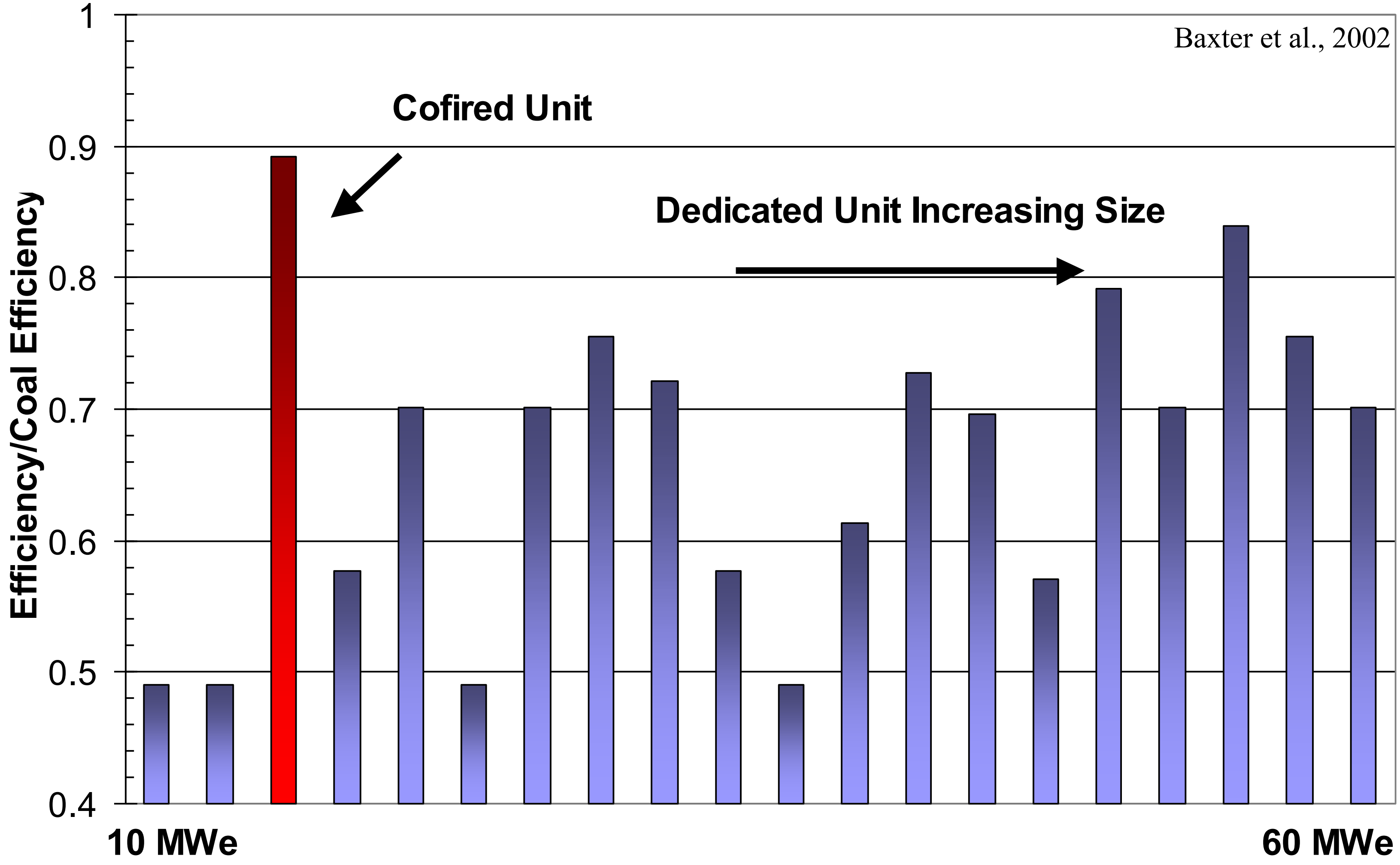
# Co-firing with Coal

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# Wood Power in the Western US

Trudy Balcom, The Independent
Dec 8, 2016

- Many western forests have experienced significant drought and beetle infestations
- Several utilities are developing projects to utilize this and related resources:
  - Salt River Project Coronado, 5% wood co-firing test burns in Fall 2016
  - Portland General Electric Boardman completed a co-firing test at 100 KPPH tons of torrefied wood on Feb 7, 2017
  - Colorado Springs Utilities Drake has installed all equipment required for woody biomass co-firing
  - PacifiCorp Hunter has tentatively decided to do a Q3 2017 Q3 co-firing demo of torrefied beetle kill
  - 4 coal plants in WY and CO have been identified by the US forest service as candidates.

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# International Wood Pellet Projects (Doosan)

Strauss, FutureMetrics, 2016

| Project Name<br>Country | Scope | Units x MWe | Contract Award | Customer |
|---|---|---|---|---|
| Lynemouth<br>UK | 100% wood pellet conversion contract award | 3 x 140 | 2016 | EPH |
| Yeong Dong<br>Korea | 100% wood pellet conversion of downshot boiler | 1 x 110 | 2015 | KOSEP |
| Lynemouth<br>UK | 100% biomass conversion FEED study | 3 x 140 | 2013 | RWE |
| Gardanne<br>France | Biomass conversion and turbine upgrade | 1 x 150 | 2013 | E.On |
| Drax<br>UK | Conversion of E-mills and associated burners to wood pellets | 2 x 660 | 2012 | Drax Power Ltd |
| Drax<br>UK | Conversion of E-mills and associated burners to wood pellets | 1 x 660 | 2011 | Drax Power Ltd |
| Ironbridge<br>UK | Convert units 1 and 2 to 100% wood pellets | 2 x 370 | 2011 | E.ON UK |
| Atikokan<br>Canada | 100% wood pellet firing | 1 x 220 | 2011 | Ontario Power Generation |
| Drax<br>UK | Conversion of two E-mills biomass | 1 x 660 | 2010 | Drax Power Ltd |
| Rybnik<br>Poland | Biomass unloading, storage and milling | 1 | 2010 | EDF |
| Drax<br>UK | Twelve direct injection biomass co-firing systems | 6 x 660 | 2009 | Drax Power Ltd |
| Hasselby CHP<br>Sweden | Conversion of coal mills and burners to 100% wood pellet firing | 1 | 1992 | Hasselby Power |

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# Fuel Properties
*(Duong et al., 2010)*

| Parameter | Wood Waste | | Corn Stover | | Switchgrass | | Eastern Bituminous Coal | |
|---|---|---|---|---|---|---|---|---|
| Proximate Analysis | Dry Basis | As Rec'd | Dry Basis | As Rec'd | Dry Basis | As Rec'd | Dry Basis | As Rec'd |
| 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 |

- Low heating value
- Potentially high moisture
- Highly variable ash content
- Typically high volatiles
- Typically low sulfur and mercury

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# Fuel Preparation

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


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# 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

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# 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

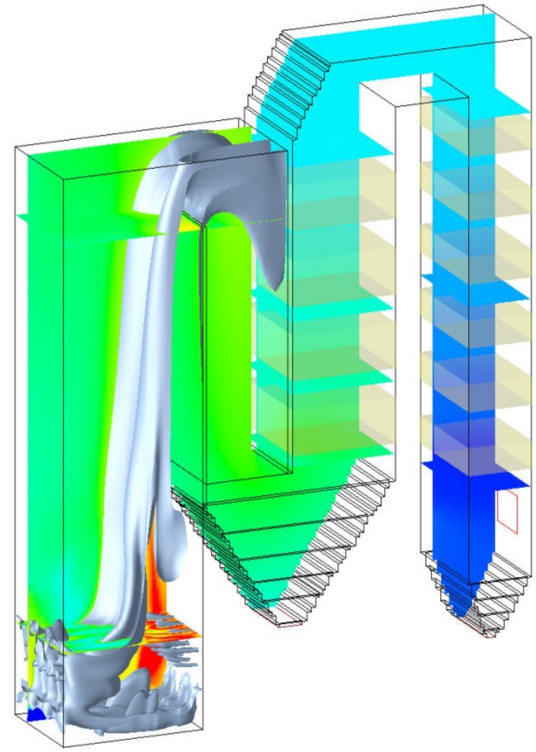
# Combustion Impacts

- **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**

# 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**

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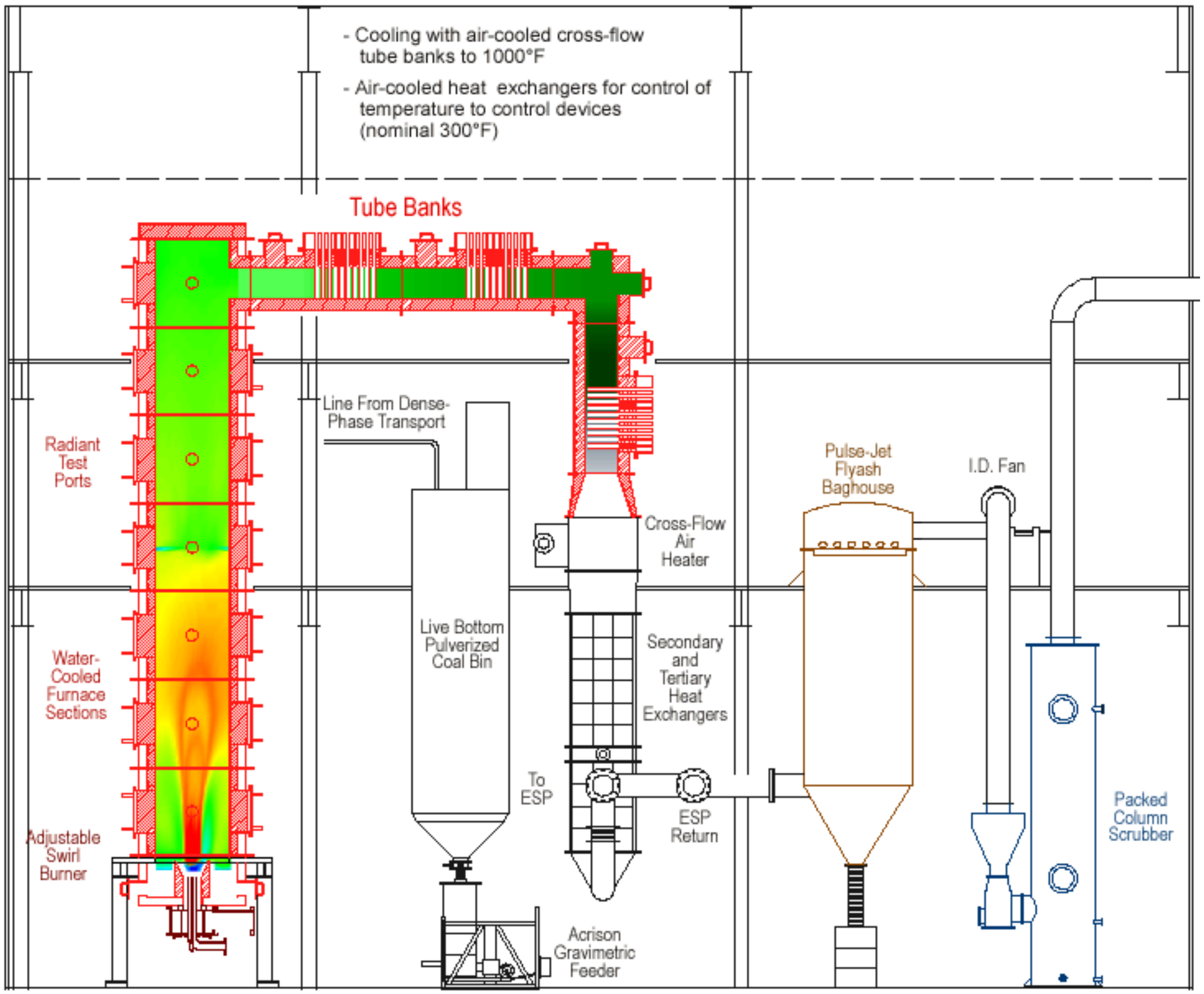
# Biomass Injection Strategies




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

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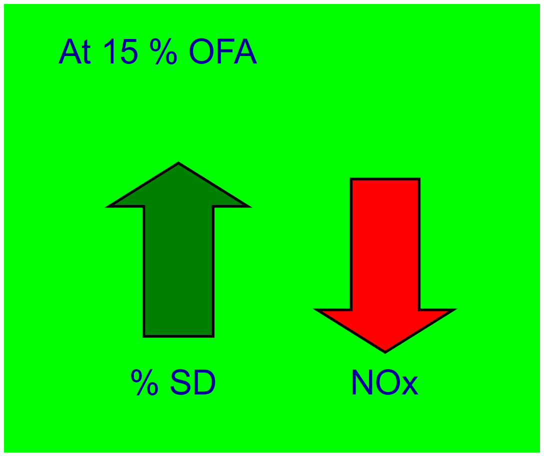
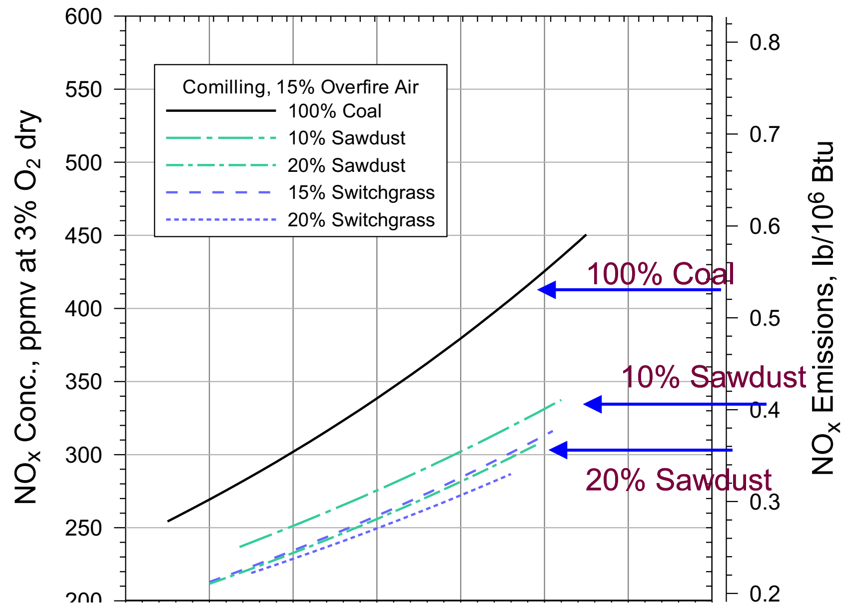
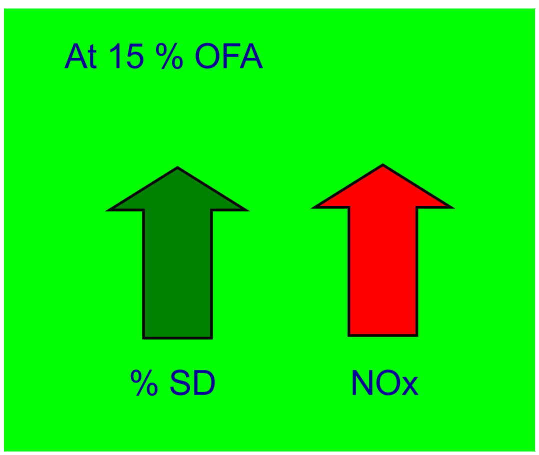
# NOx Measurements During Testing

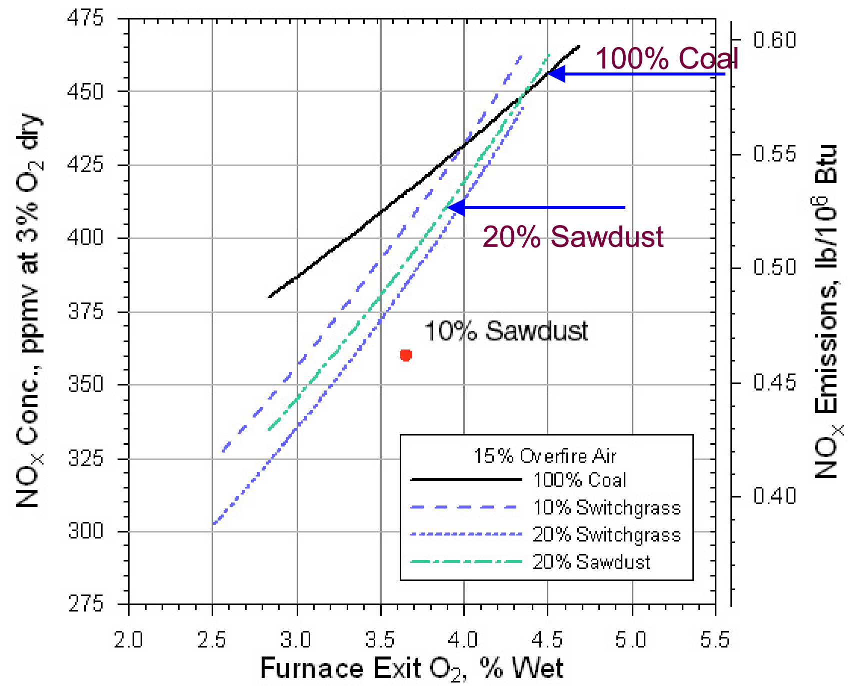
**Co-milled**




**Center Injection**

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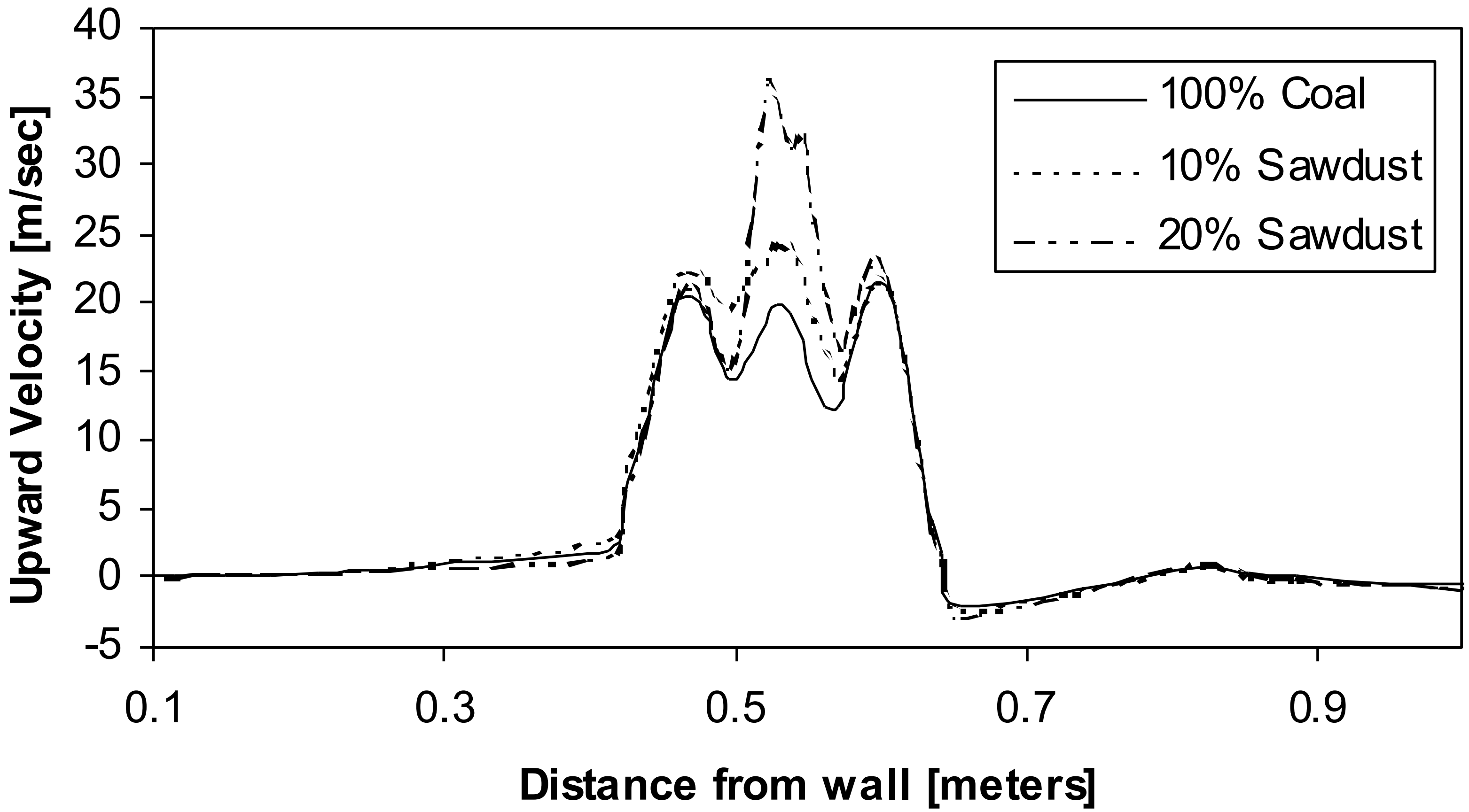
# Near Burner Velocity Profile

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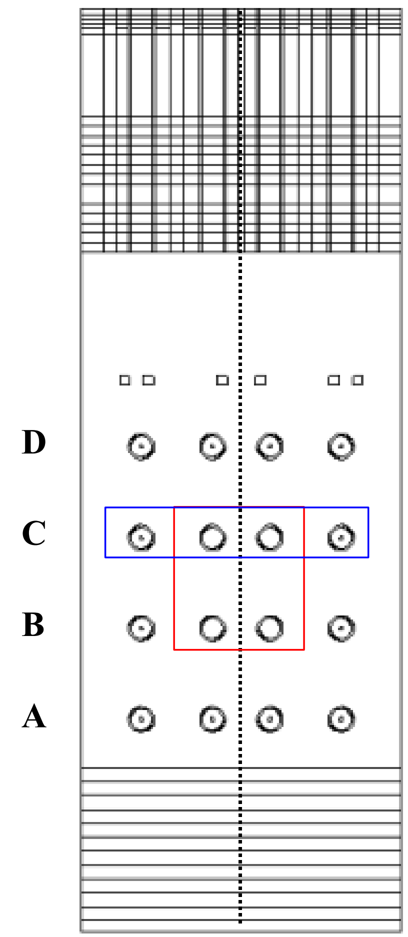
# Full-scale NOx Application

- 150 MW front wall-fired boiler
- 16 Low NOx 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

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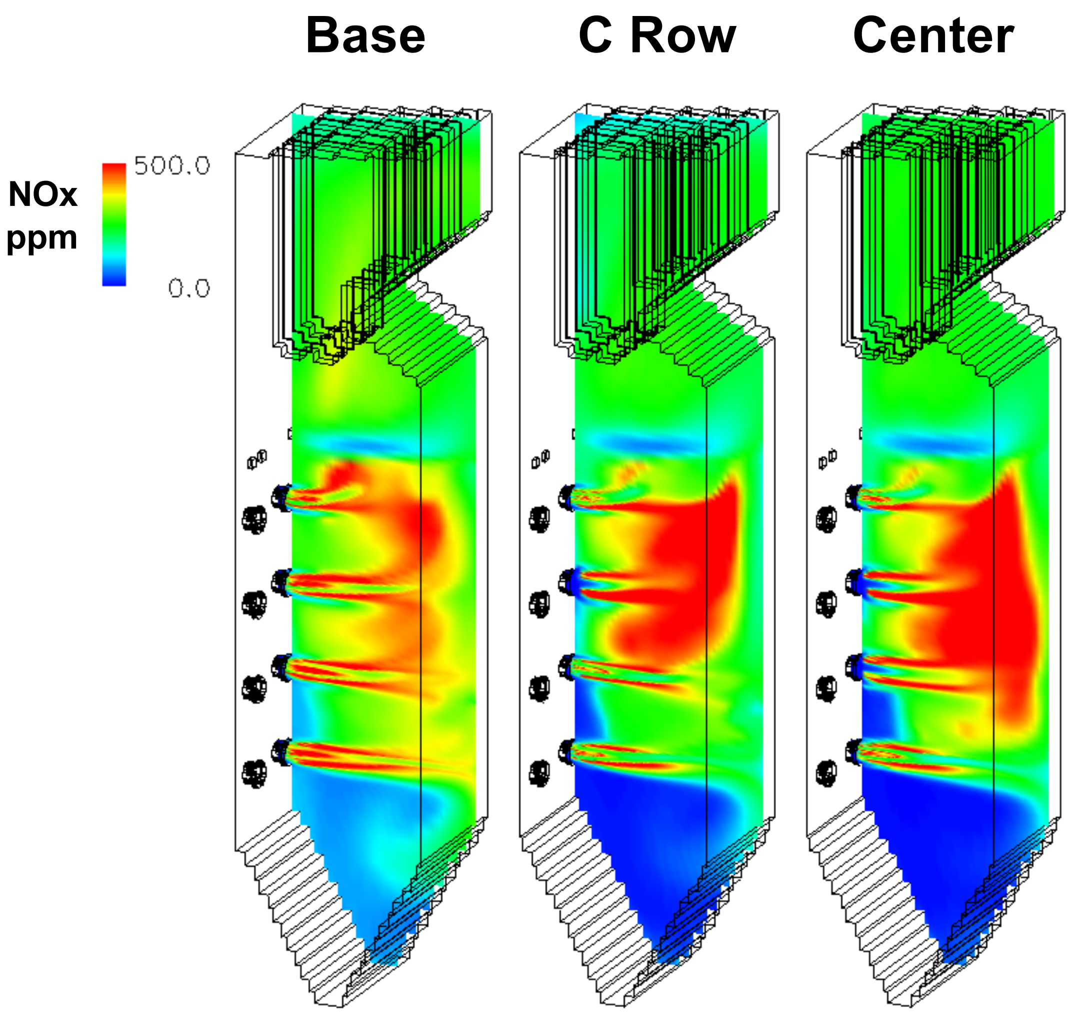
# Modeling Results

| Proximate Analysis | Coal | Biomass |
|---|---|---|
| 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 |
| **Ultimate Analysis** | | |
| 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 |

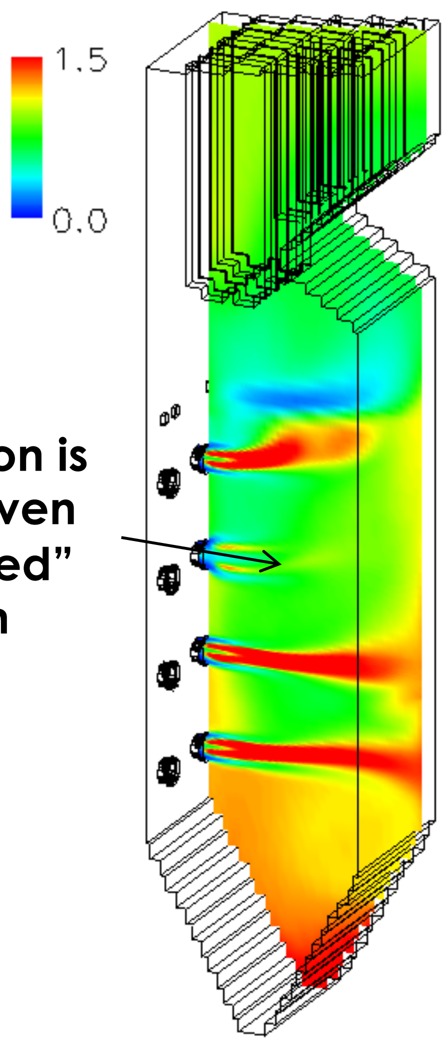
# NOx Concentration



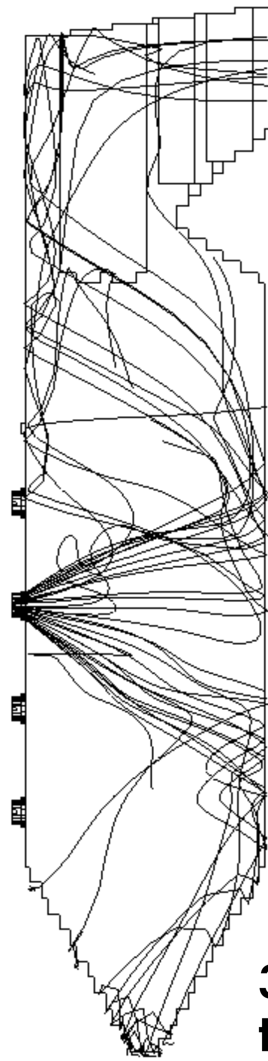

- ➔ **Co-fired burners actually produced more NOx**
- ➔ **Why did NOx go down?**

# Wood Particle Paths

Equivalence Ratio




C Row region is fuel lean even though "fired" fuel-rich



3.85 mm particle trajectories

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

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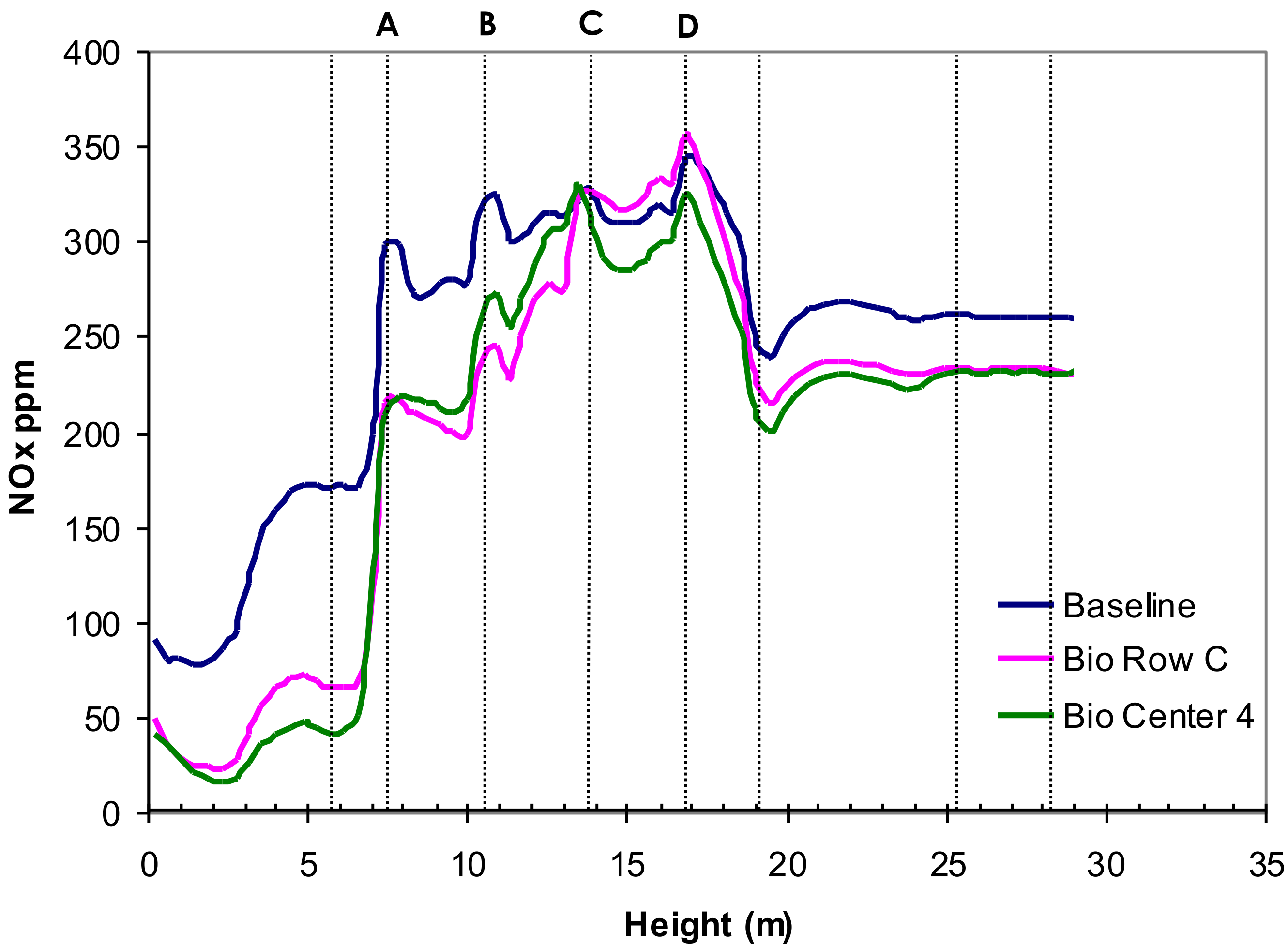
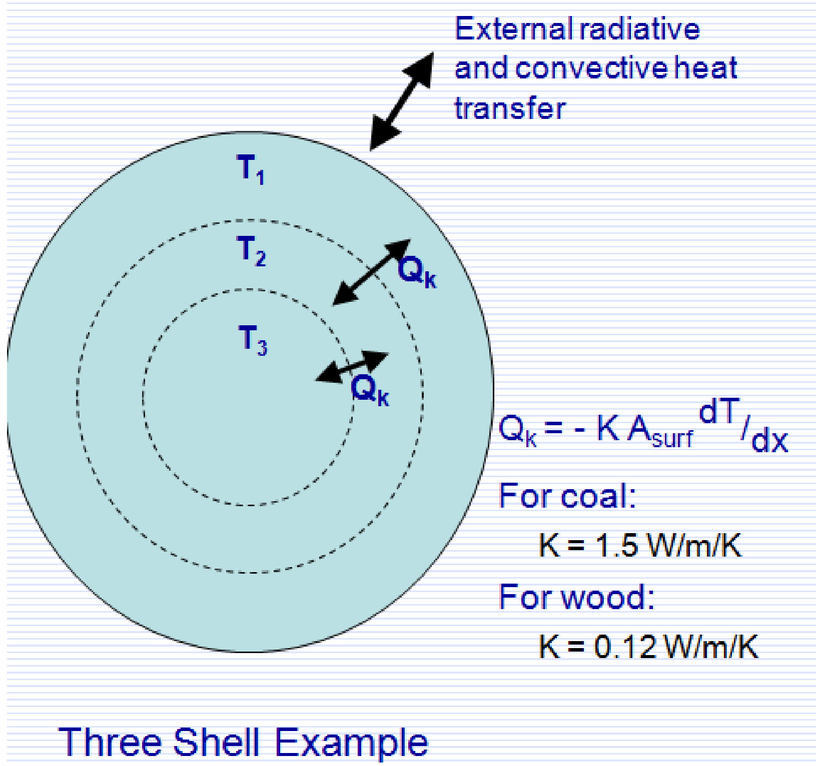
# NOx Distribution

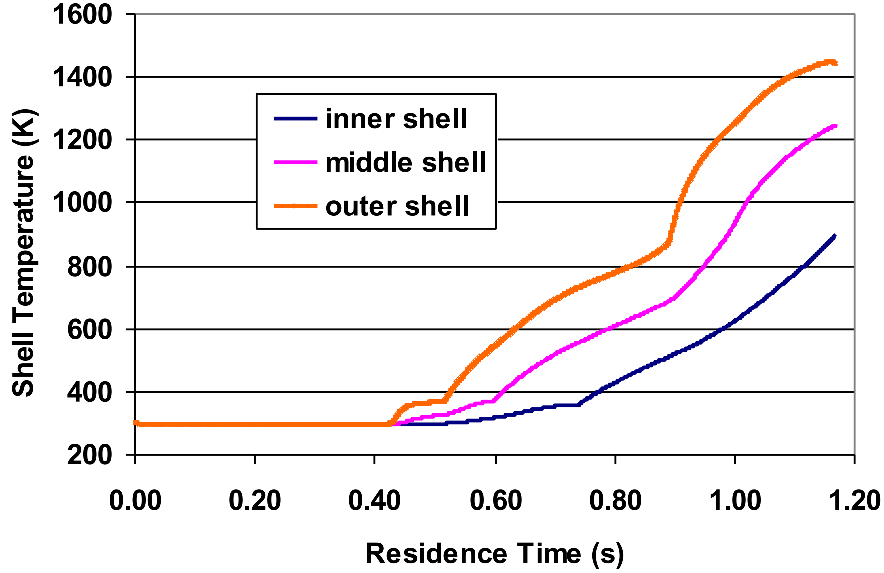


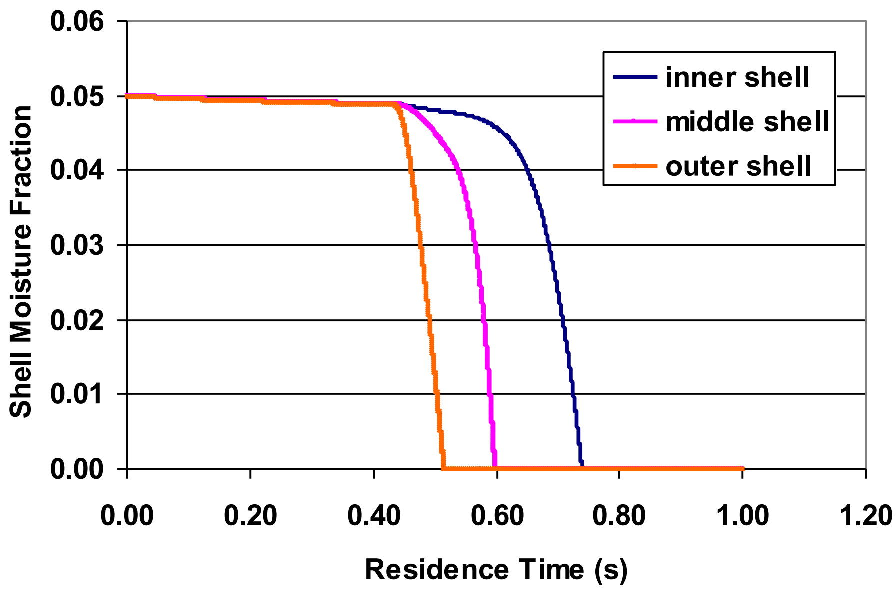
# Biomass Particle Combustion (Cyclones & Stokers)

- **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 W/m/K (wood conductivity)

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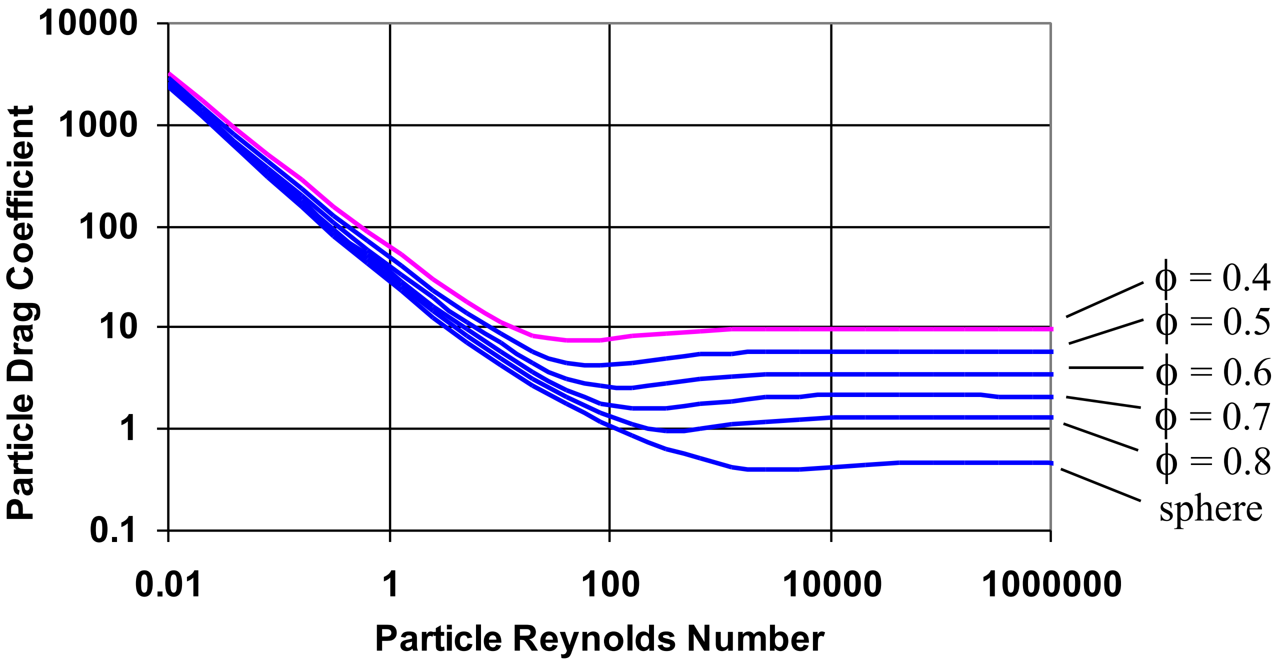
# Drag on Non-Spherical Particles

Particle drag is calculated in terms of a shape factor $\phi$ (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

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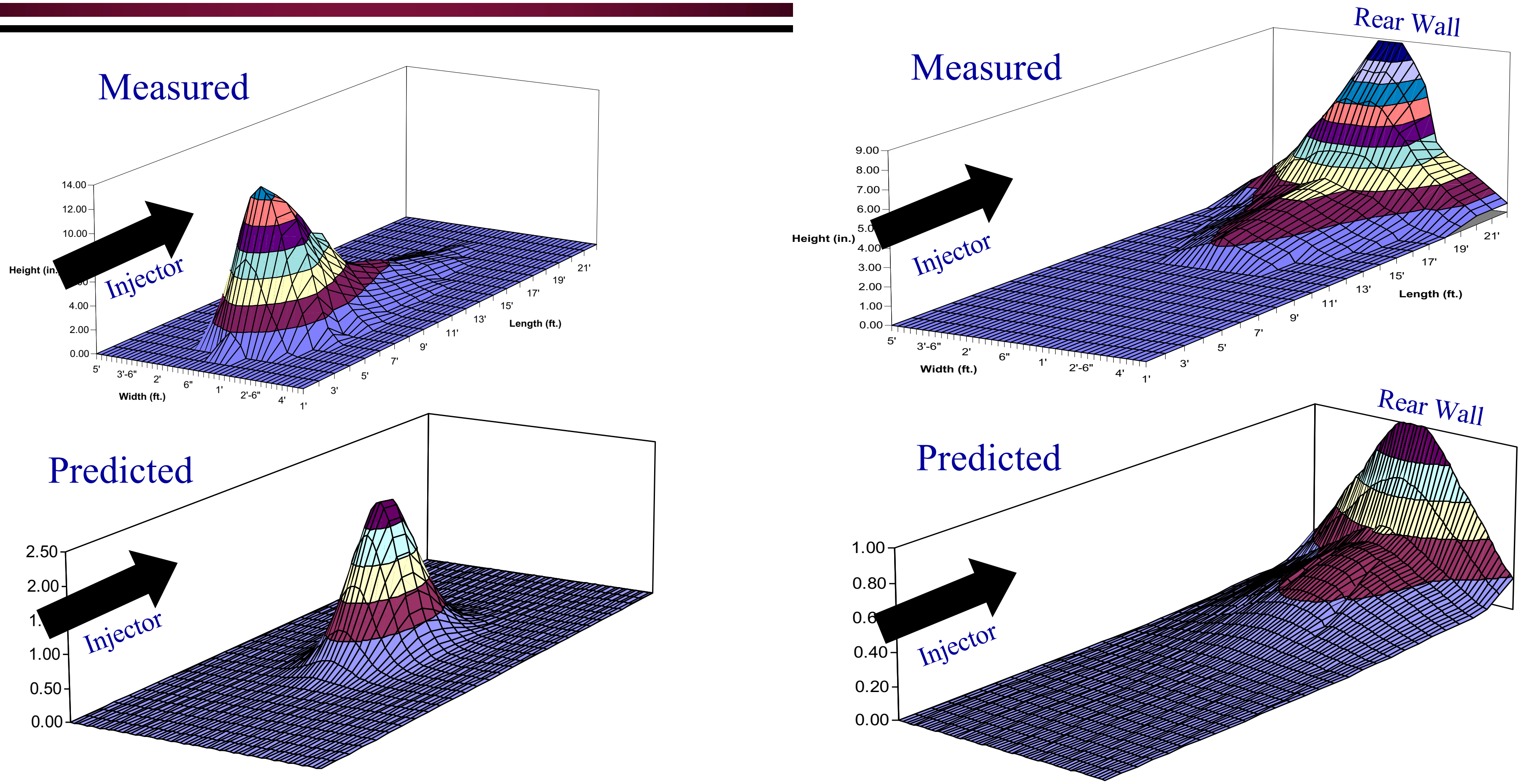
# Non-Spherical Drag Model Verification




Low air velocity

High air velocity

Wood chip spread from an air blast spreader

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# 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. |
| Fuel Mass Input | | | | |
| 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% |
| Fuel Thermal Input | | | | |
| 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

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# 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% |
| H2O | 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/ft3 | 18 lb/ft$^3$ |

## Coal Ash Fusion Temperatures

$T_{250}$ 2350°F
$T_{80}$ 2500°F

Green wood devolatization and oxidition kinetic rates are used for wood particles.

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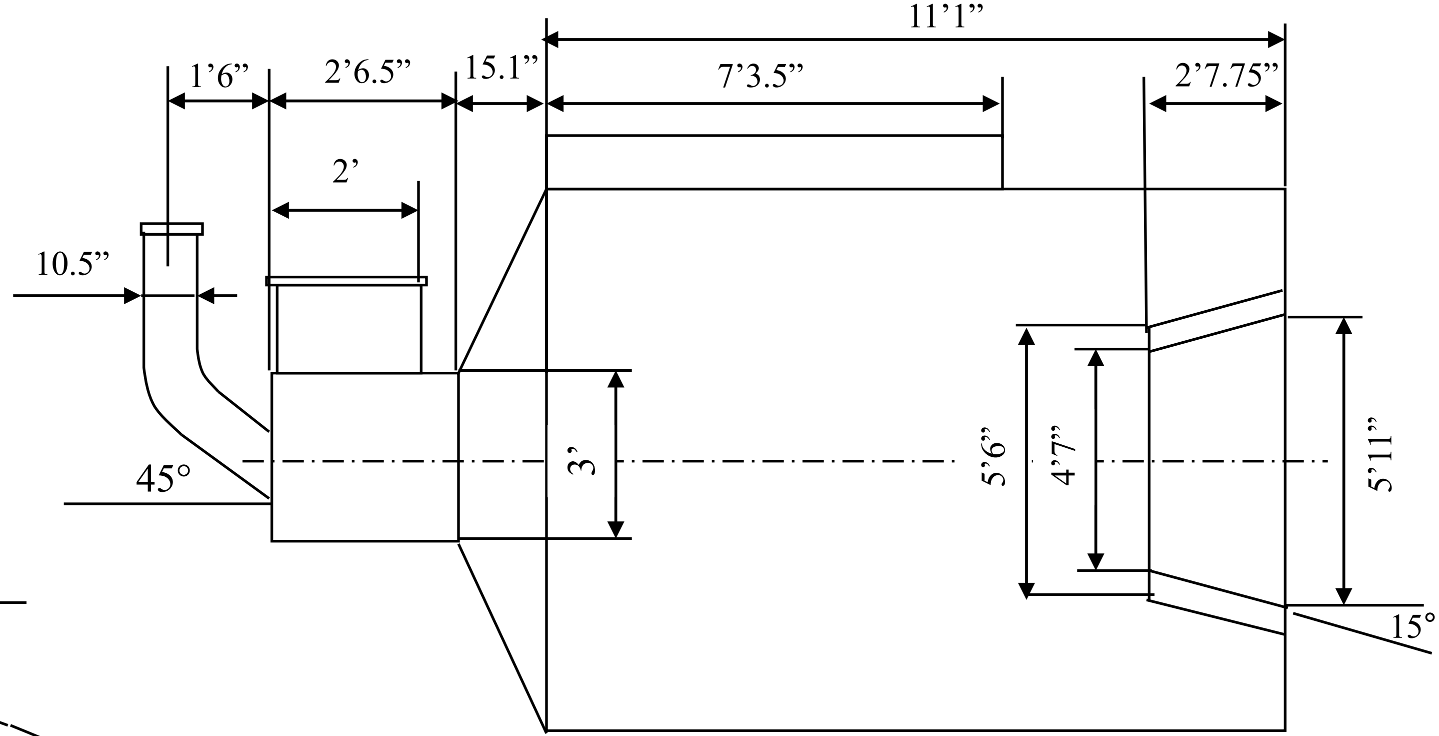
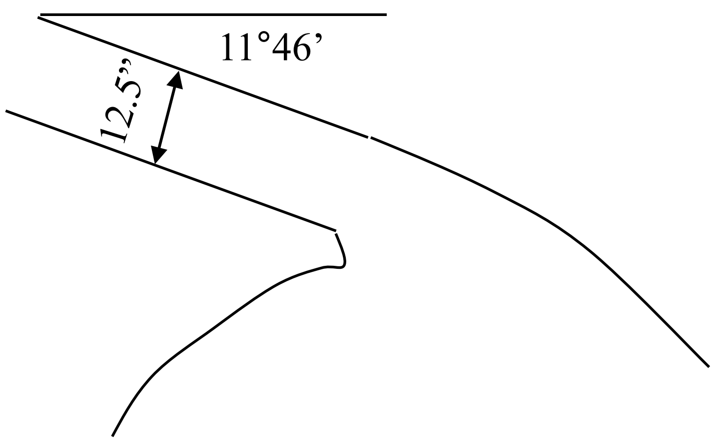
# Cyclone Barrel Geometry

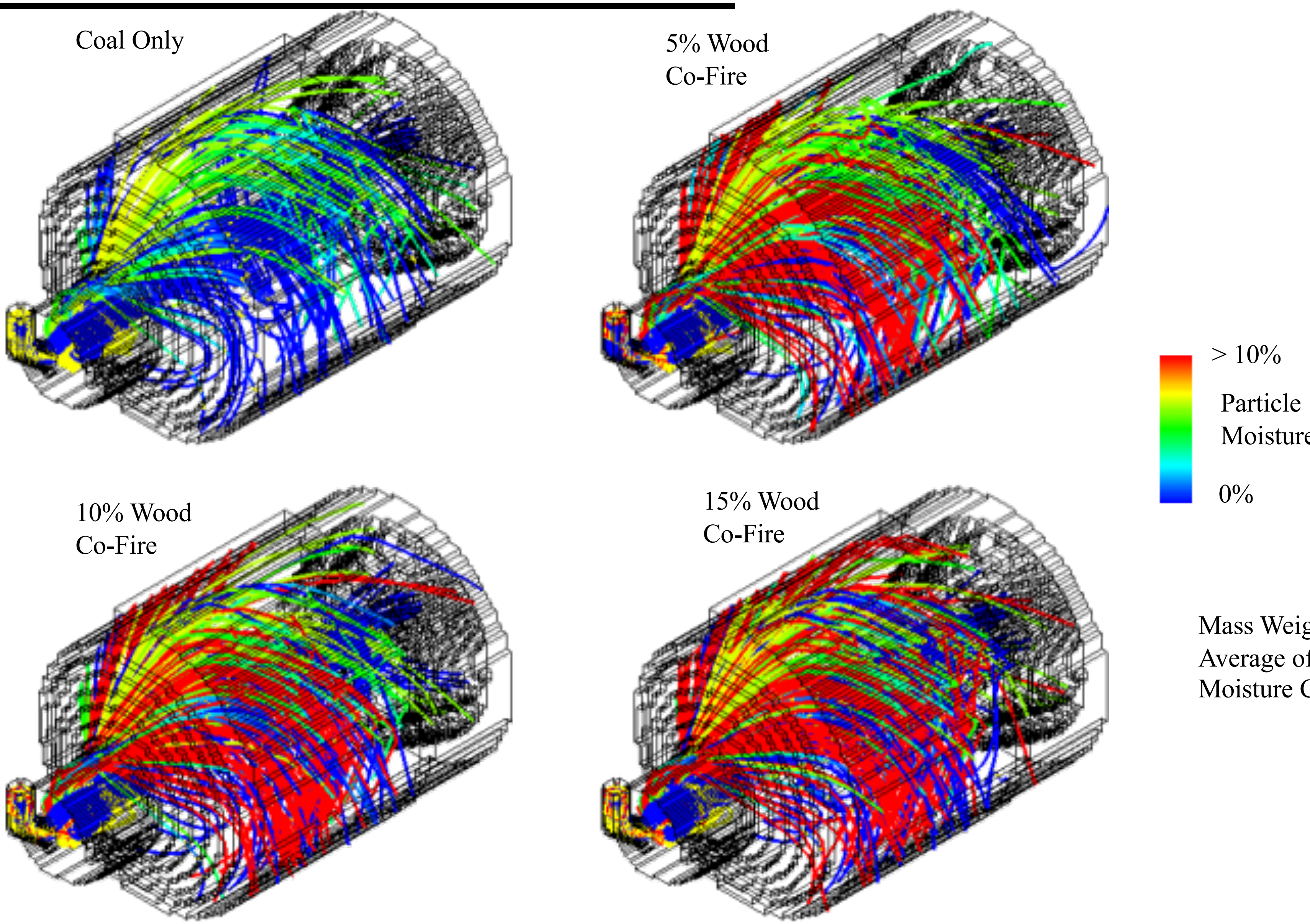



Cross-section of Cyclone



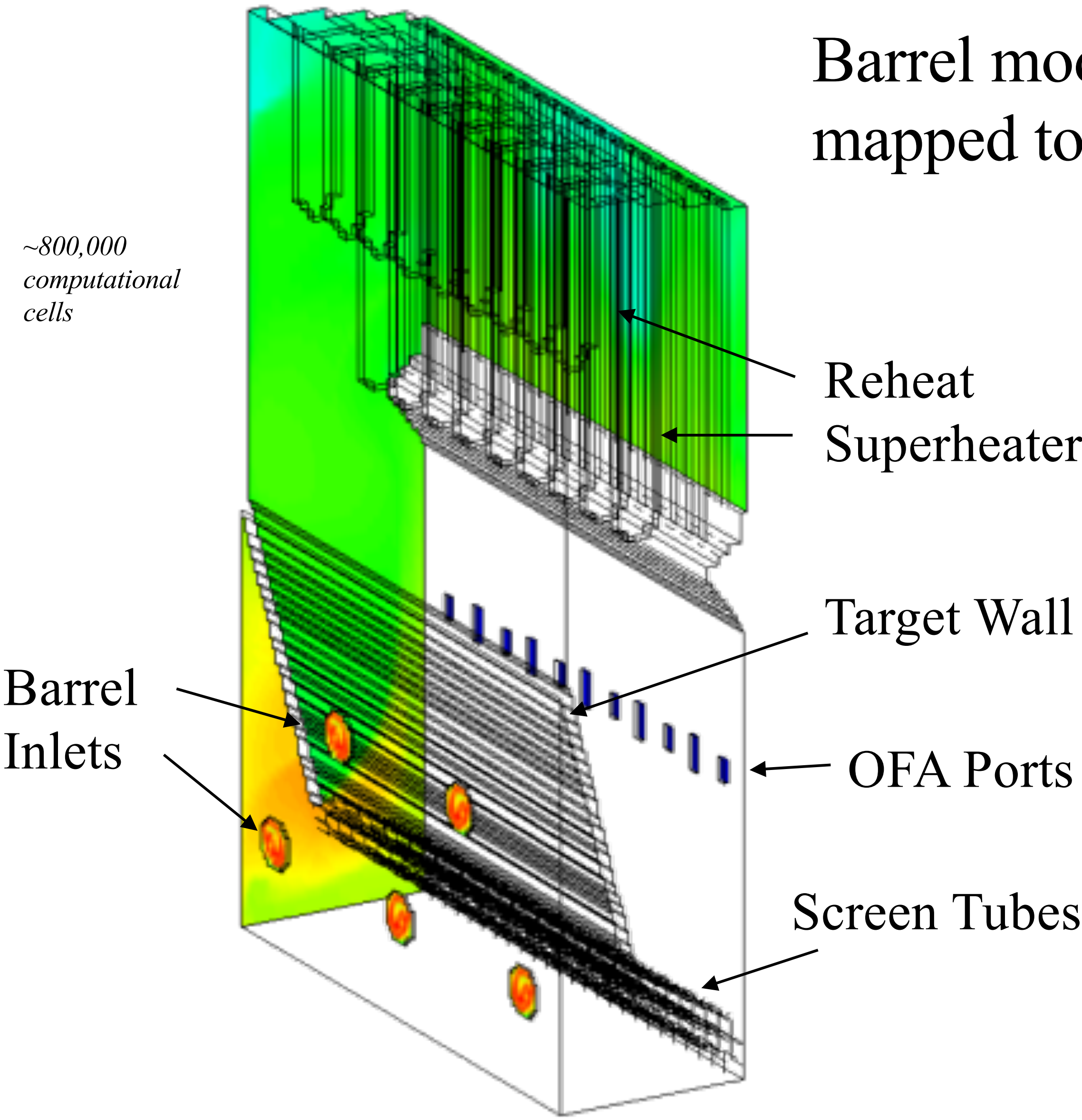

Cross-section of Secondary Inlet

# Particle Trajectories




Mass Weighted
Average of All Shell
Moisture Contents

# 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”

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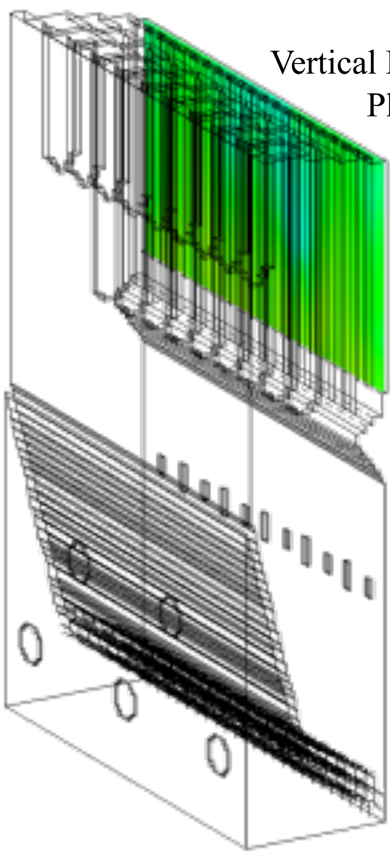
# Furnace Exit Predictions




| | 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 |
| O2 Concentration | 3.48% | 3.41% | 3.48% | 3.40% |
| NOx | 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 NOx 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)

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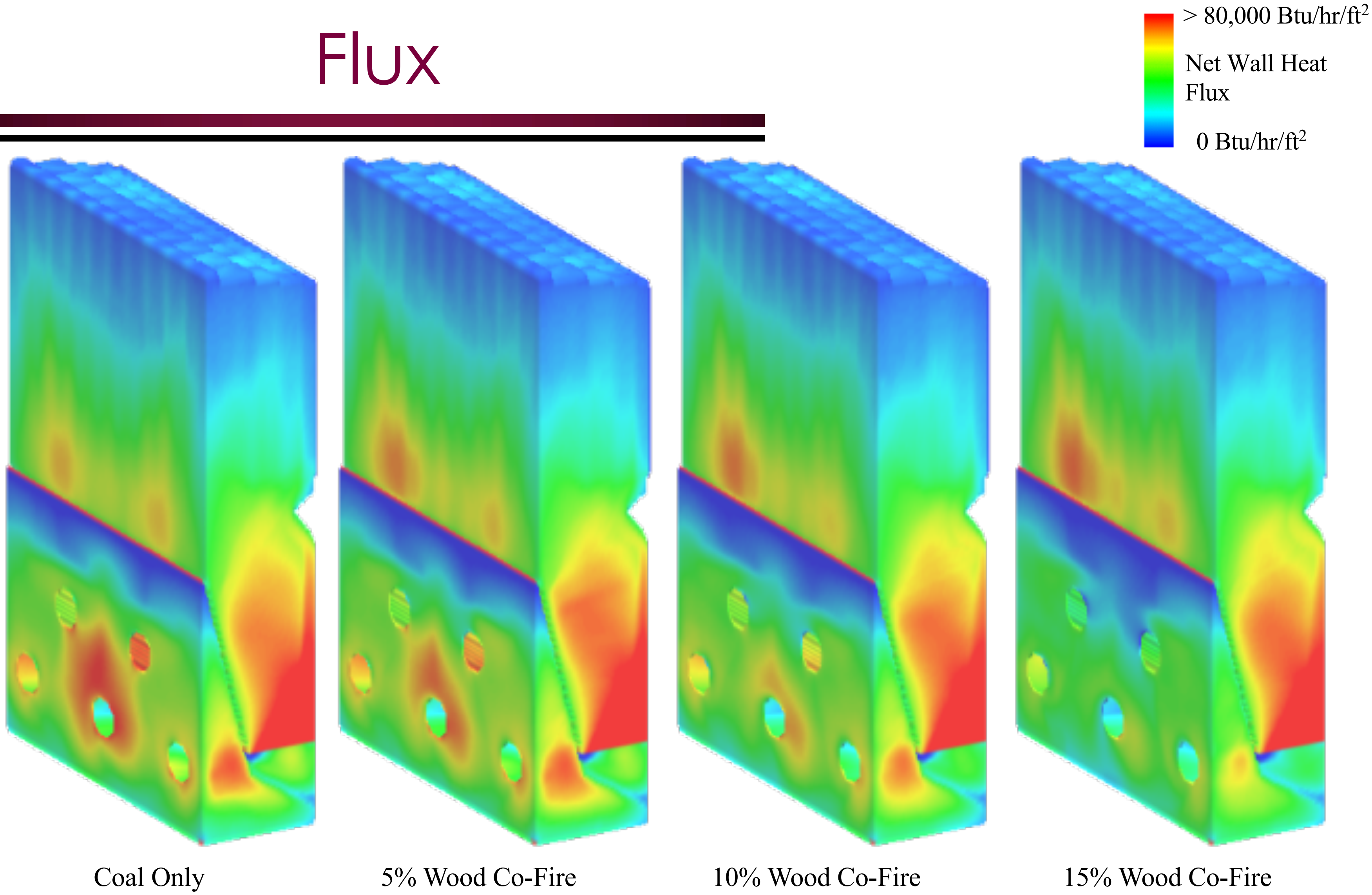
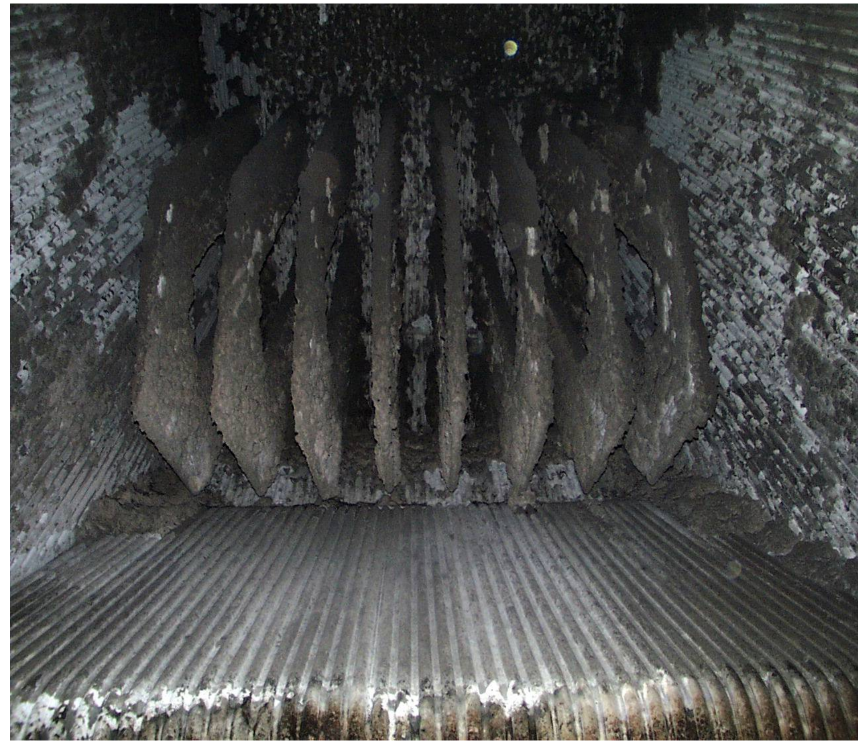
# Furnace Wall Heat Flux




- 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*

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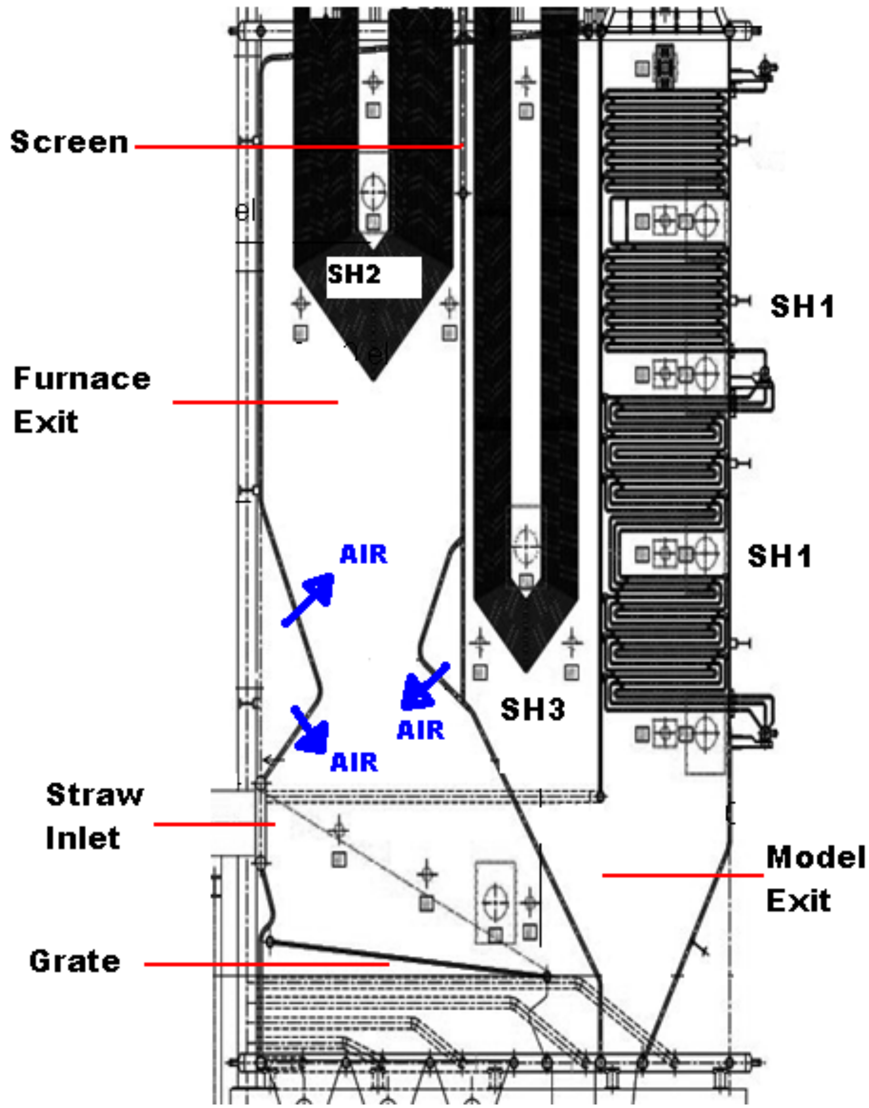
# Conventional Design



# 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. |
|---|---|---|---|
| Al2O3 | 2.1% | 0.2% | 9.1% |
| CaO | 13.3% | 7.8% | 22.0% |
| K2O | 19.6% | 11.0% | 31.5% |

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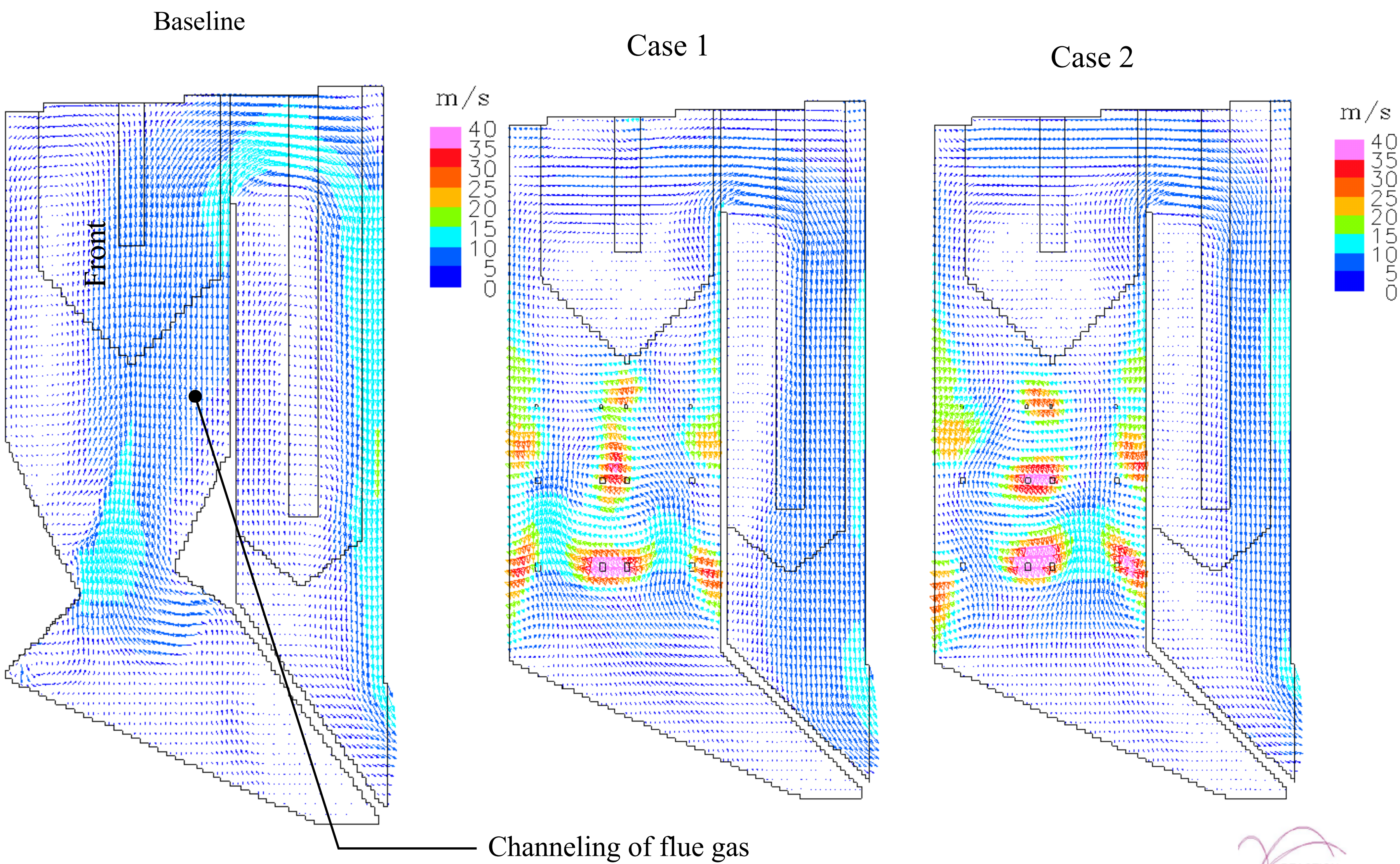
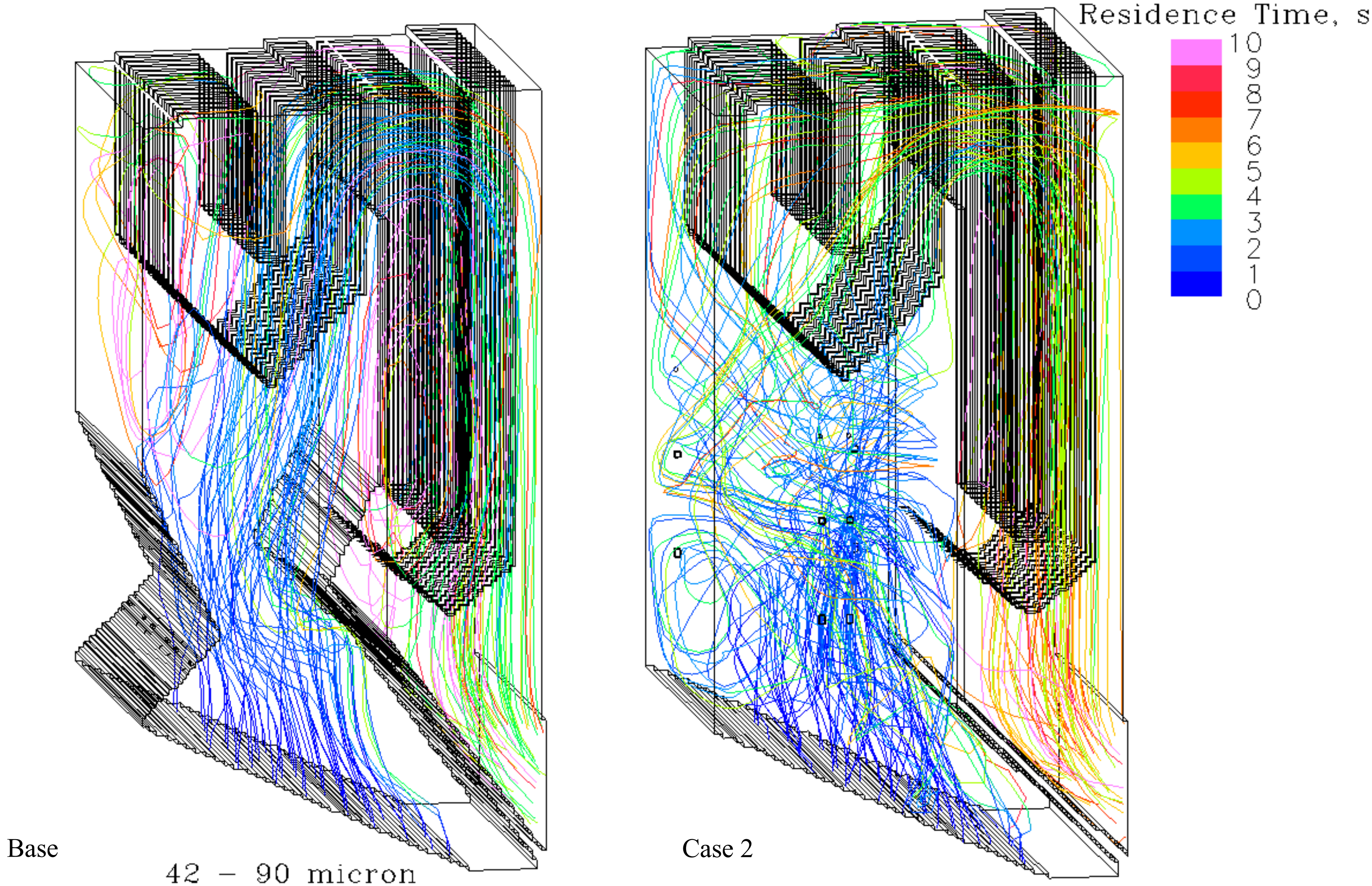
# Gas Velocity

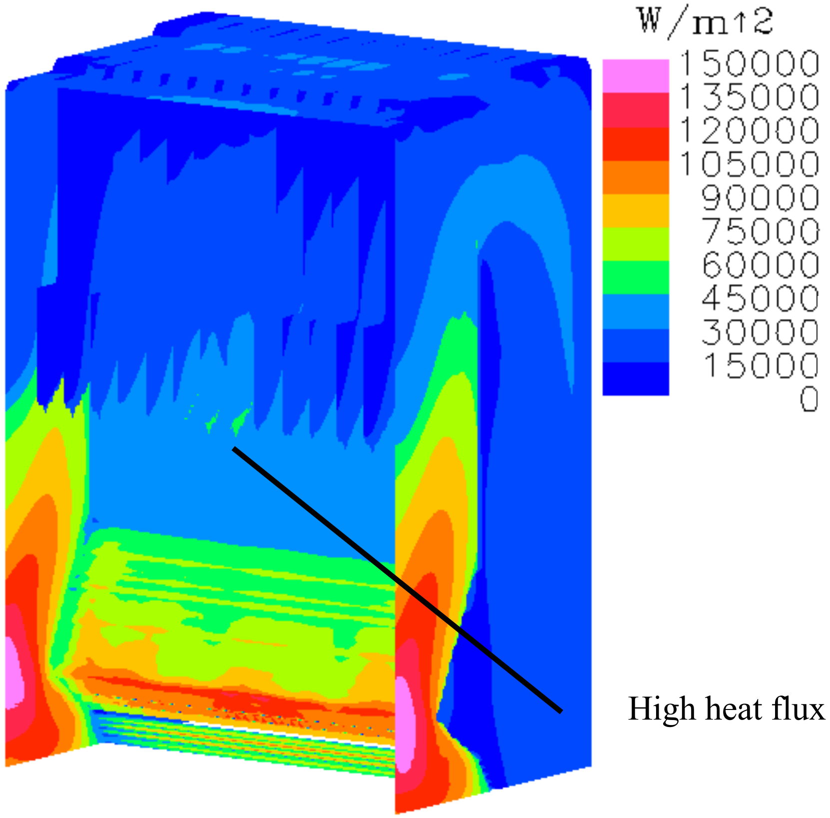


# Ash Trajectories



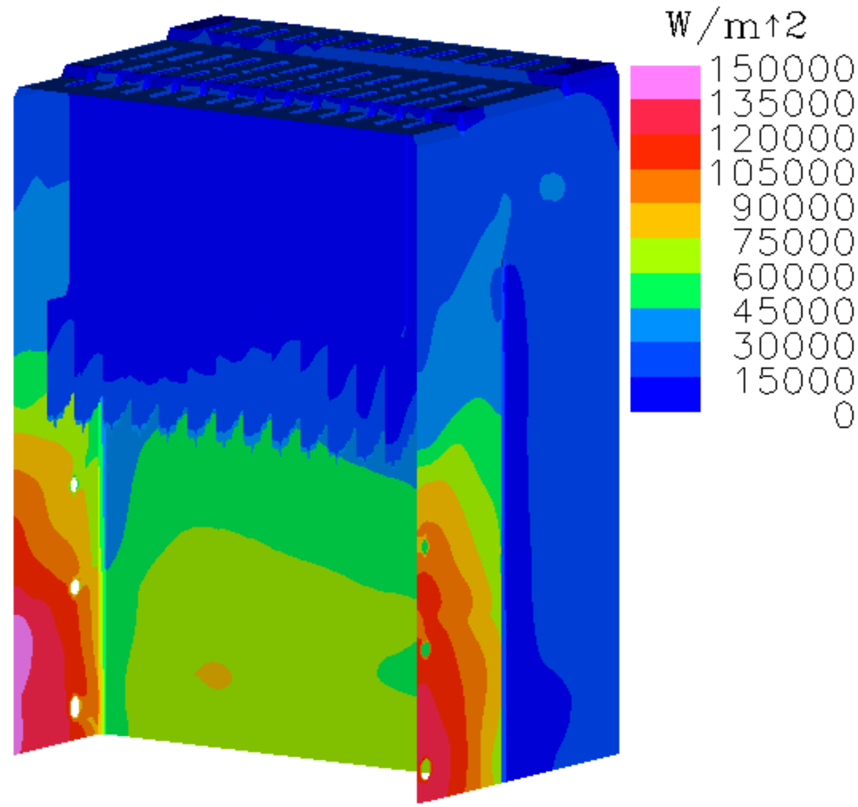
# Heat Flux

Base

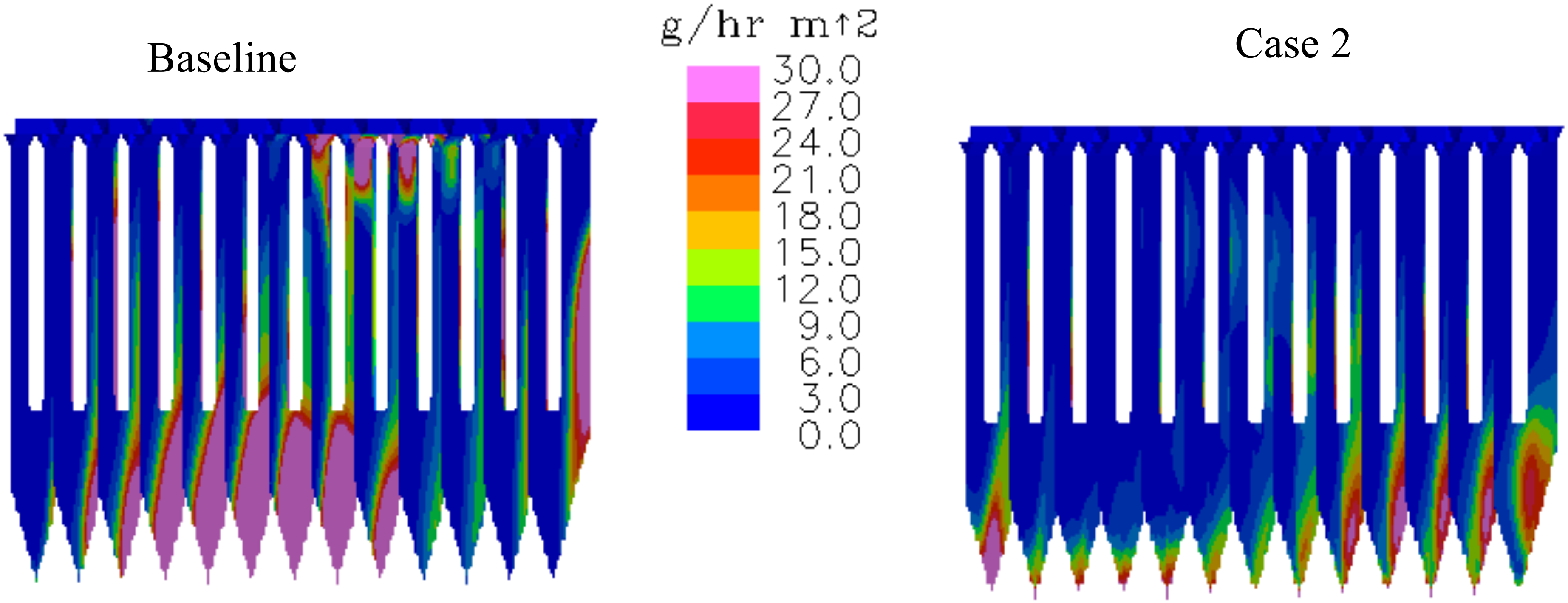



Cut away to show rear wall arch and SH

Case 2



# Ash Deposition




Cut away to show SH

# Results Summary

| | Units | Base | 2 | 5 |
|---|---|---|---|---|
| **Furnace Exit** | | | | |
| Gas Temp | C | 1145 | 1035 | 1077 |
| CO | mg/Ncu.m | 1888 | 159 | 381 |
| **Screen/Exit SH3** | | | | |
| Gas Temp | C | 976 | 854 | 848 |
| **Model Exit** | | | | |
| Gas Temp | C | 762 | 728 | 689 |
| O2(dry) | % | 5.8 | 5.8 | 4.8 |
| CO | mg/Ncu.m | 2 | 0 | 0 |
| SO2 | mg/Ncu.m | 282 | 282 | 282 |
| NOx | mg/Ncu.m | 250 | 242 | 254 |
| PM | g/Ncu.m | 1.03 | 0.55 | 0.57 |
| **Heat Flux** | | | | |
| Total Furnace | kW/sq.m | 201 | 296 | 296 |
| SH2 | kW/sq.m | 14 | 14 | 14 |
| SH3 | kW/sq.m | 7 | 3 | 3 |
| **Ash Deposition** | | | | |
| SH2 | g/h | 4860 | 1860 | 1050 |
| Screen/Exit SH2 | g/h | 175 | 57 | 22 |
| SH3 | g/h | 1360 | 770 | 340 |

# OFA Improvement Implications

- Practically no CO oxidation in SH, lowering $T_{gas}$ at screen
- Reduction of combustion air possible
- More uniform gas flow and temperature at the inlet to the SH
- Eliminated flow channeling and erosion potential near rear wall
- Better utilization of the furnace volume and SH2
- Reduced gas temperature at exit to SH3/inlet to SH1
- Increased heat transfer in the lower furnace
- Reduced ash deposition

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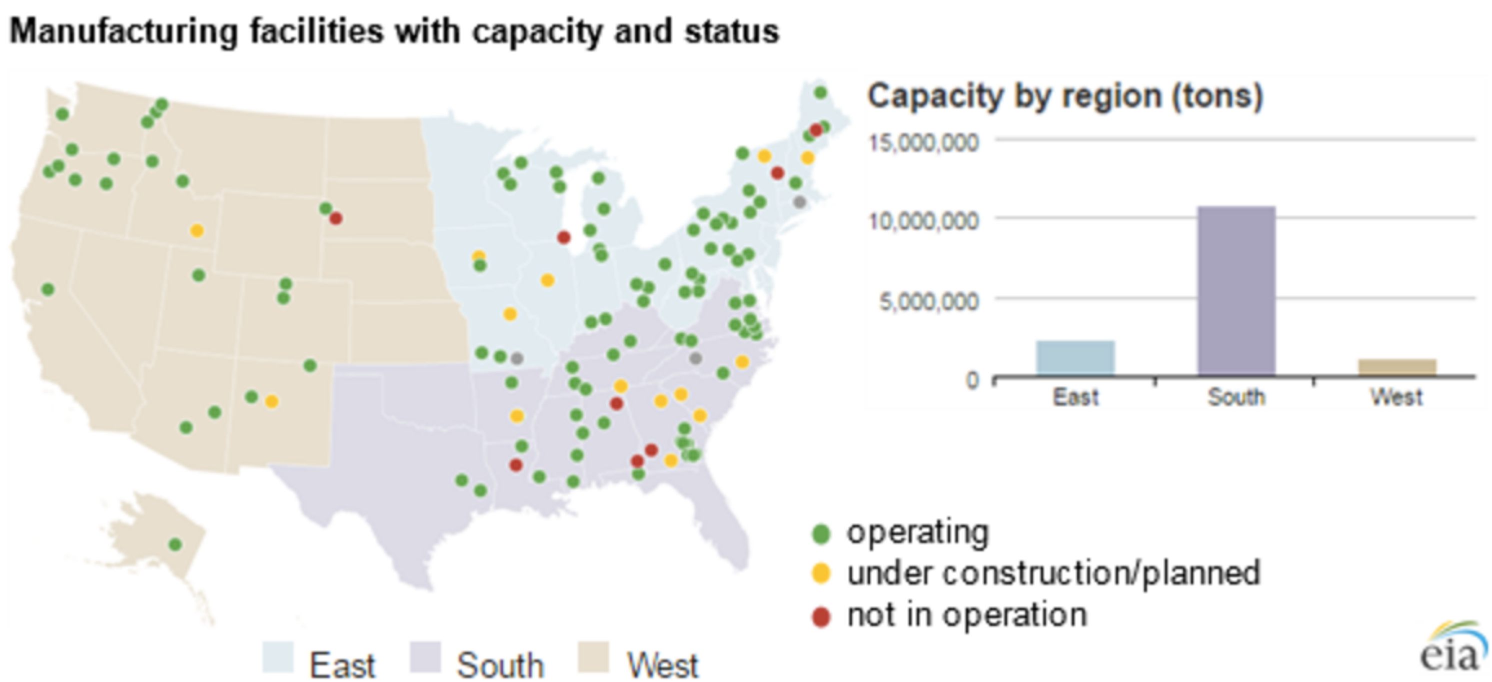
# Wood Pellet Energy

- 120 planned/operational facilities with a capacity of 11.4 tpy
- >75% of pellet production used by electric utilities
- During the first half of 2016, about 82% of pellets were exported - 85% to Drax power plant.

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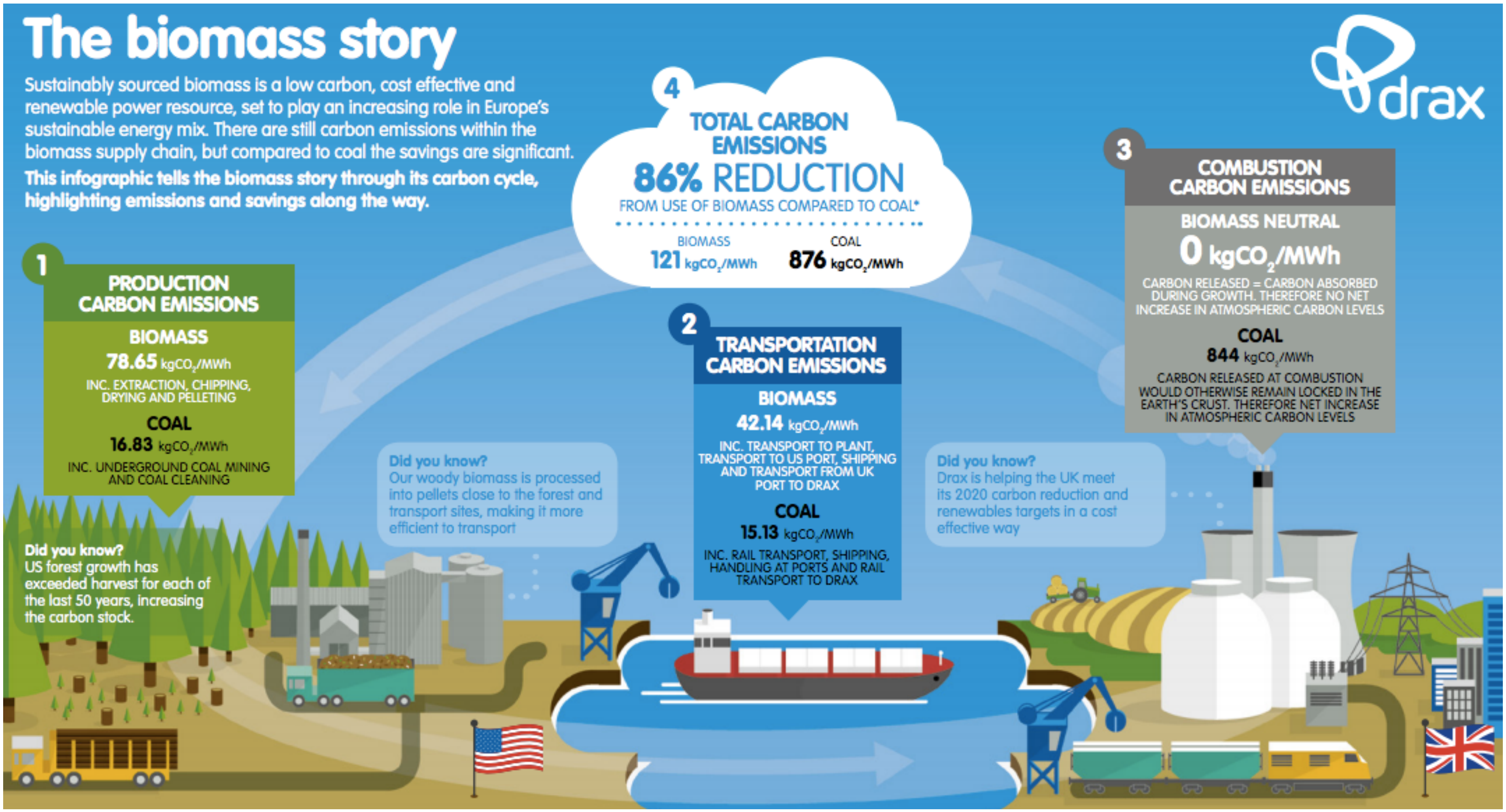
# Coal to Biomass: Drax, UK

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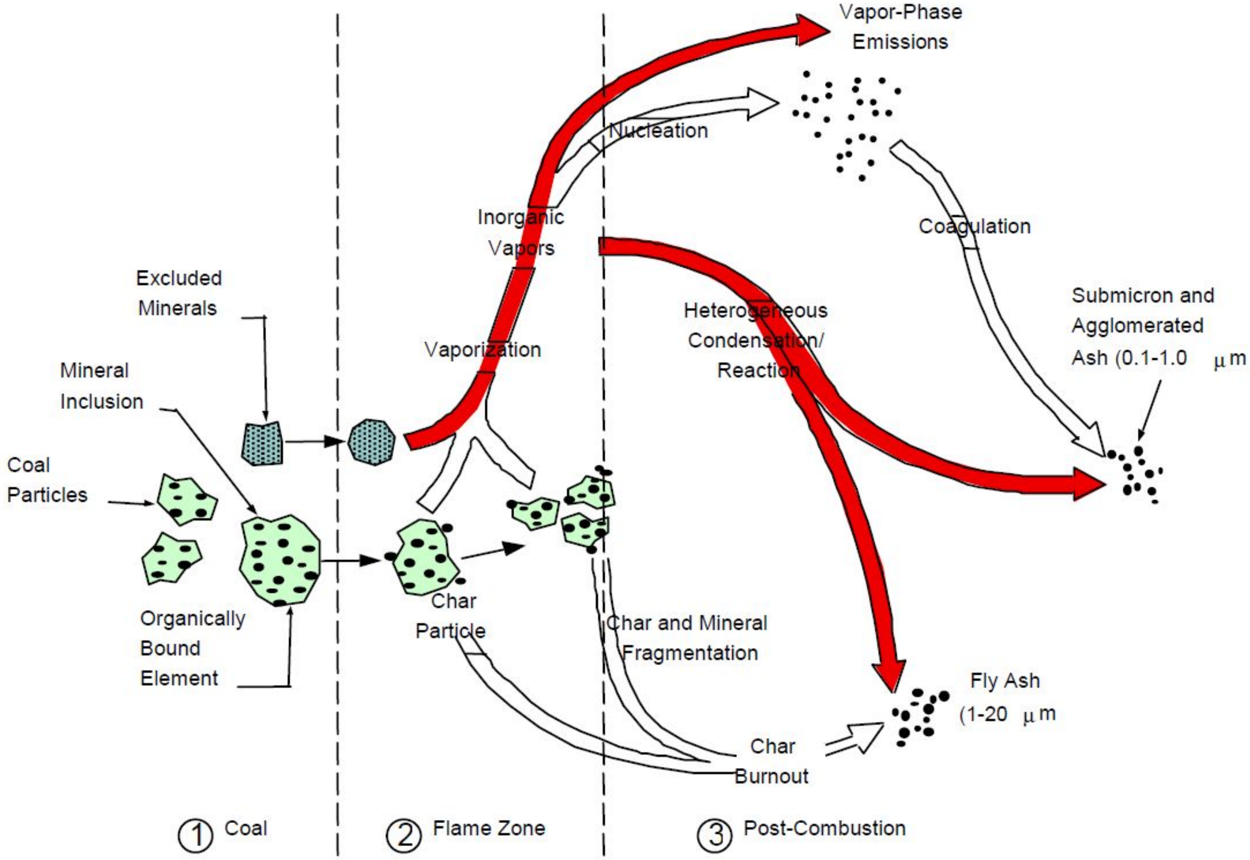
# Pellet Evaluation

- **Objective**:
  - Apply a CFD-based model to evaluate deposition, slagging and corrosion in converting Drax Power Station Unit 1 from coal to 60% biomass co-firing
- **Approach**:
  - Develop a baseline model of coal firing to verify the CFD model under coal-only conditions – excellent agreement with observations of deposit build-up/sintering and quantitative measurements of tube wastage rates
  - Use the model to evaluate impacts of biomass co-firing
- **Simulation Workscope**:
  - Combustion, $NO_x$, CO, carbon-in-ash and deposition and corrosion results for:
    - Baseline 100% coal firing
    - WP1 40% coal / 60% Wood 1biomass firing
    - WP2 40% coal / 60% Wood 2 biomass firing
    - WP3 40% coal / 60% Wood 3 biomass firing
    - WP1+SP1 40% coal / 42% Wood 1 biomass / 18% straw firing

# Analysis for Deposition Model

- Predicting ash deposition requires information about mineral form of ash and melting temperature of ash
- Mineral matter transforms during combustion

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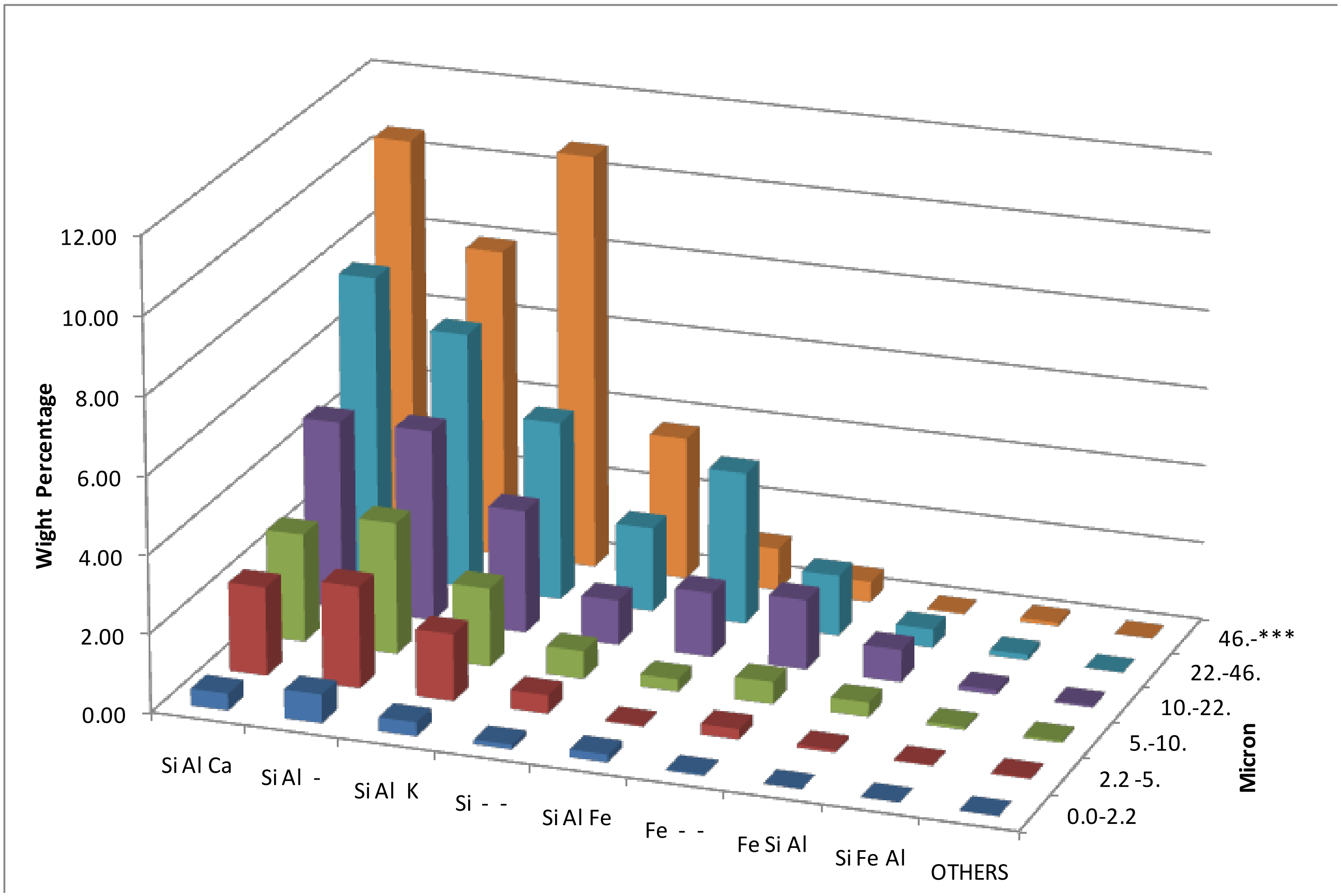
# Analysis for Deposition Model

- Computer controlled scanning electron microscopy (CCSEM)
  - SEM is used to find mineral particles both included and excluded in raw fuel
  - CCSEM determines forms and relative weight percentages of minerals
- Partial Chemical Fractionation (PCF)
  - Technique to determine fraction of each element that are organically bound and likely to volatilize → no longer part of ash particles in boiler
  - Elements are selectively extracted from the fuel based on solubility in water, ammonium acetate, and HCL.
  - Water soluble and Ammonium Acetate soluble inorganics are modeled as volatile
- Combine CCSEM and PCF with traditional Ash elemental analysis by ICP
  - Predicts ash mineral evolution and likeliness to stick to walls based on local environments

# Coal Fly Ash

## *Predicted Fly Ash Composition and Size Distributions*

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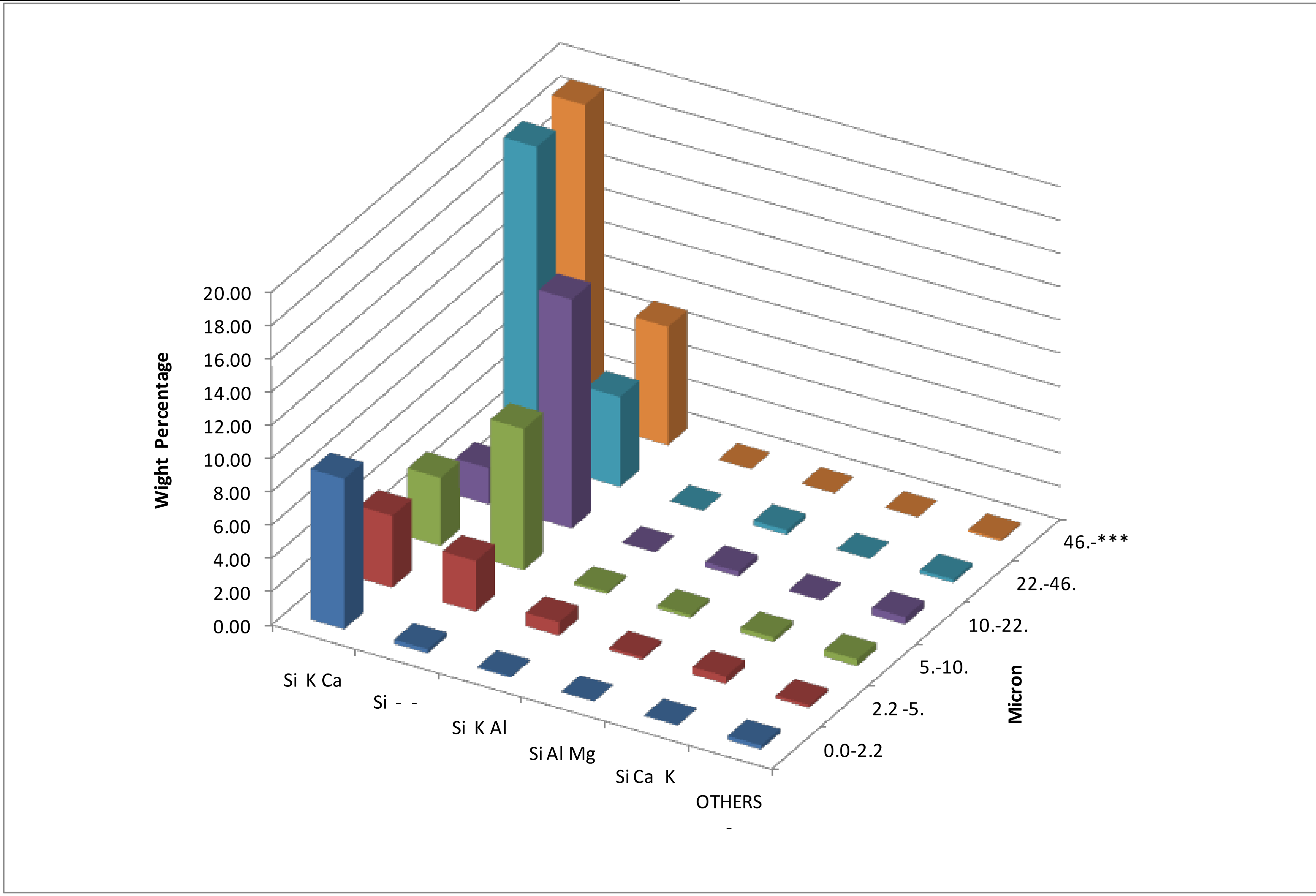
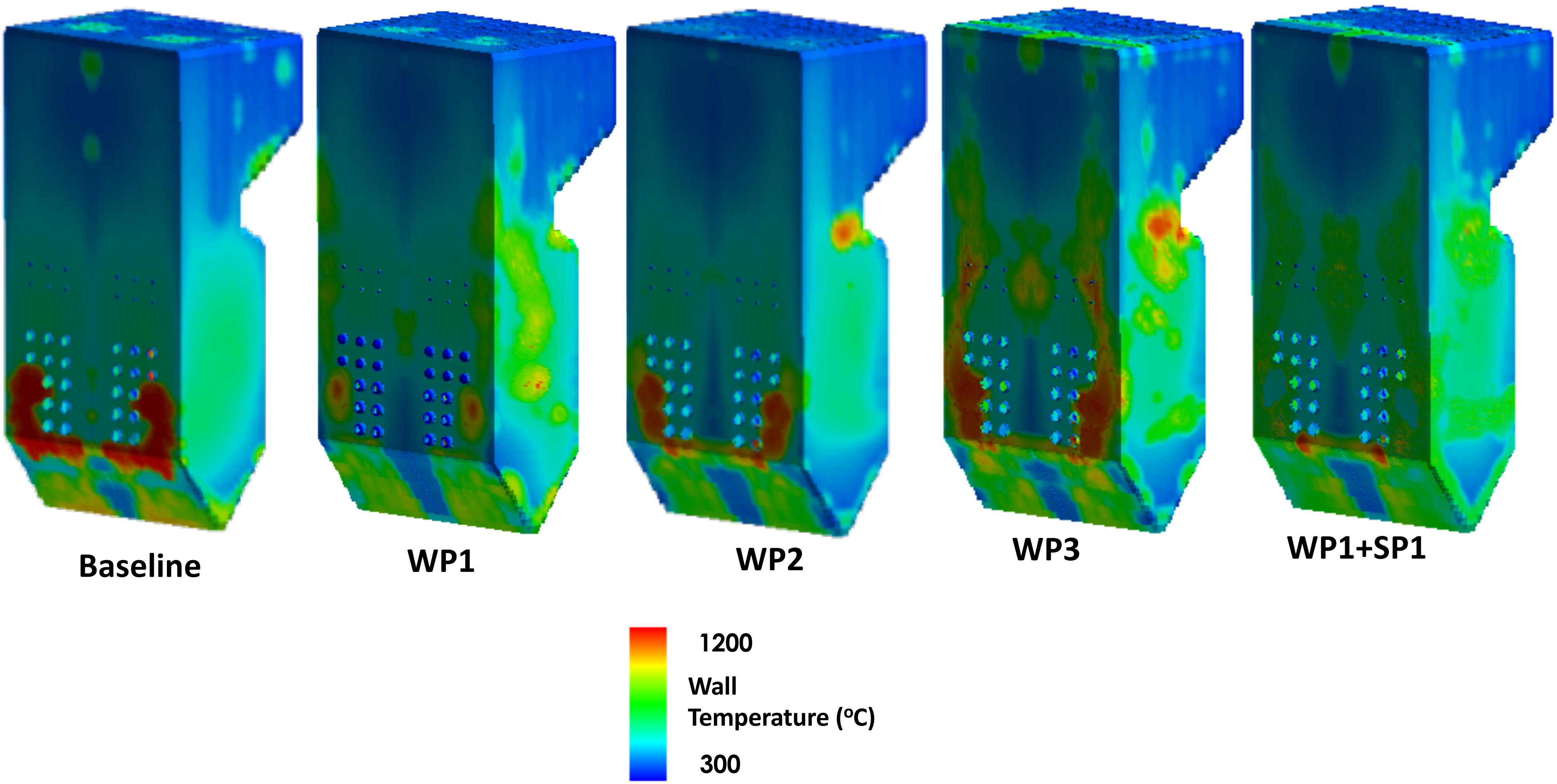
# Straw Pellet Fly Ash

## *Predicted Fly Ash Composition and Size Distributions*



# Wall Temperature
## *(Four Hours)*

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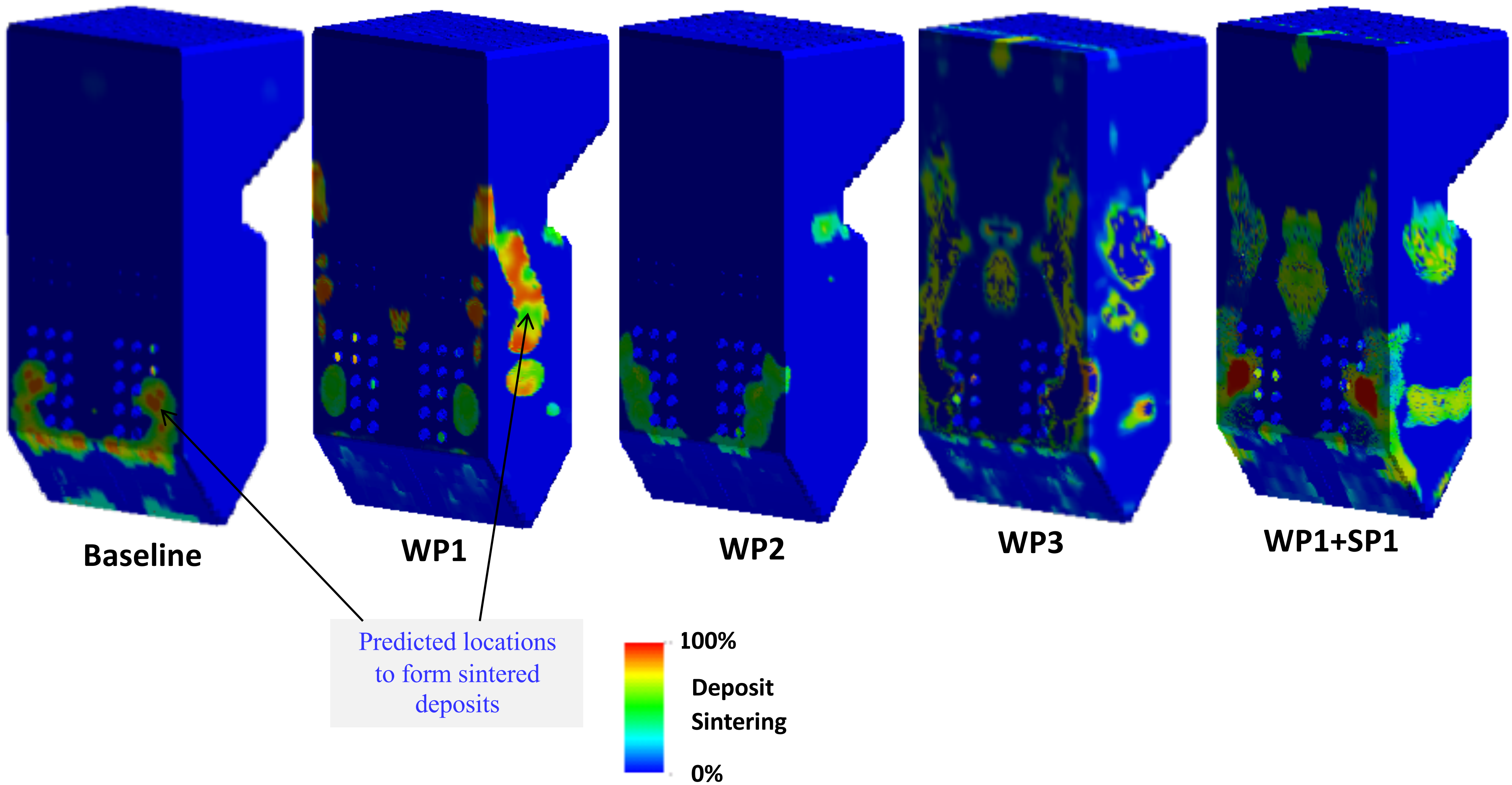
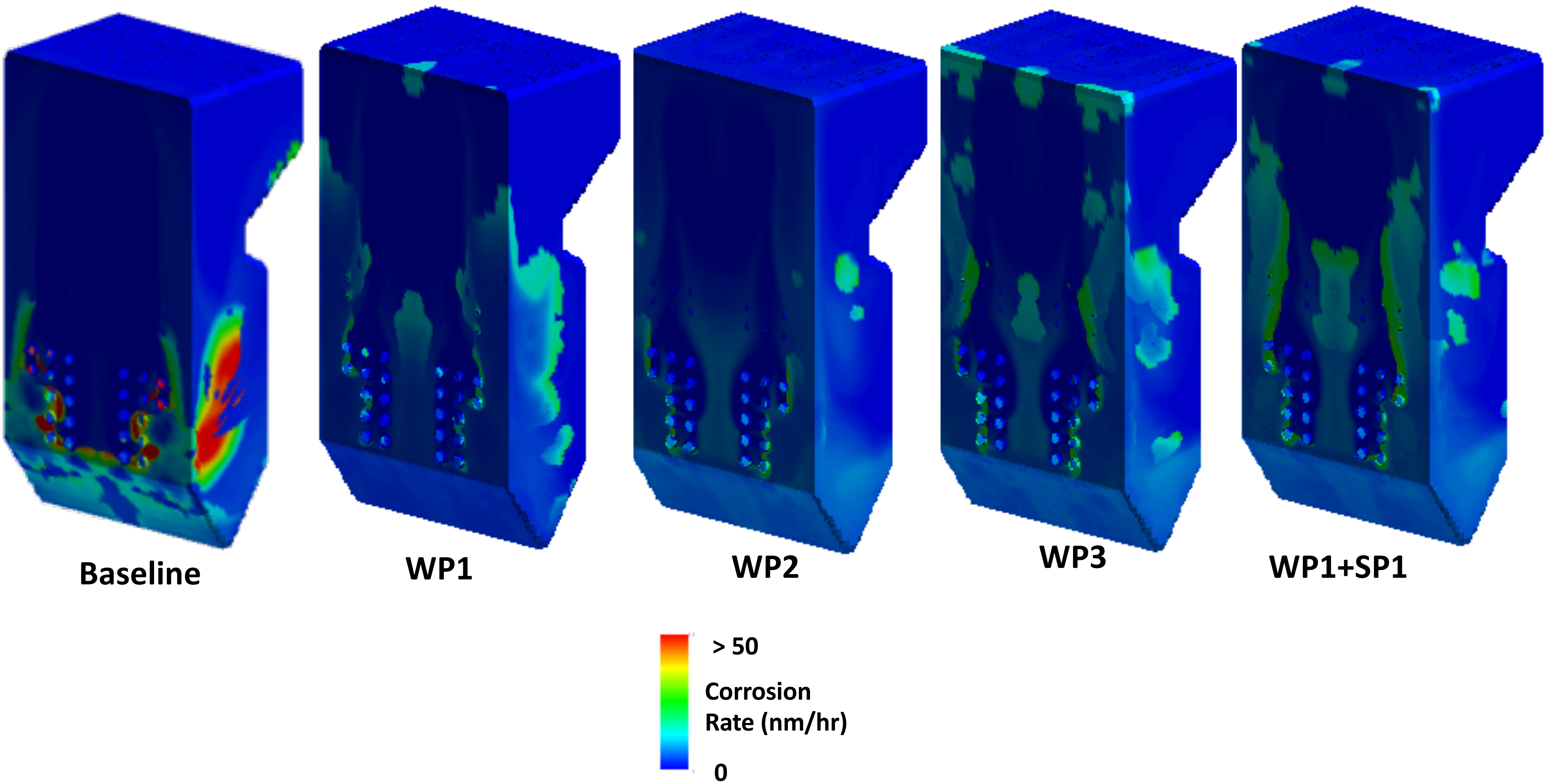
# Deposit Sintering Extent
## *(Four Hours)*



# Total Corrosion Rate

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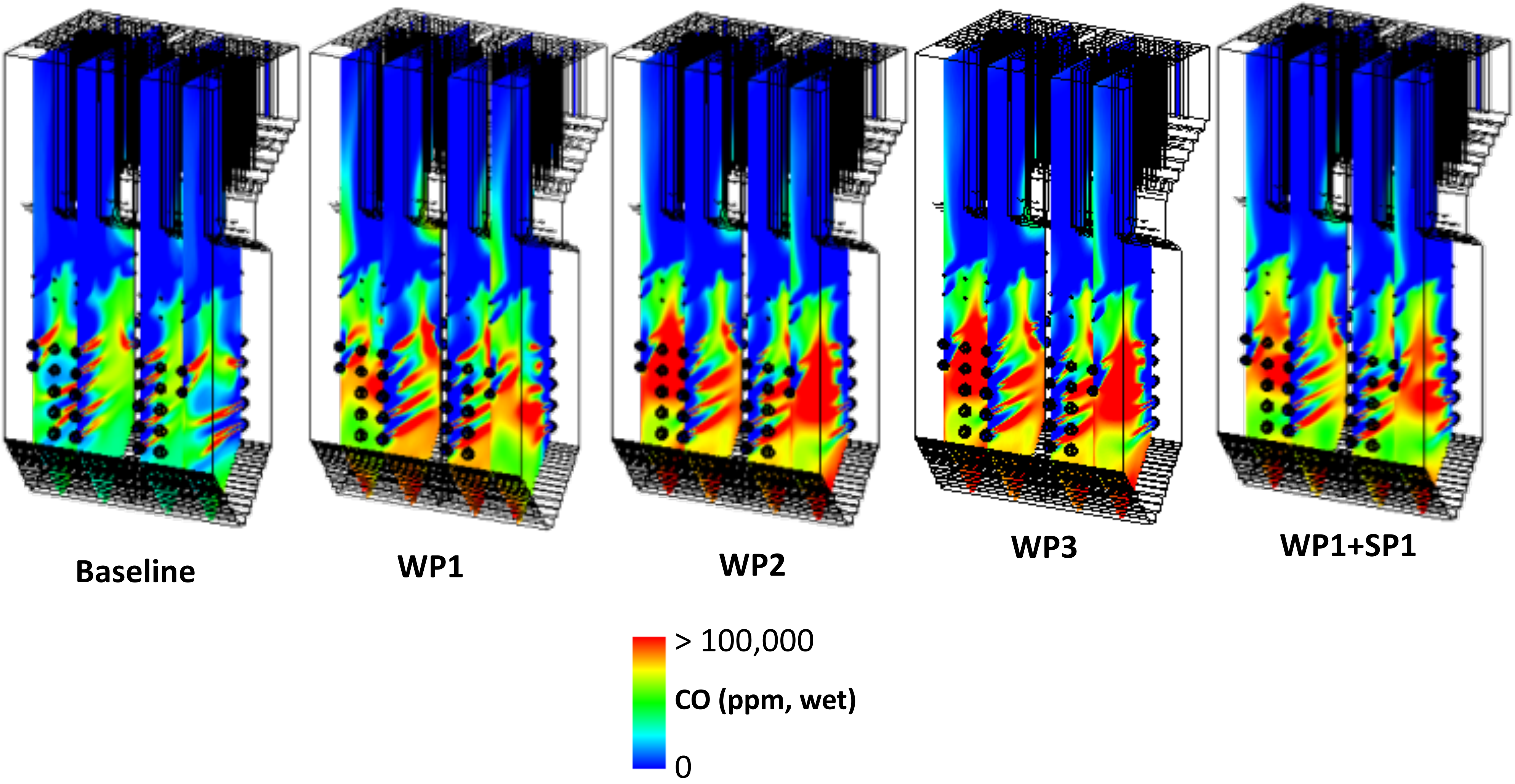
# CO Concentration

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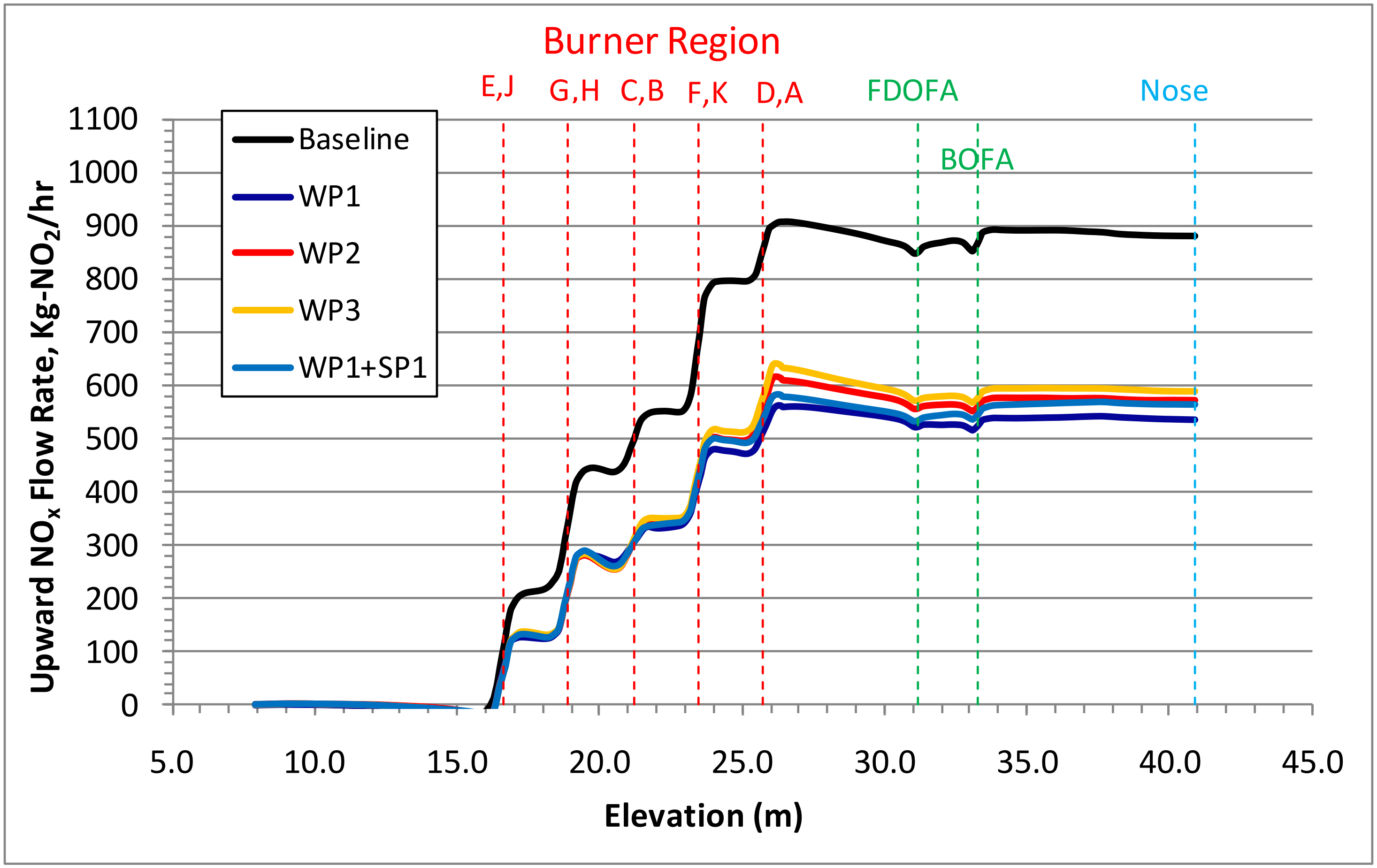
# Upward $NO_x$ Flow Rate




The majority of NOx chemistry happens in the burner region

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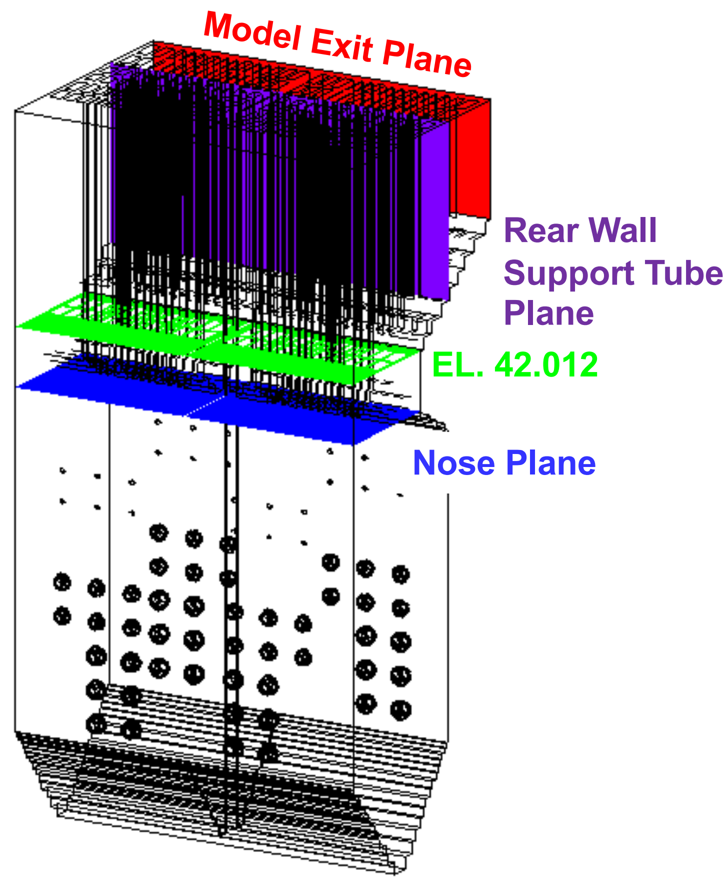
# Overall Results

| | Revised Baseline | WP1 | WP2 | WP3 | WP1+SP1 |
|---|---|---|---|---|---|
| Nose Plane, EL. 38.405 m | | | | | |
| Gas Temperature, °C | 1,244 | 1,309 | 1,298 | 1,325 | 1,311 |
| CO Concentration, ppm wet | 6,419 | 10,970 | 8,959 | 9,509 | 8,910 |
| CO Concentration, ppm dry | 7,094 | 12,408 | 10,163 | 10,787 | 10,137 |
| $O_2$ Concentration, vol. % wet | 3.16 | 3.15 | 3.01 | 3.03 | 2.92 |
| $O_2$ Concentration, vol. % dry | 3.44 | 3.50 | 3.35 | 3.36 | 3.26 |
| $NO_x$ Concentration, ppm wet | 221 | 136 | 147 | 149 | 144 |
| $NO_x$ Concentration, ppm dry | 242 | 151 | 165 | 167 | 161 |
| Gas Temperature, °C, EL. 42.012 m | 1,186 | 1,263 | 1,242 | 1,276 | 1,249 |
| Gas Temp., °C, Rear Wall Support Tubes | 956 | 1006 | 987 | 1020 | 1001 |
| | | | | | |
| Model Exit Plane | | | | | |
| Gas Temperature, °C | 871 | 917 | 899 | 928 | 913 |
| CO Concentration, ppm wet | 206 | 126 | 178 | 319 | 204 |
| CO Concentration, ppm dry | 228 | 143 | 202 | 362 | 232 |
| $O_2$ Concentration, vol. % wet | 2.57 | 2.29 | 2.35 | 2.29 | 2.32 |
| $O_2$ Concentration, vol. % dry | 2.82 | 2.57 | 2.64 | 2.57 | 2.54 |
| $NO_x$ Concentration, ppm wet | 223 | 135 | 146 | 148 | 142 |
| $NO_x$ Concentration, ppm dry | 245 | 152 | 164 | 167 | 161 |
| $NO_x$ emission (Kg-$NO_2$/hr) | 880 | 529 | 564 | 581 | 555 |
| $NO_x$ emission (lb-$NO_2$/MBtu) | 0.34 | 0.20 | 0.22 | 0.22 | 0.21 |
| $NO_x$ emission (mg-$NO_2$/$Nm^{3)}$ | 458 | 276 | 298 | 303 | 291 |
| Unburned Carbon in Fly ash, % | 6.5 | 3.5 | 4.8 | 4.4 | 3.4 |
| Fuel Burnout, % | 98.7 | 99.6 | 99.6 | 99.6 | 99.6 |
| Percent Ash Exiting As Fly Ash | 89.2 | 78.4 | 79.4 | 67.6 | 70.4 |

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# Drax Summary

- Four biomass co-firing CFD simulations of Drax Unit 1 were evaluated and results compared to the coal-fired Baseline simulation
- Simulation results indicate:
  - ✓ Predicted horizontal nose plane (El 38.405 m) average gas temperature increases from 1244°C in the Baseline simulation 1298 - 1325 °C in the biomass co-firing simulations
  - ✓ Predicted model exit average gas temperature increases from 871°C in the Baseline simulation to 899 - 928 °C in the biomass co-firing simulations
  - ✓ With biomass co-firing, predicted model exit CO concentration varies from 126 - 318 ppm (vs. 206 ppm in the Baseline simulation). Since model exit temperatures are higher than the CO oxidation quench temperature of ~ 630$^{o}$ C, further CO oxidation in the convective path is expected.
  - ✓ With biomass co-firing, predicted $NO_x$ emission decreases 35% - 40% from the Baseline value of 458 mg-$NO_2$/$Nm^3$ at $O_2$ level of 2.6% (wet). The majority of the $NO_x$ chemistry happens in the burner region.
  - ✓ Predicted carbon in fly ash decreases slightly from 6.5% in the Baseline simulation to 3.4% - 4.8% in the biomass co-firing simulation. Fuel burnout increases from 98.7% in the Baseline case to 99.6% in the co-firing cases.
  - ✓ The higher deposition predicted on the front and rear walls is a result of the unopposed burners.
  - ✓ In the Baseline simulation, peak corrosion rates are predicted to occur on the rear and side walls with a magnitude of ~ 50 nm/hr. Corrosion rates are reduced with biomass co-firing.

# Biomass Torrefaction


Strauss, FutureMetrics, 2016

## ➔ What is it?

- A mild pyrolysis process performed at 250-320°C intended to break down the hemicellulosic structure
- Typically ~ 70% of the dry mass and 90% of the energy content remains
- The product is coal-like in nature and can be utilized with limited modifications to standard equipment for coal conversion

## ➔ Why do it?

- The product is hydrophobic, friable, high energy density like coal
- The product has less sulfur and toxic metals, and is renewable like biomass

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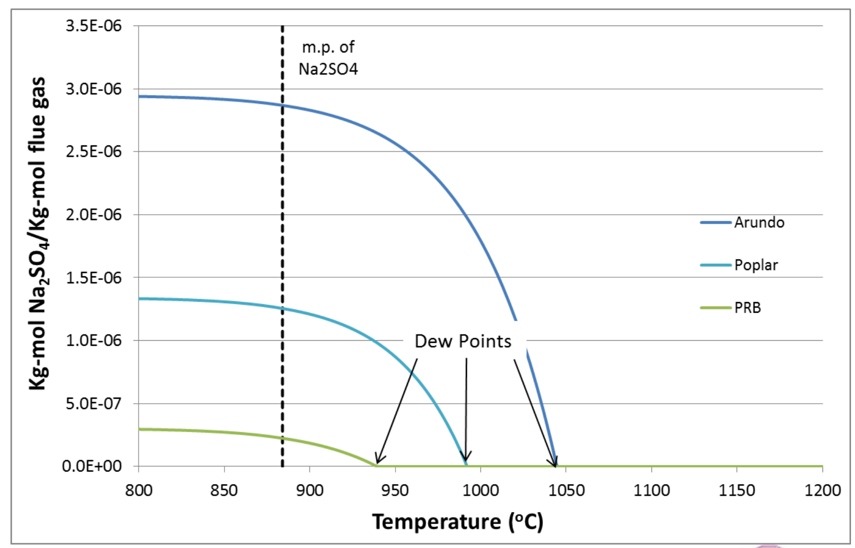
# Full-scale Conversion of a Coal Boiler

| Average Corrosion Rate, full Furnace (mil/yr) | | | |
|---|---|---|---|
| | Baseline | Arundo | Poplar |
| $H_2S$ | 1.15 | 0.89 | 0.18 |
| FeS | 0.34 | 0.34 | 0.00 |
| Cl | 0.00 | 14.94 | 0.00 |
| Total | 1.49 | 16.17 | 0.18 |

- **REI asked to perform a model-based evaluation of torrefied biomass firing in a 500MW coal–boiler for PGE and EPRI**
- **Torrefied fuel milling, combustion and emissions behavior can be tailored to perform very similar to that of the design coal**
- **However, the composition of the ash of the parent biomass material has key impacts on deposition, fouling and corrosion**

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# Amaron Technology

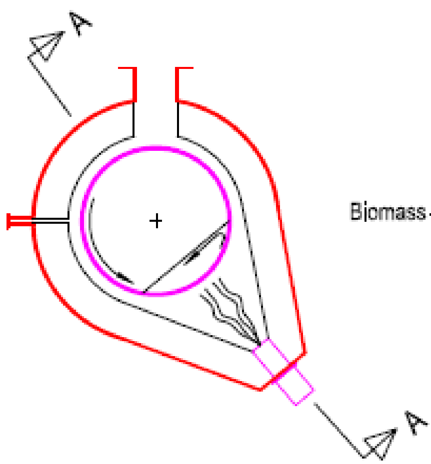


Fig. 1 Section BB of Fig 2

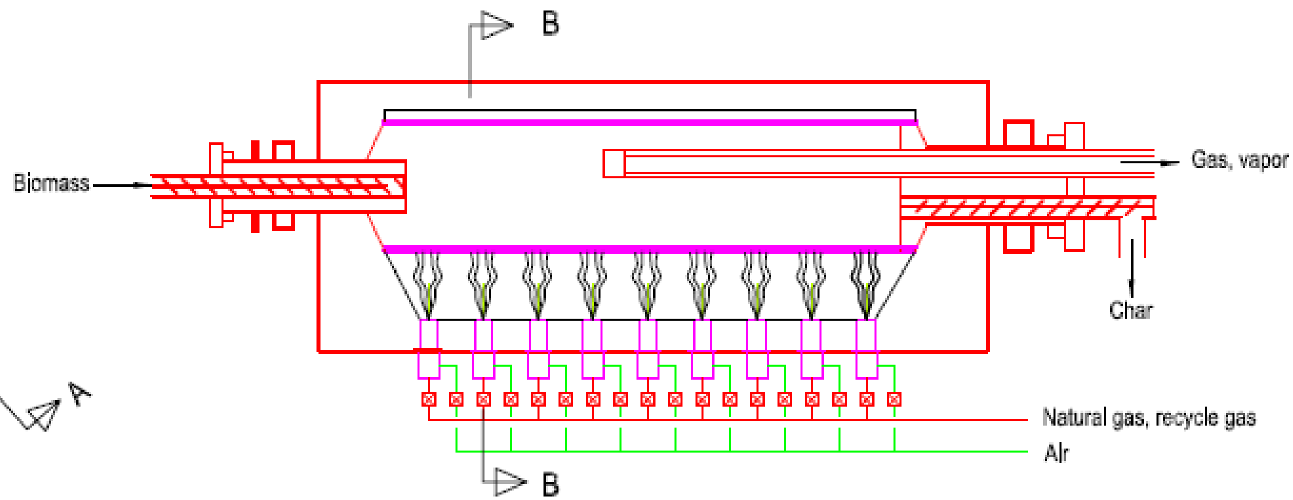


Fig. 2 Section AA of Fig. 1

- Patented* flexible heating approach in a rotary kiln design provides for:
  - operation ranging from torrefaction through full pyrolysis
  - a wide variety of feedstock properties
  - limited physical degradation of solid product

** Coates, R.L., Smoot, L.D. and K.E. Hatfield, U.S. Patent 8298406, "Method and apparatus for maximizing throughput of indirectly heated rotary kilns," 2012. Coates, R.L., Coates. B.R. and J.L. Coates, US Patent 8999017, "Method and apparatus for fast pyrolysis of biomass in a rotary kiln," 2015.*

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# 20 TPD Commercial Field Demonstrations

Eureka, Utah– September, 2014
Cle Elum, Washington – October, 2014
Eureka, Nevada – June, 2015

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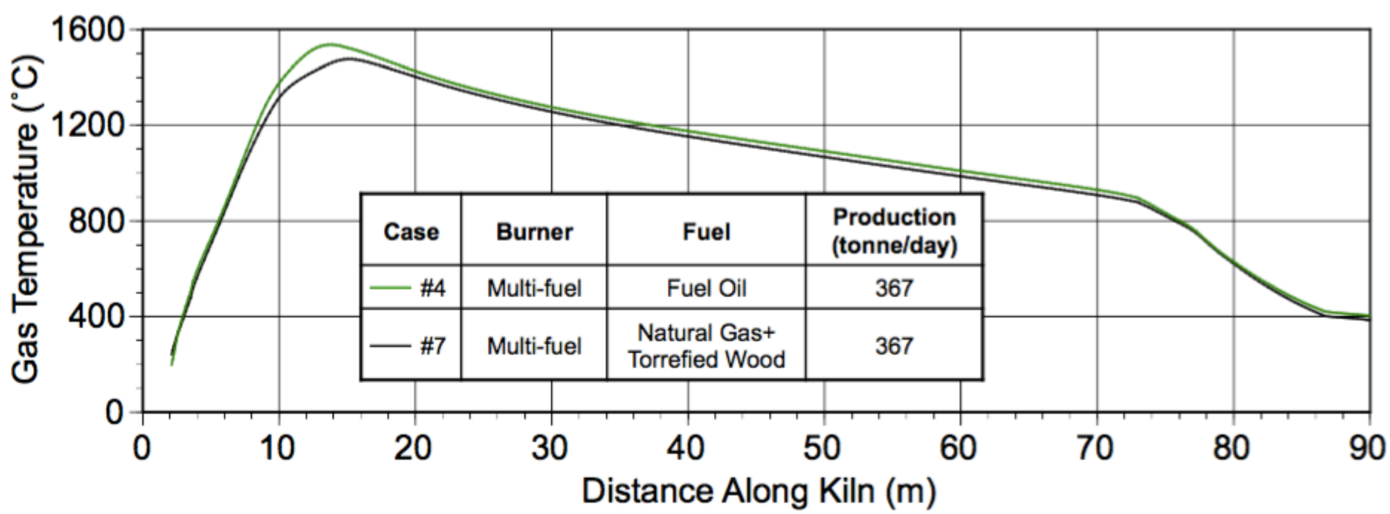
# Co-firing of Torrefied Biomass and Natural Gas

- Fuel costs are resulting in increased use of natural gas
- For lime kilns >10% derating due to reduced heat transfer
- Co-firing 23% torrefied wood with natural gas will match the heat transfer profile of the design fuel

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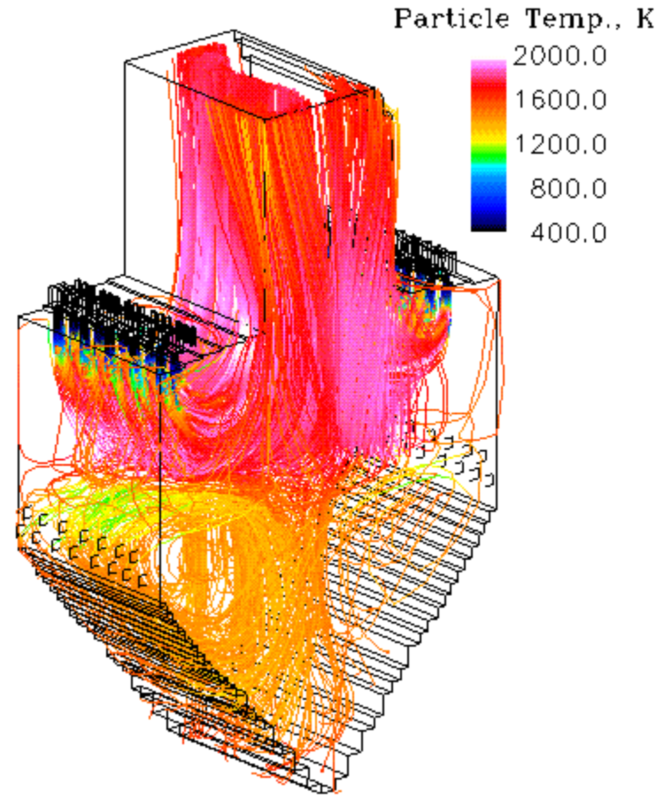
# Summary

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




Korean Arch-fired Boiler

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