

REINHOLD ENVIRONMENTAL Ltd.



**2013 NO_x-Combustion Round Table
& Expo Presentations**

February 18 & 19, 2013, in Salt Lake City, UT / Hosted by PacifiCorp

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Predicting Impact of Furnace Ash Deposits on Furnace Temperature, NO_x, and CO Emissions



*For Energy and
Environmental
Solutions*

REACTION ENGINEERING INTERNATIONAL

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NO_x Combustion Roundtable

Salt Lake City, UT

February 18 - 19, 2013

Discussion Outline

- Furnace issues associated with ash deposition
- Fuel issues
- CFD Modeling of Boilers
- Advanced slagging model
- Application of CFD Based Model
 - ◆ Coal firing
 - ◆ Biomass Co-firing
- Evaluation of heat balance impacts
- Summary and Conclusions

Ash Deposition Issues in Boilers

- ➔ Management of coal ash is one of the most important fuel property aspects in design and operation of utility boilers
- ➔ Ash related problems are one of the primary causes of unscheduled outages, unit derating, and unavailability
- ➔ Slagging incidents cost the global utility industry several billion dollars annually in reduced power generation and equipment maintenance
- ➔ Cofiring of other fuels with coal represents one of the biggest challenges to power plant operation



Ash Related Impacts in Boilers

- Reduced heat transfer
- Impedance of gas flow
- Corrosion of pressure parts
- Erosion of pressure parts
- Other physical damage of pressure parts (e.g. slag falls)

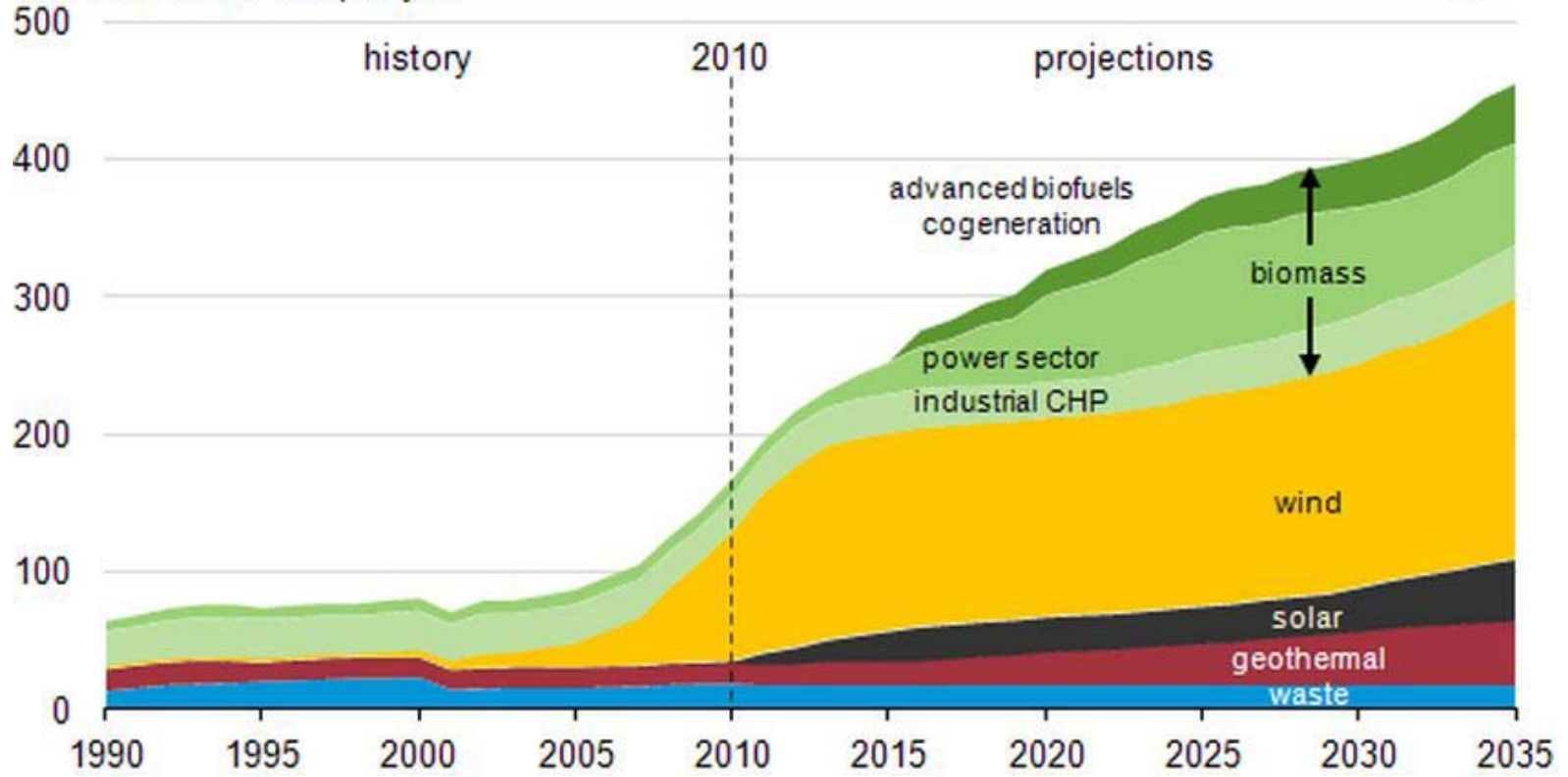
Fuel Switching

- Fuels for reduced emissions (e.g. low S)
- Reduced costs
- Fuel blending
- Biomass co-firing



Biomass Power: The Past & Future of Renewable Power?

Projected non-hydropower renewable electricity generation, 2010-2035
billion kilowatthours per year



Role of Biomass

→ Wind and Biomass dominate projected increases in renewable power

→ Biomass co-firing drivers:

- ◆ US State level RPS
- ◆ Favorable economics in regions with forest residues
- ◆ European Union Directive 2009/28/EC
- ◆ UK incentives issued through Renewables Obligation Certificates (ROCs)

→ May 2012 projections based on the Clean Energy Standard Act of 2012 see biomass growth increasing from 4x (Nov 2011) to 7x (May 2012)



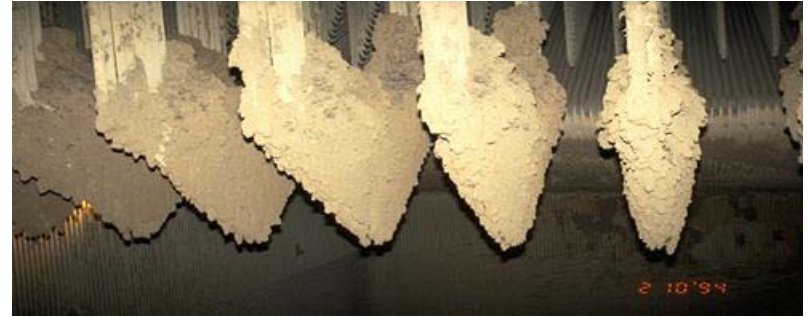
Operational Impacts

→ Deposition, Slagging, Sintering and Fouling

- ◆ Depends on deposition rates and ash chemistry
- ◆ 100% biomass systems more susceptible
- ◆ Co-firing less susceptible (minimal impacts with <10 wt%)

→ Potential for corrosion

- ◆ Chlorine
- ◆ Alkali

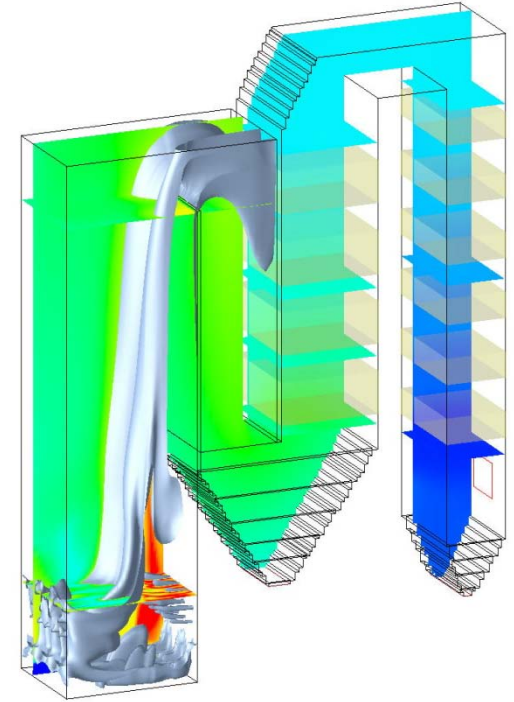


*Fenger, L.D., The use of Straw as Energy Source-example
Denmark, Proceedings of European Biomass Conference, Graz,
2008*

Predictive Technical Assessment

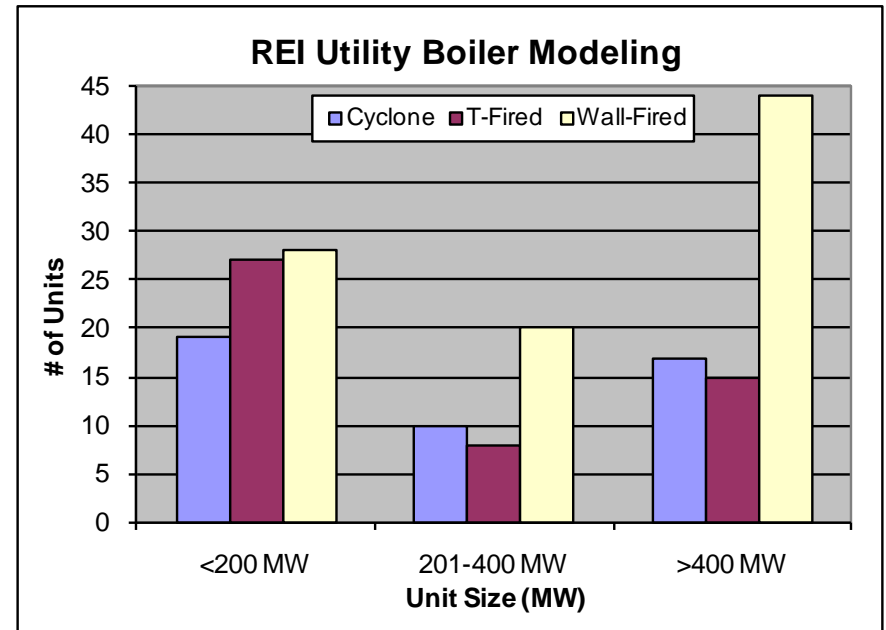
- ➔ Application of fuel switching should be assessed on a case-by-case basis
 - ◆ Characterization of combustion system
 - ◆ Characterization of fuel
 - ◆ Appropriate modeling of biomass firing

- ➔ 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, deposition, slagging, sintering, fouling and corrosion



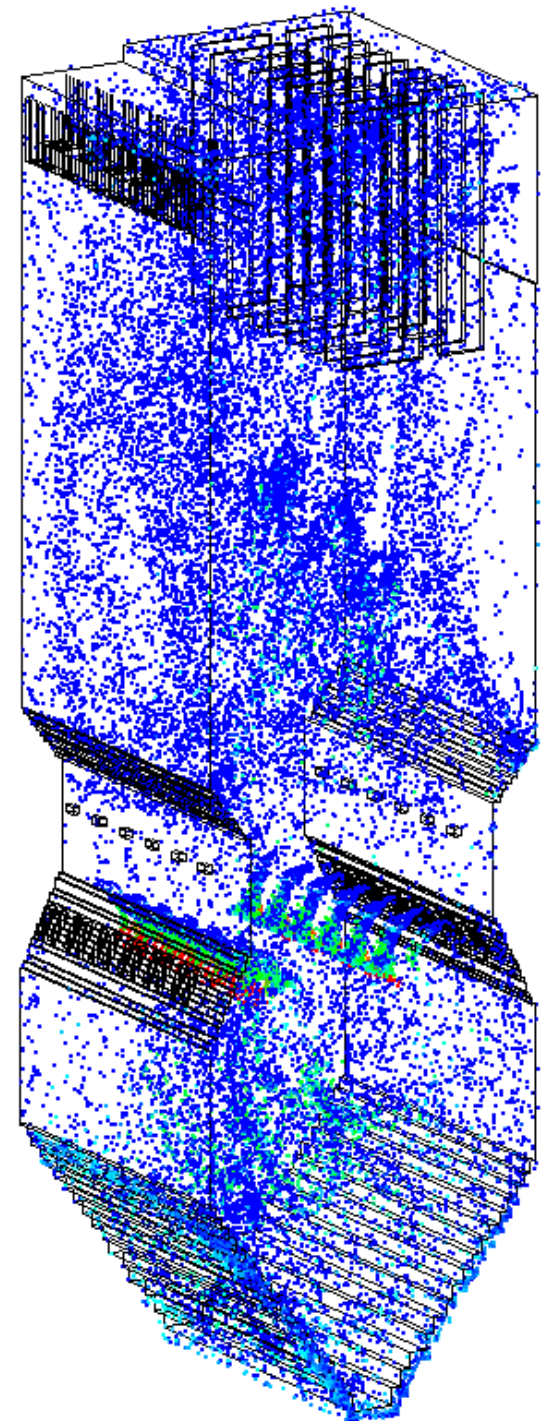
Boiler CFD Modeling

- ❑ ~200 Utility Boilers Modeled (~70,000 MW of Capacity)
- ❑ Cyclone, Wall, Turbo & T-fired
- ❑ Firing Coal, Oil, Gas, Biomass, Petcoke, TDF, Blends, Oxygen
- ❑ Stokers, Industrial Boilers, Fluidized Beds, Gasifiers
- ❑ Emission Reduction Strategies
- ❑ Operational Impacts
 - ❑ CO Oxidation
 - ❑ Unburned Carbon-in-Ash (LOI)
 - ❑ Waterwall Wastage
 - ❑ Slagging



GLACIER Capabilities

- ◆ Steady-state, laminar or turbulent flows
- ◆ Complex 3-D geometries
- ◆ Multiphase systems with full mass, momentum, and energy coupling
- ◆ Full coupling between turbulent fluid mechanics, radiative and convective heat transfer, chemical reactions, and particle combustion
- ◆ Multiple reaction rate processes for solid fuel thermal decomposition, char oxidation, and liquid vaporization
- ◆ Statistical description of particles including models of particle dispersion
- ◆ Particle deposition and slag formation
- ◆ Radiative heat transfer involving surfaces, particles and gases
- ◆ Pollutant formation kinetics for NO_x, SO_x, CO, Hg and fine particles



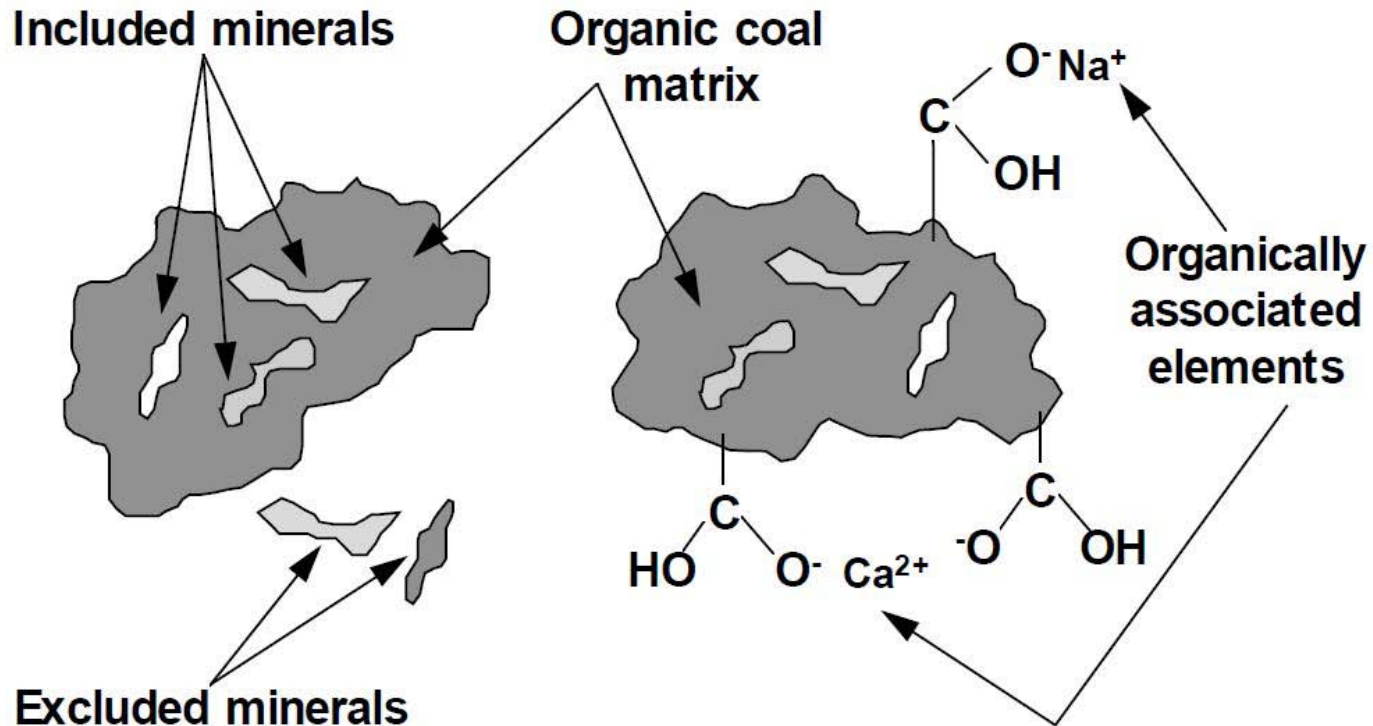
Fuel ASTM Ash Analysis

Mineral Ash Analysis*		
	Analysis	Normalized
SiO ₂	25.61	25.39
Al ₂ O ₃	12.69	12.58
TiO ₂	0.99	0.98
CaO	21.45	21.27
Fe ₂ O ₃	4.83	4.79
K ₂ O	0.23	0.23
MgO	5.51	5.46
Na ₂ O	1.03	1.02
SO ₃	26.89	26.66
P ₂ O ₅	0.65	0.64
BaO	0.53	0.53
MnO ₂	0.03	0.03
SrO	0.42	0.42
Undet.	-0.86	
Alkalie Content	0.08	
Silica Value	44.62	
Base to Acid Ratio	0.84	
T250 (Est.)	<2310	

Ash Fusion Temperatures (Reducing)	
Initial Deformation	2210 °F
Height = Width	2220 °F
Height = ½ Width	2245 °F
Fluid	2310 °F

* Percent Weight Ignited Basis

Coal Mineral Matter



[1] Benson, S.A., Jones, M.L. and Harb, J.N., 1993, Ash formation and deposition. In Smoot, L.D. (Ed), *Fundamentals of Coal Combustion - for Clean and Efficient Use*, Coal Science and Technology 20, Elsevier Science Publishers, Amsterdam, ISBN 0-444-89643-0, Chapter 4, pp. 299-373

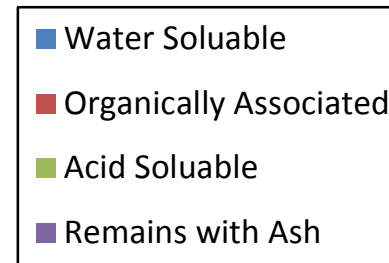
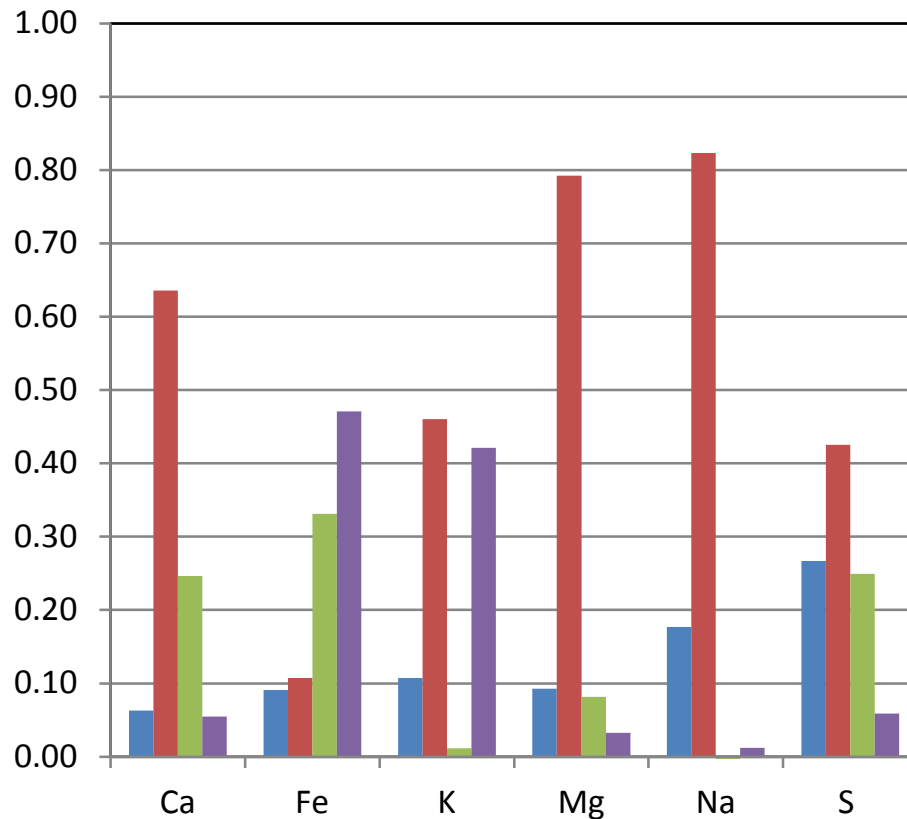
Coal Ash CCSEM

Minerals with Size Distribution

WEIGHT PERCENT ON A MINERAL BASIS

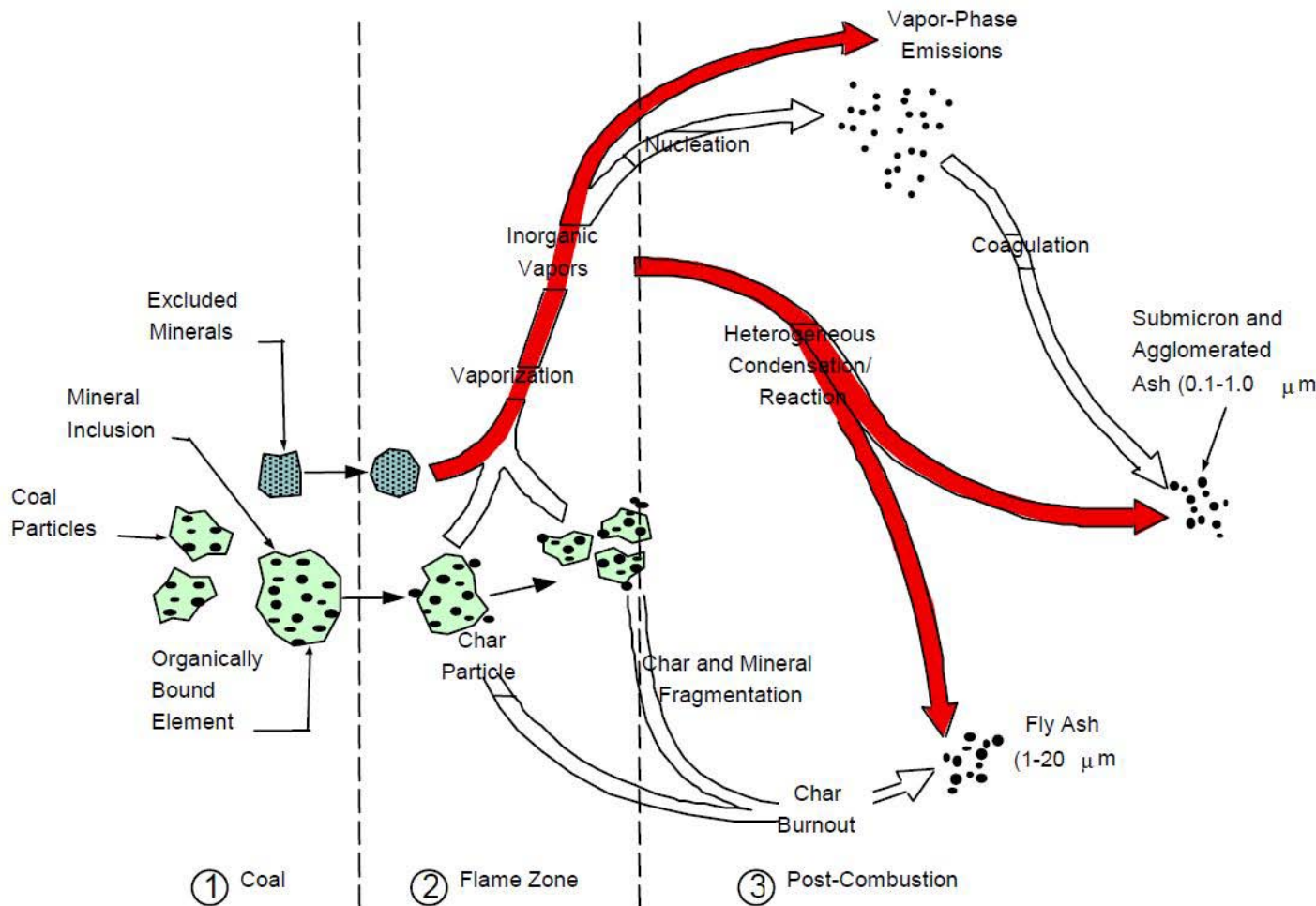
	1.0 TO 2.2	2.2 TO 4.6	4.6 TO 10.0	10.0 TO 22.0	22.0 TO 46.0	46.0 TO 400.0	TOTALS
QUARTZ	.3	.9	.9	1.2	2.0	4.0	9.1
IRON OXIDE	.0	.0	.0	.2	.3	.4	.8
PERICLASE	.0	.0	.0	.0	.0	.0	.0
RUTILE	.0	.0	.0	.0	.0	.0	.0
ALUMINA	.0	.0	.0	.0	.0	.0	.0
CALCITE	.0	.1	.0	.0	.3	.1	.5
DOLOMITE	.0	.1	.2	.4	1.0	.7	2.5
ANKERITE	.0	.0	.0	.2	.0	.0	.2
KAOLINITE	.6	2.5	2.0	1.8	4.4	3.9	15.3
MONTMORILLONITE	.1	.7	.5	1.0	.9	3.5	6.8
K AL-SILICATE	.8	3.2	2.6	3.3	4.6	9.5	24.0
FE AL-SILICATE	.1	.4	.3	.3	.4	.0	1.5
CA AL-SILICATE	.0	.0	.0	.0	.0	.0	.1
NA AL-SILICATE	.0	.1	.0	.0	.1	.1	.3
ALUMINOSILICATE	.1	.2	.2	.7	.5	.5	2.3
MIXED AL-SILICA	.2	.2	.2	.2	.2	.2	1.1
FE SILICATE	.0	.0	.0	.1	.0	.0	.1
CA SILICATE	.0	.0	.0	.0	.0	.0	.0
CA ALUMINATE	.0	.0	.0	.0	.0	.0	.0
PYRITE	.1	1.0	2.1	5.1	3.0	1.5	12.8
PYRRHOTITE	.0	.1	.0	.5	.2	.0	.8
OXIDIZED PYRRHO	.0	.0	.0	.1	.1	.0	.3
GYPSUM	.0	.0	.3	.4	.4	.6	1.7
BARITE	.0	.0	.0	.0	.0	.0	.0
APATITE	.0	.0	.0	.0	.1	.0	.1
CA AL-P	.0	.0	.0	.0	.0	.0	.0
KCL	.0	.0	.0	.0	.0	.0	.0
GYPSUM/BARITE	.0	.0	.0	.0	.0	.0	.0
GYPSUM/AL-SILIC	.0	.2	.1	.1	.2	.0	.6
SI-RICH	.1	.5	.3	.5	.6	1.7	3.5
CA-RICH	.0	.0	.2	.1	.1	.1	.5
CA-SI RICH	.0	.0	.0	.0	.0	.0	.0
UNKNOWN	.5	2.4	1.5	1.4	3.3	5.7	14.9
TOTALS	2.9	12.6	11.6	17.7	22.7	32.5	100.0

Partial Chemical Fractionation

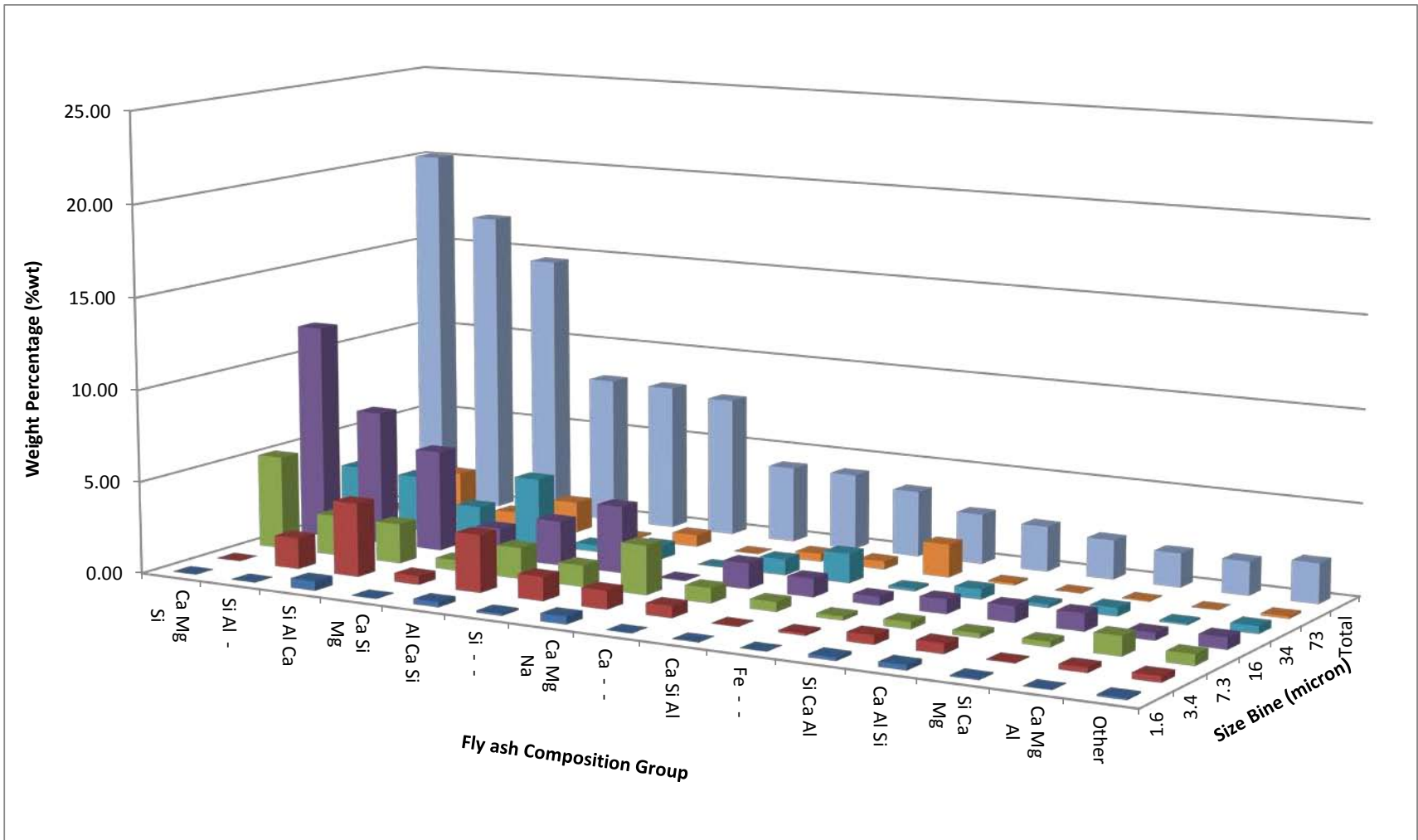


Elemental Associations (Mass Fraction)				
	Water Soluable	Organically Associated	Acid Soluble	Remains Bound
Ca	0.06	0.64	0.25	0.05
Fe	0.09	0.11	0.33	0.47
K	0.11	0.46	0.01	0.42
Mg	0.09	0.79	0.08	0.03
Na	0.18	0.82	-0.01	0.01
S	0.27	0.42	0.25	0.06

Mineral Matter Transformation



Fly ash Size and Composition Distribution



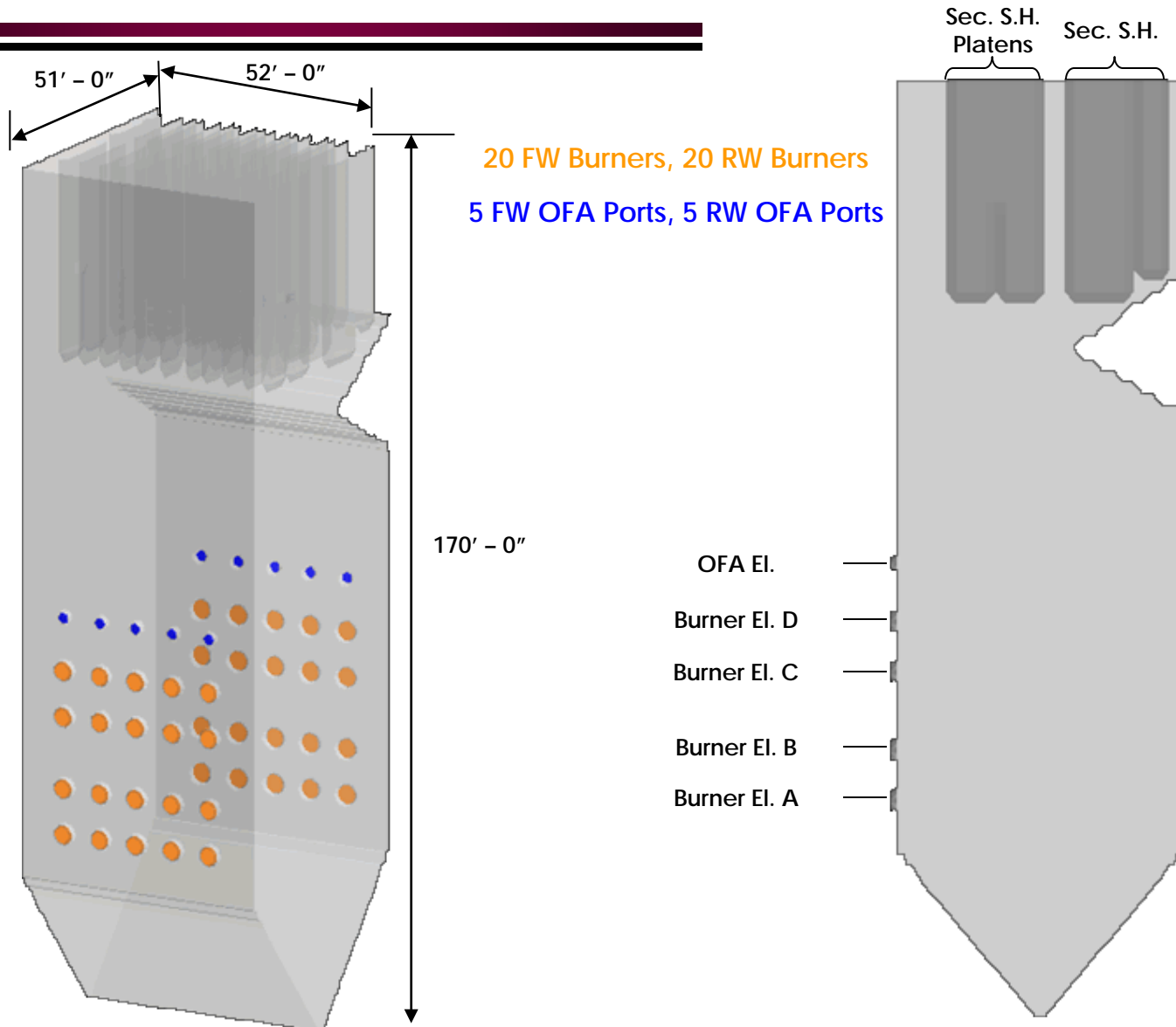
Advanced Model of Mineral Matter/Ash Behavior

- CCSEM and Partial Chemical Fractionation, in addition to bulk ash elemental analysis, are used to characterize inorganically and organically associated elements
- The Partial Coalescence Model (Beer & Sarofim) is used for prediction of fly ash particle size and particle-size dependent composition
 - ◆ Coal particles are divided into a number of size bins
 - ◆ The mineral particles (as determined from CCSEM) are distributed into randomly selected coal particles and organically associated elements are distributed proportional to ash-free volume
 - ◆ Fragmentation (partial coalescence) estimates are then used to complete prediction of fly ash size and composition distribution.
- A viscosity model (Senior and Srinvasachar) is used to calculate the viscosity of silicate glass particles as a function of both temperature and composition. Particle “stickiness” is calculated based on the viscosity of an impacting particle in comparison with its critical viscosity
- This model is then implemented within a CFD framework and as coal particles interact with boiler surfaces, the fraction of particles that deposit is calculated using a method outlined by Walsh and co-workers
- Local occurrence of slagging and the extent of sintering are then predicted as the deposit accumulates using a pseudo steady state approach

Case 1

450 MW Opposed-Wall PC Unit Bituminous Coal

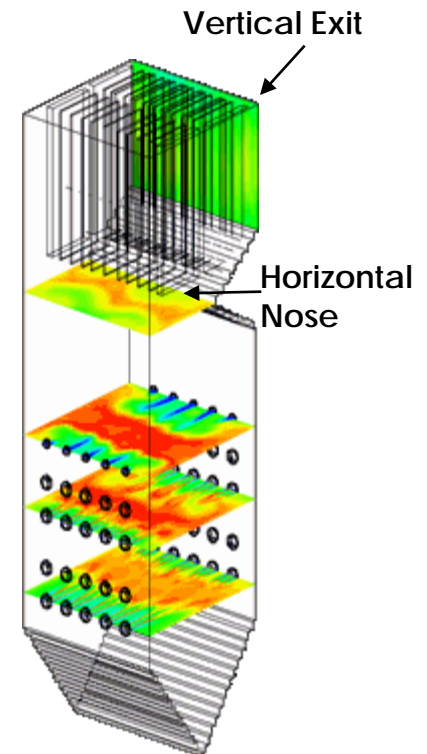
Opposed Wall-Fired PC Unit



Overall Results

Representative of the difference before and after soot blowing cycles observed at plant

	Baseline	Baseline Slagging
Horizontal Nose Plane		
Temperature (°F)	2399	2499
CO Concentration, wet (ppm)	4350	5874
O ₂ Concentration, wet (%)	3.7%	3.6%
NO _x , wet (ppm)	160	157
Vertical Exit Plane		
Temperature (°F)	1862	1938
CO Concentration, wet (ppm)	792.0	1188.8
O ₂ Concentration, wet (%)	3.1%	3.3%
NO _x , wet (ppm)	168	162
NO _x (lb/MBtu)	0.256	0.247
Unburned Carbon in Fly Ash	7.0%	4.6%
Particle Burnout	98.8%	99.3%

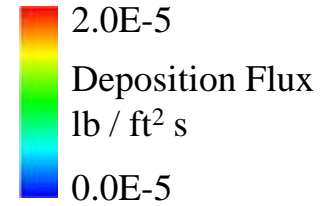


Much better LOI prediction

Particle Deposition

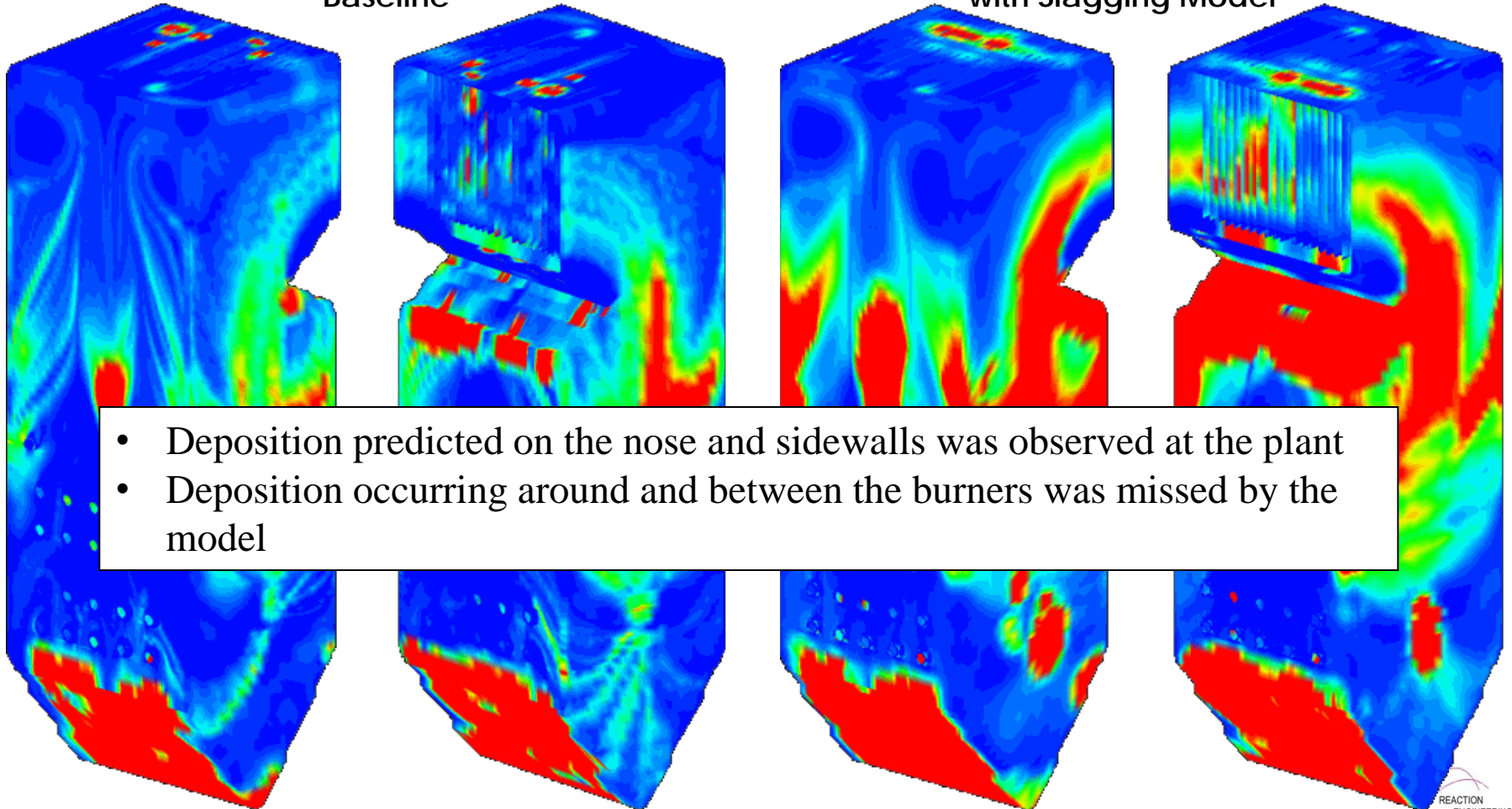
12.7% of Coal Mineral Matter Is Deposited

27.0% of Coal Mineral Matter Is Deposited



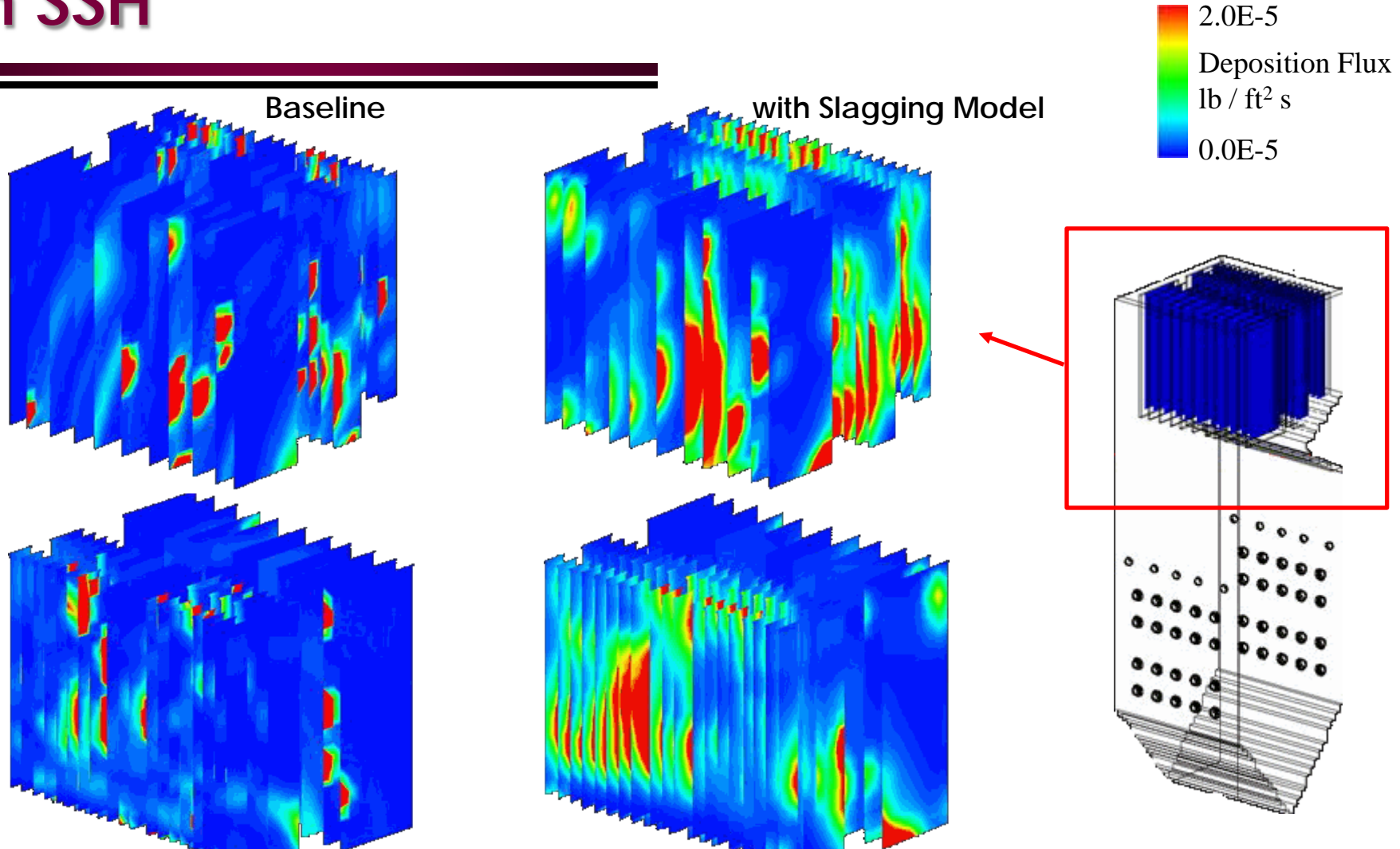
Baseline

with Slagging Model



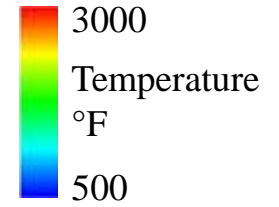
- Deposition predicted on the nose and sidewalls was observed at the plant
- Deposition occurring around and between the burners was missed by the model

Particle Deposition on SSH

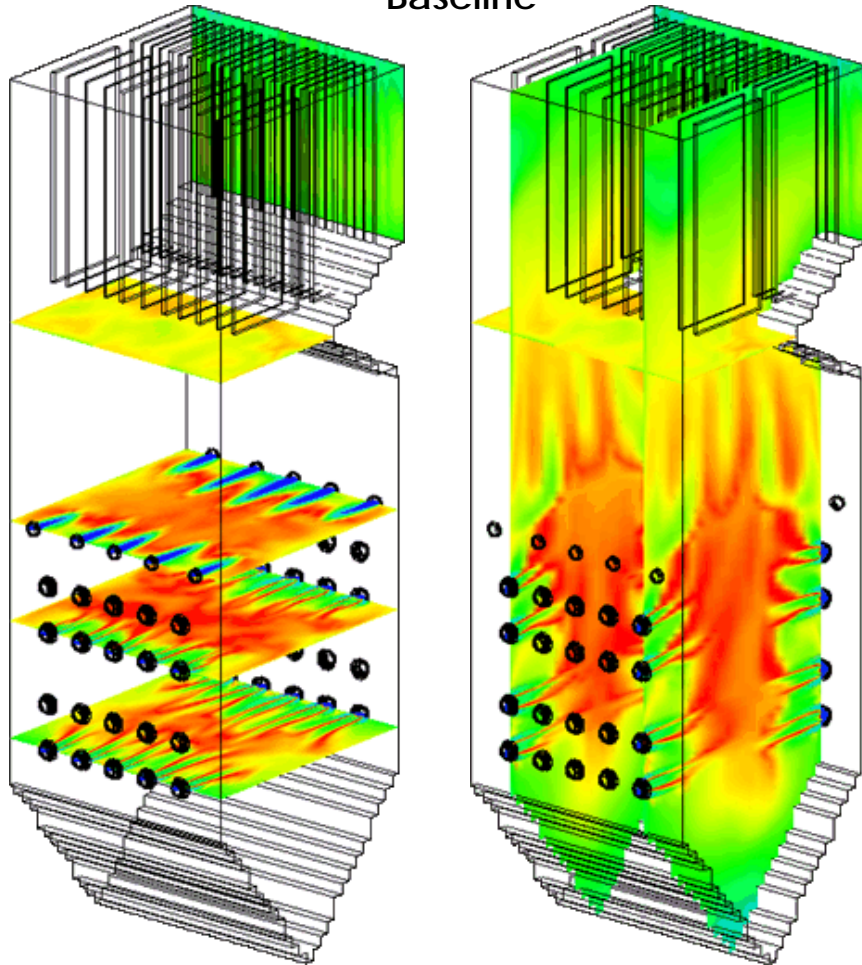


Deposition patterns on the leading edge of the Platens and Pendants are consistent with observations from the plant

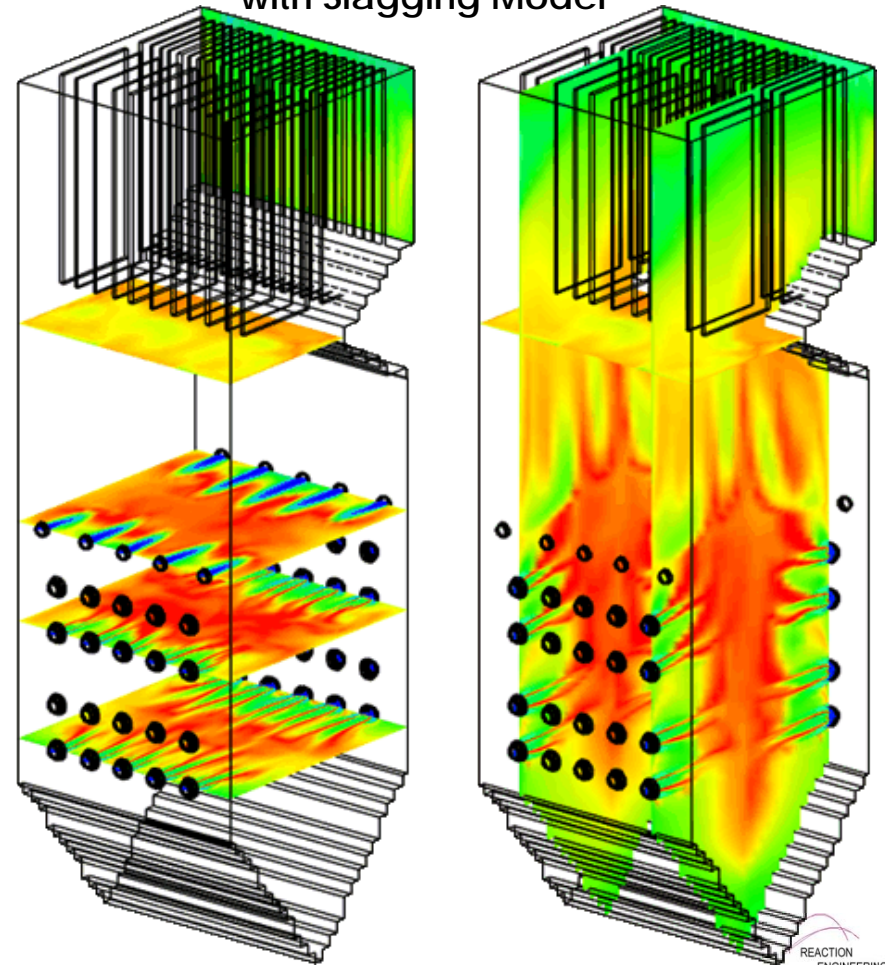
Gas Temperatures



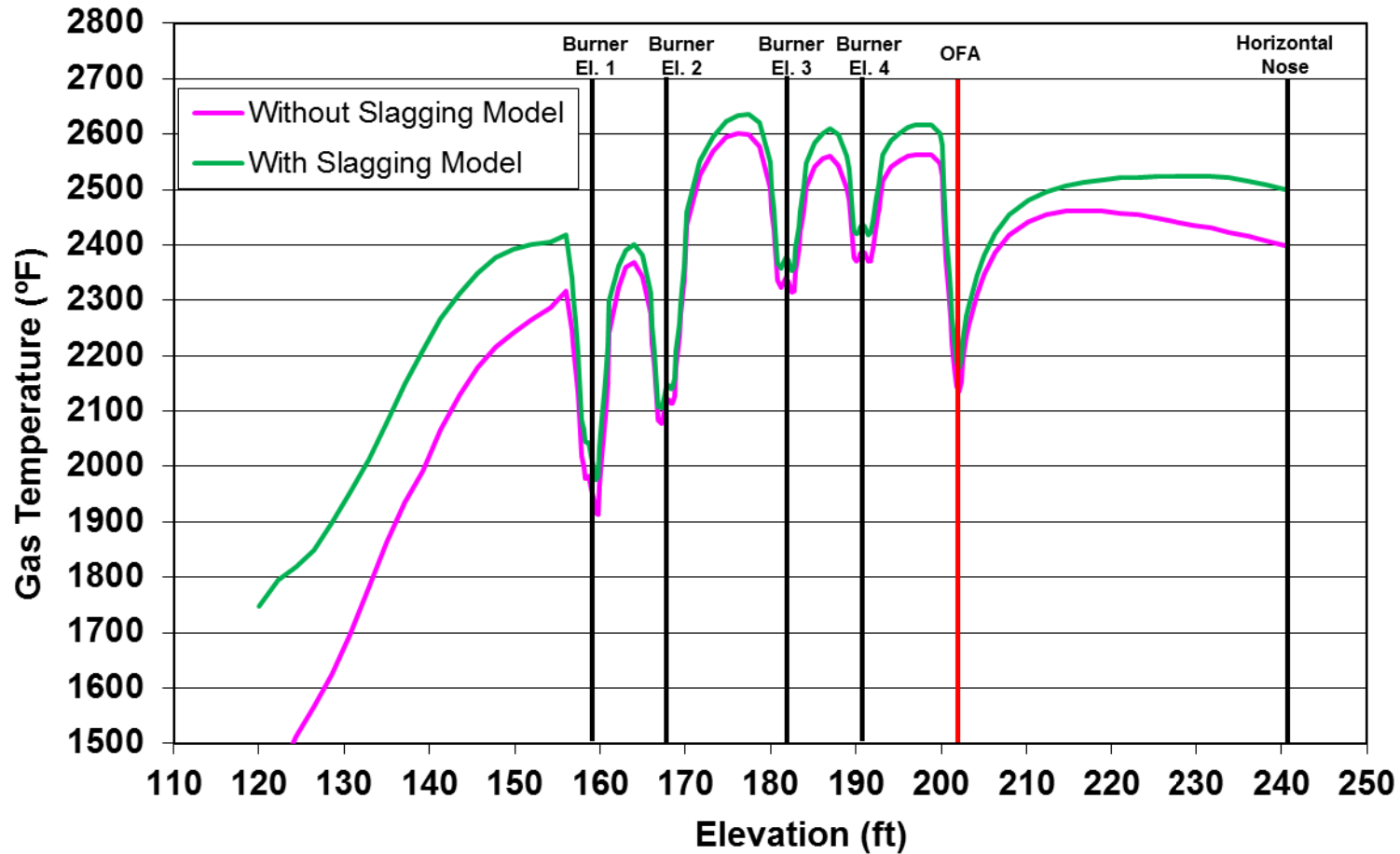
Baseline



with Slagging Model

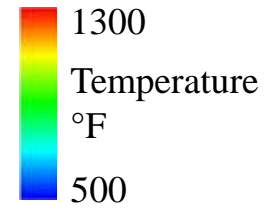


Gas Temperature Profiles

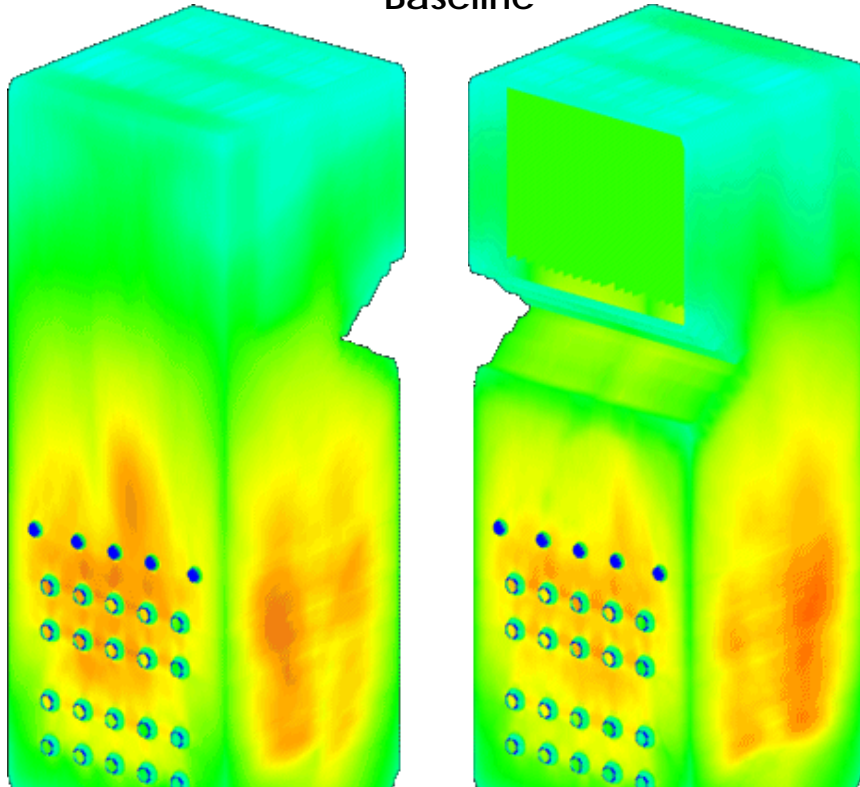


- Gas temperatures are higher in all regions of the boiler when using the slagging model, indicative of the reduction of heat transfer due to deposits

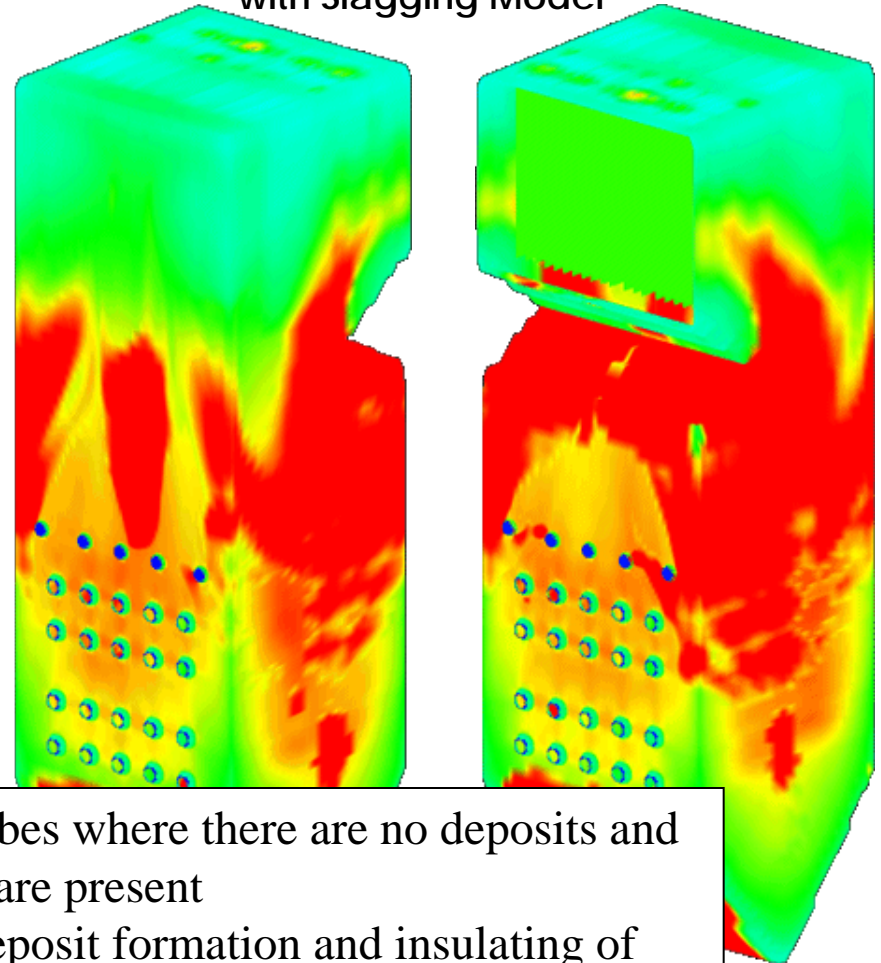
Deposit Surface Temperatures



Baseline

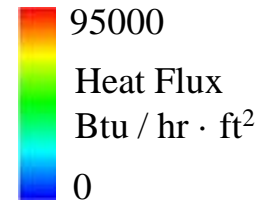


with Slagging Model



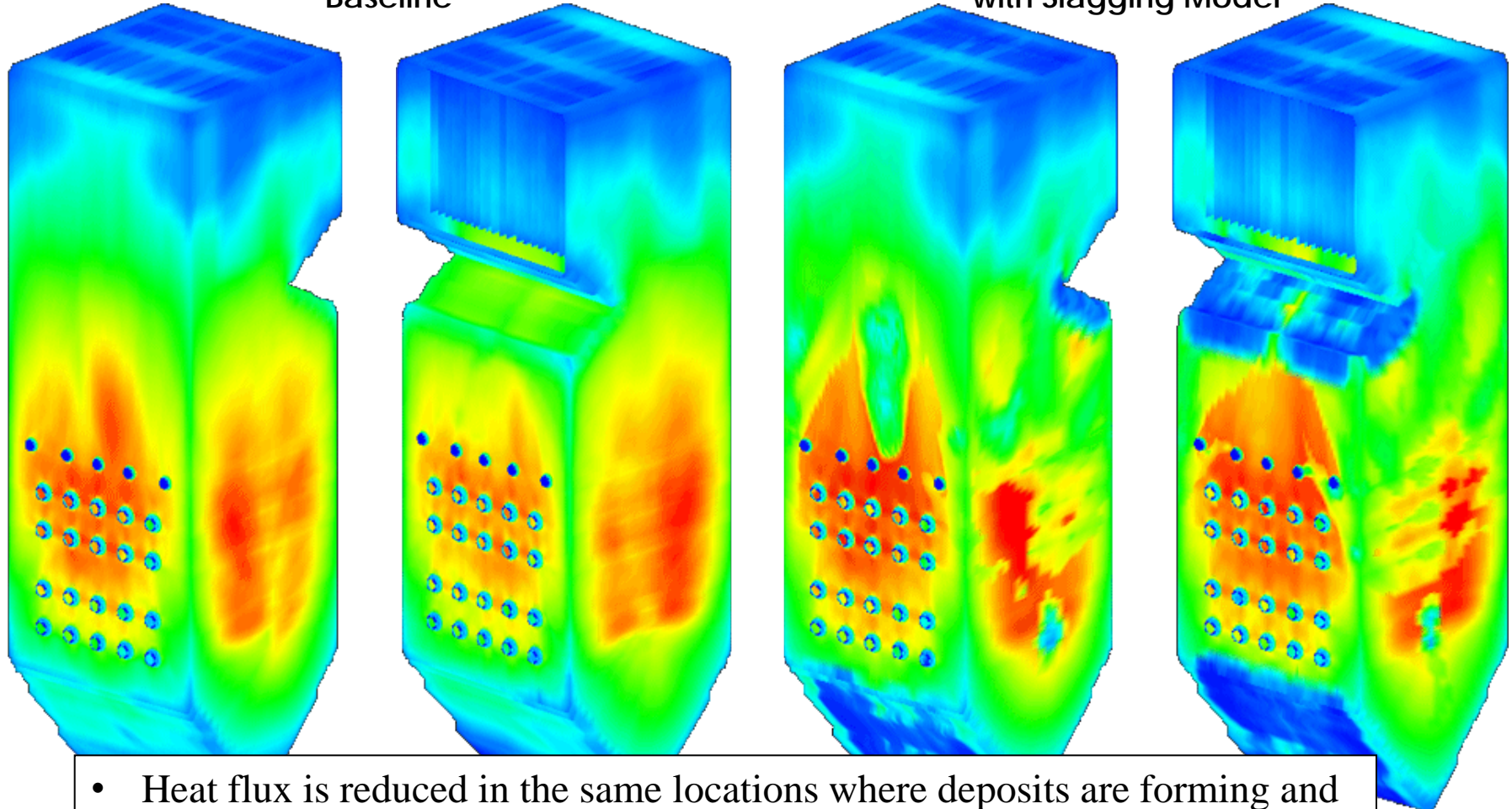
- Surface temperatures represent bare tubes where there are no deposits and the wetted deposit surface where they are present
- High temperature regions are due to deposit formation and insulating of the heat transfer surfaces, reducing heat transfer

Wall Heat Flux



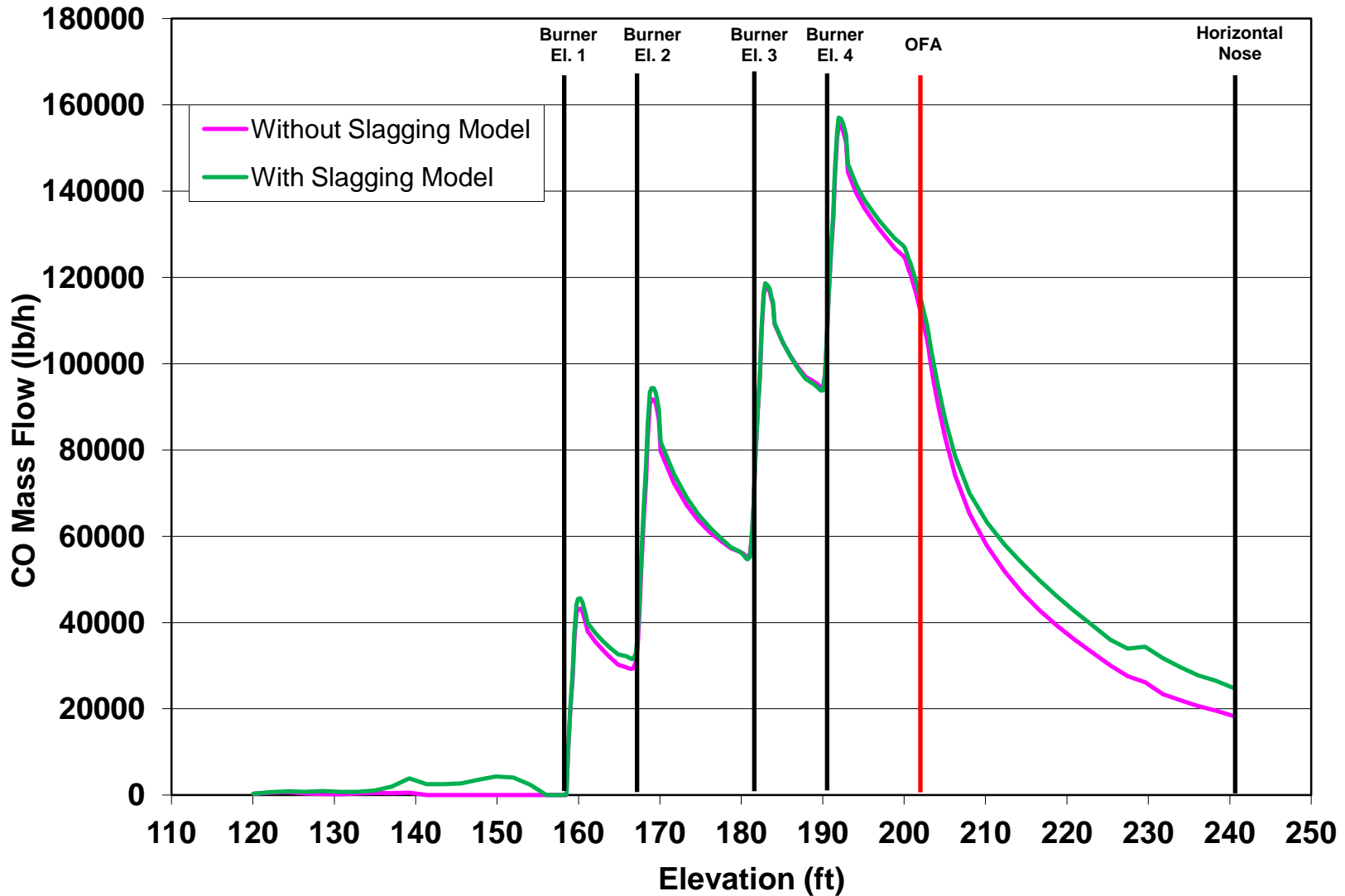
Baseline

with Slagging Model

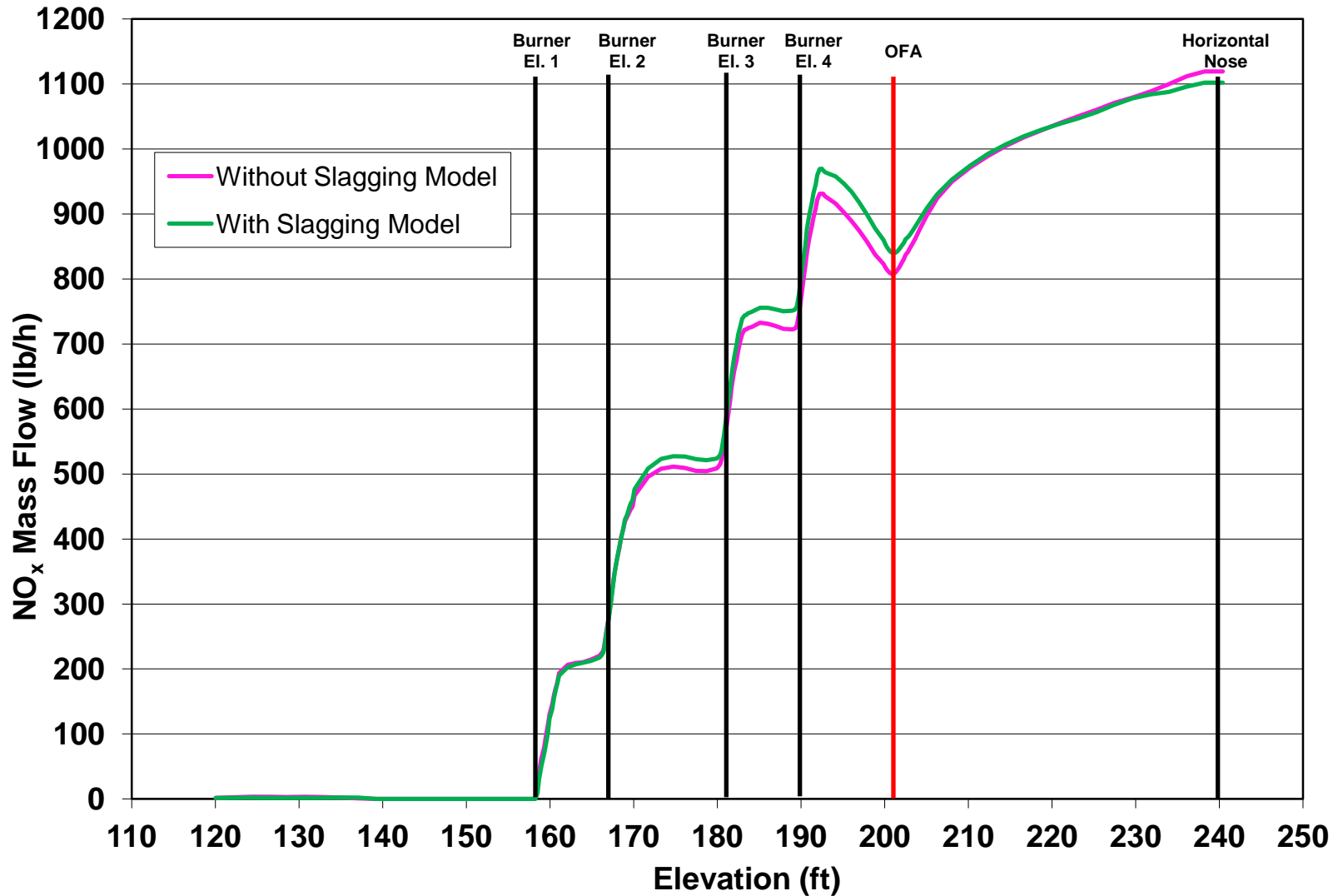


- Heat flux is reduced in the same locations where deposits are forming and the surface temperatures are high

CO Mass Flow



NO_x Flow

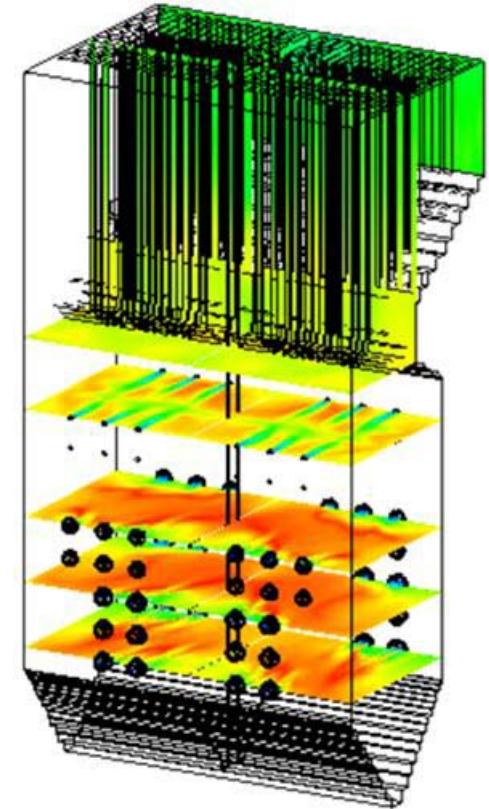


Case 2

660 MW Opposed-Wall PC Unit Biomass Co-Firing

Case Study: PC to Biomass Pellet Co-firing

- ➔ 660 MW opposed-wall, pulverized coal fired unit
- ➔ Comparison of Coal-only and 60% biomass pellet co-firing:
 - ◆ 3 woods (WP1, WP2, WP3)
 - ◆ 1 wood & straw mixture (WP1&SP1)
- ➔ Overall simulation results indicate:
 - ◆ Modest increase in FEGT for biomass firing
 - ◆ Some reduction in wall heat transfer
 - ◆ 35-40% decrease in NO_x emissions
 - ◆ Similar CO emissions
 - ◆ Slight decrease in carbon in flyash



Nominal Operating Conditions

	Units	Baseline	WP1	WP2	WP3	WP1+SP1
		Coal	Pinnacle	Green Circle	Gesfinu	Pinnacle+Straw
System Firing Rate	[MMBtu/hr]	5699	5706	5706	5712.0	5717.0
System Firing Rate	[MWth]	1670	1672.2	1672.2	1674.0	1675.4
System Load	[MWe gross]	671	660	660	660	660
System Excess Air	[%]	14.40	14.40	14.40	14.40	14.40
System Excess O2	[% dry]	2.80				
System Excess O2	[% wet]	2.63				
System Coal Flow	[kg/s]	71.00	28.21	28.21	28.21	28.21
System Wood Pellet Flow	[kg/s]		53.74	52.86	53.81	37.86
System Straw Pellet Flow	[kg/s]					18.73
System Air Flow	[kg/s]	651.60	623.00	613.36	621.98	616.88
Primary Air Flowrate	[kg/s]	146.26	185.18	185.18	185.18	185.18
Secondary Air Flowrate	[kg/s]	179.77	56.59	55.05	56.43	55.61
Tertiary Air Flowrate	[kg/s]	169.82	226.36	220.21	225.71	222.45
BOFA Air Flowrate	[kg/s]	85.36	81.61	80.35	81.48	80.81
FD OFA Air Flowrate	[kg/s]	46.26	44.23	43.55	44.16	43.80
Core Air Flowrate	[kg/s]	24.12	29.02	29.02	29.02	29.02
Primary Air Temp	[C]	82	See Tables on Following Slides			
Core Air Temp	[C]	34	34	34	34	34
Secondary Air Temp	[C]	294	294	294	294	294
Tertiary Air Temp	[C]	294	294	294	294	294
BOFA Air Temp	[C]	281	281	281	281	281
FD OFA Air Temp	[C]	281	281	281	281	281

Fuel Properties

Proximate Analysis		Coal only	WP1	WP2	WP3	SP3
Volatiles Matter	[wt % ar]	27.33	80.80	80.40	77.40	71.80
Fixed Carbon	[wt % ar]	43.16	14.10	15.20	16.90	15.30
Moisture	[wt % ar]	14.47	4.60	4.10	4.20	7.40
Ash	[wt % ar]	15.04	0.50	0.30	1.50	5.50
HHV	[kJ/kg]	23523.5	18769.7	19080.4	18775.6	16083.4
LHV	[kJ/kg]	22337.8	17458.2	17741.5	17435.6	14816
Ultimate Analysis						
C	[wt % ar]	59.70	49.42	48.91	48.86	41.67
H	[wt % ar]	3.73	5.64	5.75	5.75	5.00
S	[wt % ar]	1.24	0.01	0.01	0.02	0.07
O	[wt % ar]	4.67	39.62	40.62	39.30	39.86
N	[wt % ar]	1.15	0.22	0.31	0.37	0.50
Cl	[wt % ar]	0.260	0.003	0.003	0.021	0.114
H2O	[wt % ar]	14.47	4.60	4.10	4.20	7.4
Ash	[wt % ar]	15.04	0.50	0.30	1.50	5.5

Fuel Ash Elemental Analyses

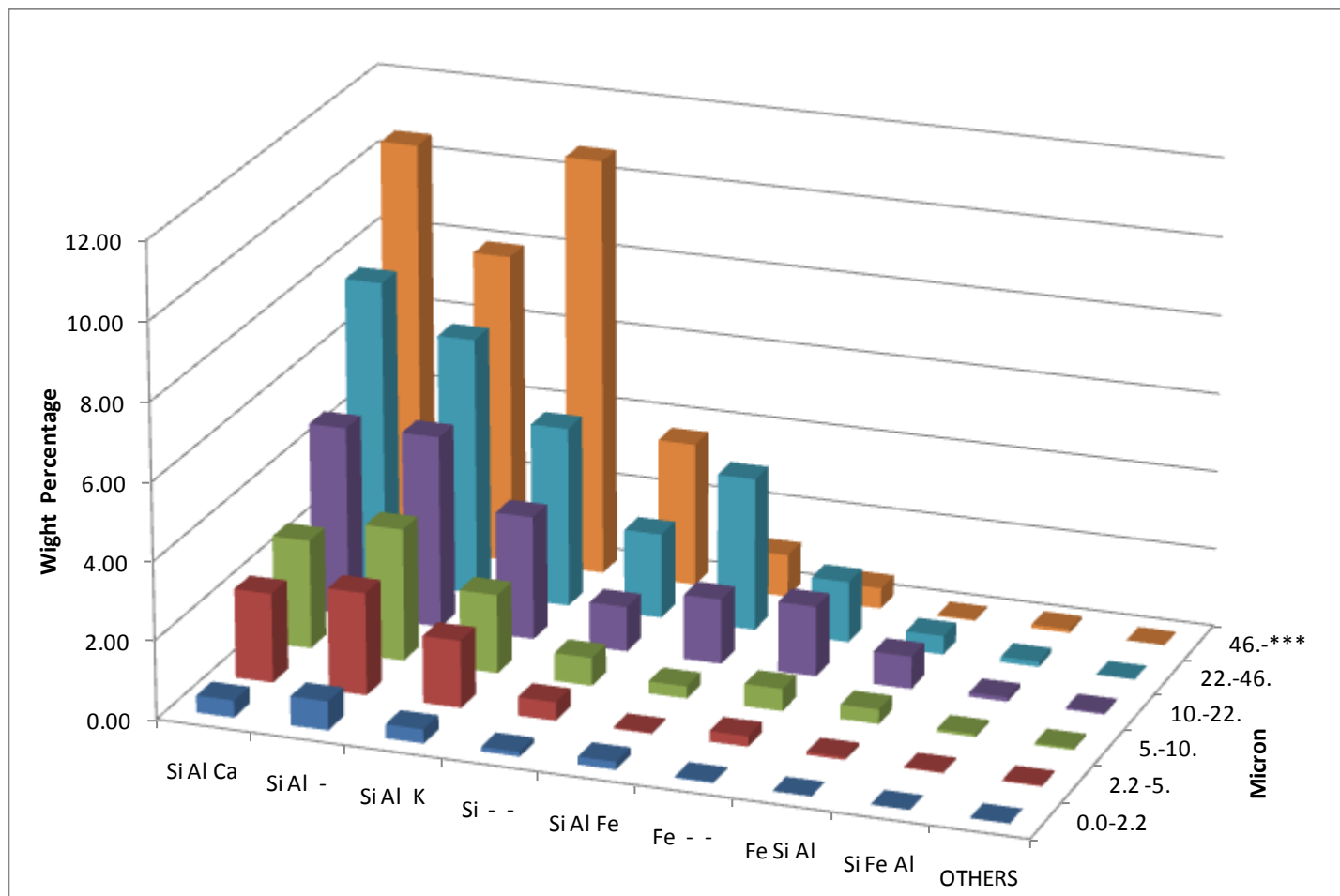
ASTM Bulk Analysis					
Ash Elemental Oxides (wt%)	<i>Coal</i>	<i>WP1</i>	<i>WP2</i>	<i>WP3</i>	<i>SP1</i>
SiO ₂	50.67	28.44	33.94	38.73	67.68
Al ₂ O ₃	23.77	5.84	7.00	5.48	1.62
Fe ₂ O ₃	10.70	2.99	2.66	3.53	0.91
TiO ₂	1.00	0.26	0.24	0.37	0.10
CaO	3.85	32.47	23.79	19.00	10.40
MgO	2.03	7.92	8.09	6.46	2.12
Na ₂ O	0.72	1.30	3.02	1.95	0.71
K ₂ O	2.77	13.25	11.47	17.78	12.02
Mn ₃ O ₄	0.14	2.34	3.02	0.73	0.10
P ₂ O ₅	0.21	3.77	3.99	3.53	2.12
SO ₃	4.02	1.43	2.78	2.44	2.22

Biomass Particle Size Distribution

Model Biomass Size Distribution, Hammer Mill			Model Biomass Size Distribution, Phoenix Mill (Mills A & B)		
Lognormal Fit of Measured Values			Lognormal Fit of Measured Values		
Size	Mass Fraction	Avg. Diam. (µm)	Size	Mass Fraction	Avg. Diam. (µm)
1	0.05	115.302	1	0.05	97.3619
2	0.1	185.634	2	0.1	162.751
3	0.15	246.223	3	0.15	219.805
4	0.2	320.042	4	0.2	290.441
5	0.2	417.39	5	0.2	385.163
6	0.15	543.217	6	0.15	509.669
7	0.1	714.425	7	0.1	681.779
8	0.05	1017.57	8	0.05	991.093
Measured Values			Measured Values		
Overall PSD for biomass from hammer mill			Overall PSD for biomass from phoenix mill (mills A and B)		
Size (um)	Percent		Size (um)	Percent	
< 4000	100		< 4000	100	
< 2000	100		< 2000	100	
< 1000	58.2		< 1000	78.055	
< 500	32.4		< 500	38.315	
< 100	11.3		< 106	5.225	
< 85	1.6		< 75	3.495	

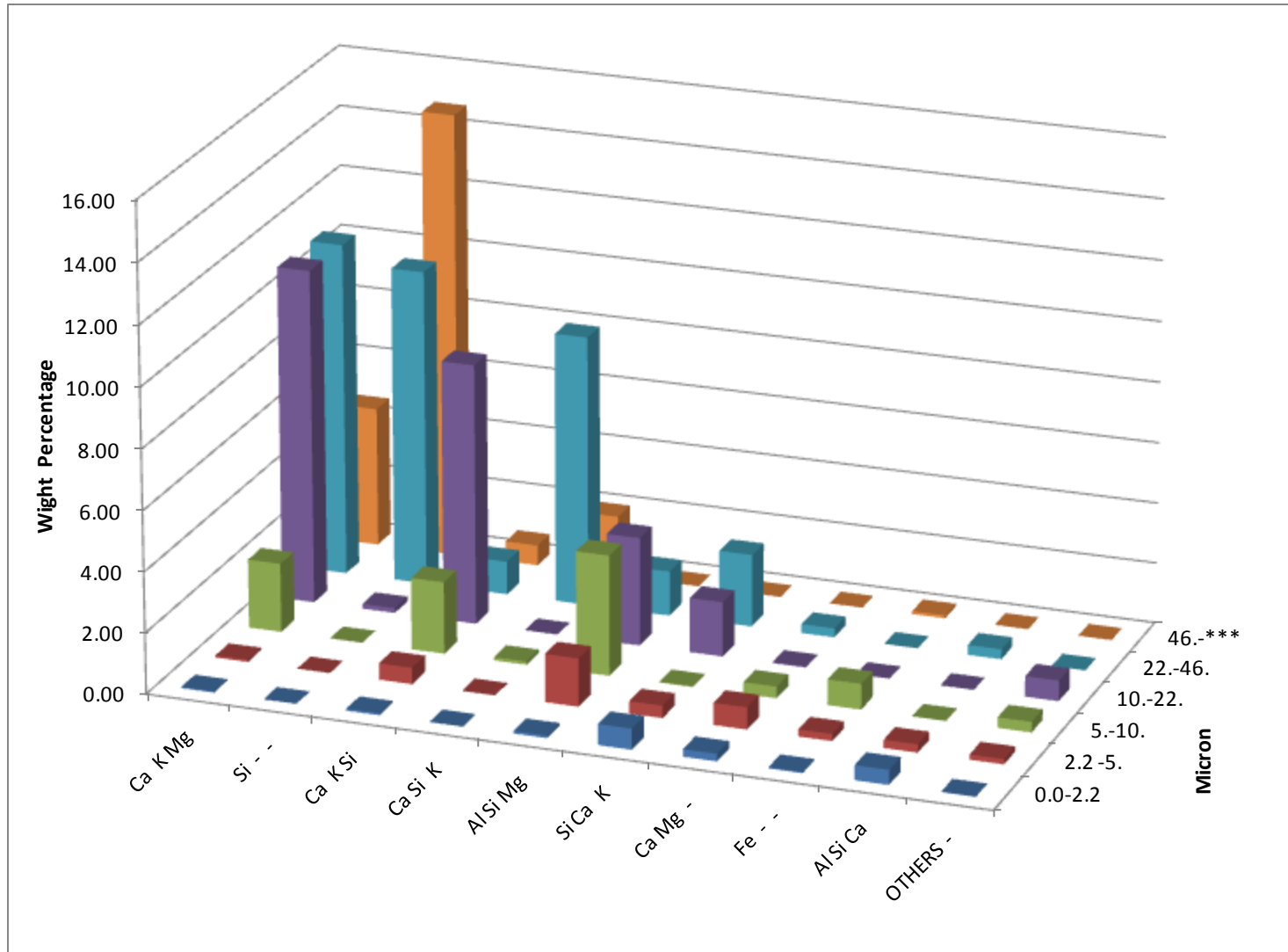
Coal Fly Ash

Predicted Fly Ash Composition



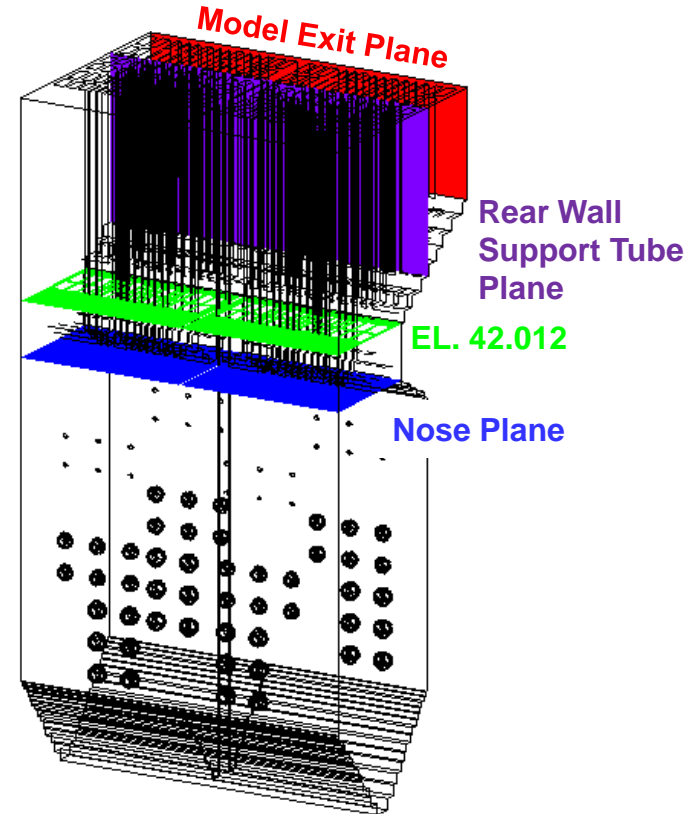
WP1

Predicted Fly Ash Composition

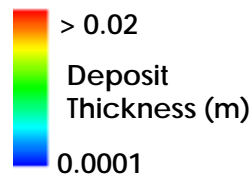
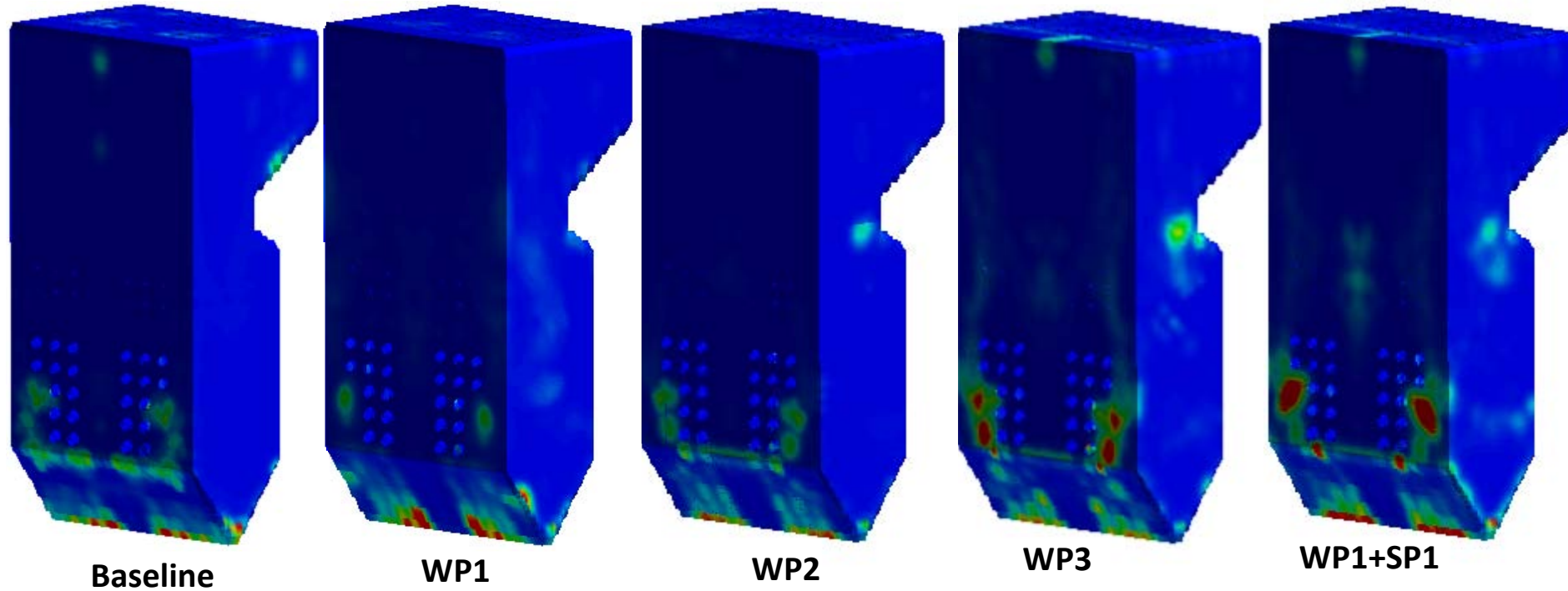


Overall Results

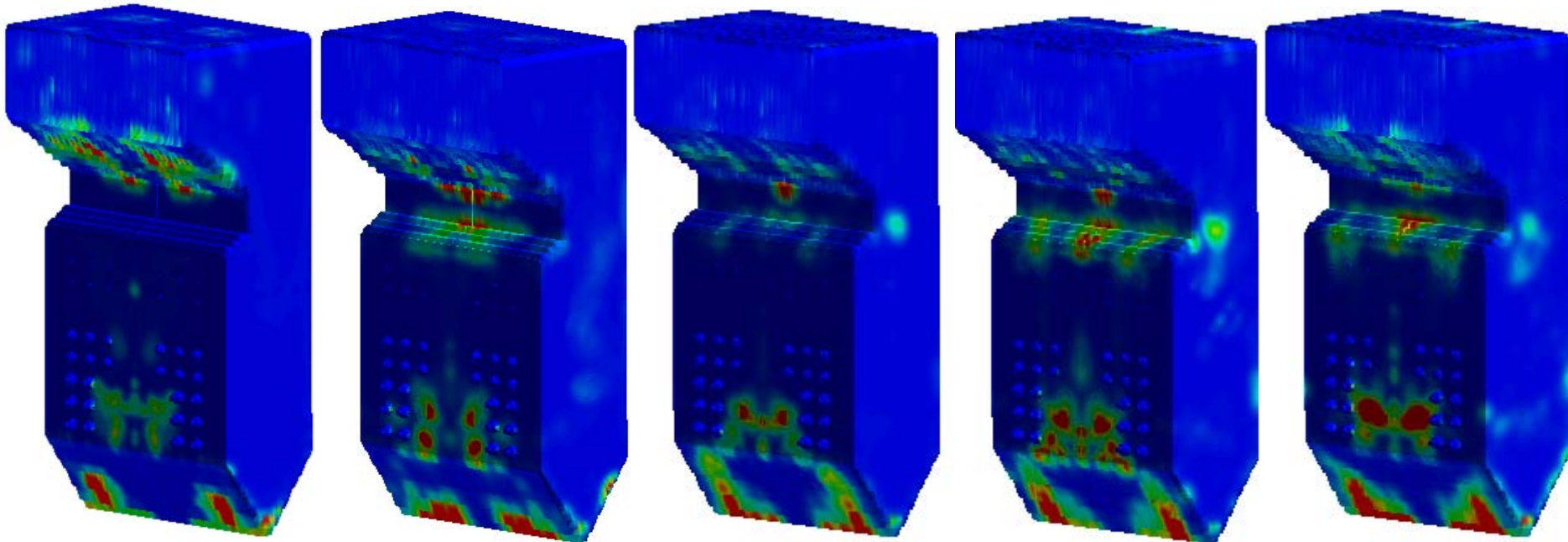
	Revised Baseline	WP1	WP2	WP3	WP1+SP1
Nose Plane, EL. 38.405 m					
Gas Temperature, °C	1,244	1,309	1,298	1,325	1,311
CO Concentration, ppm wet	6,419	10,970	8,959	9,509	8,910
CO Concentration, ppm dry	7,094	12,408	10,163	10,787	10,137
O ₂ Concentration, vol. % wet	3.16	3.15	3.01	3.03	2.92
O ₂ Concentration, 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



Deposit Thickness After Four Hours



Deposit Thickness After Four Hours



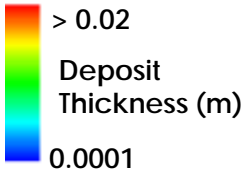
Baseline

WP1

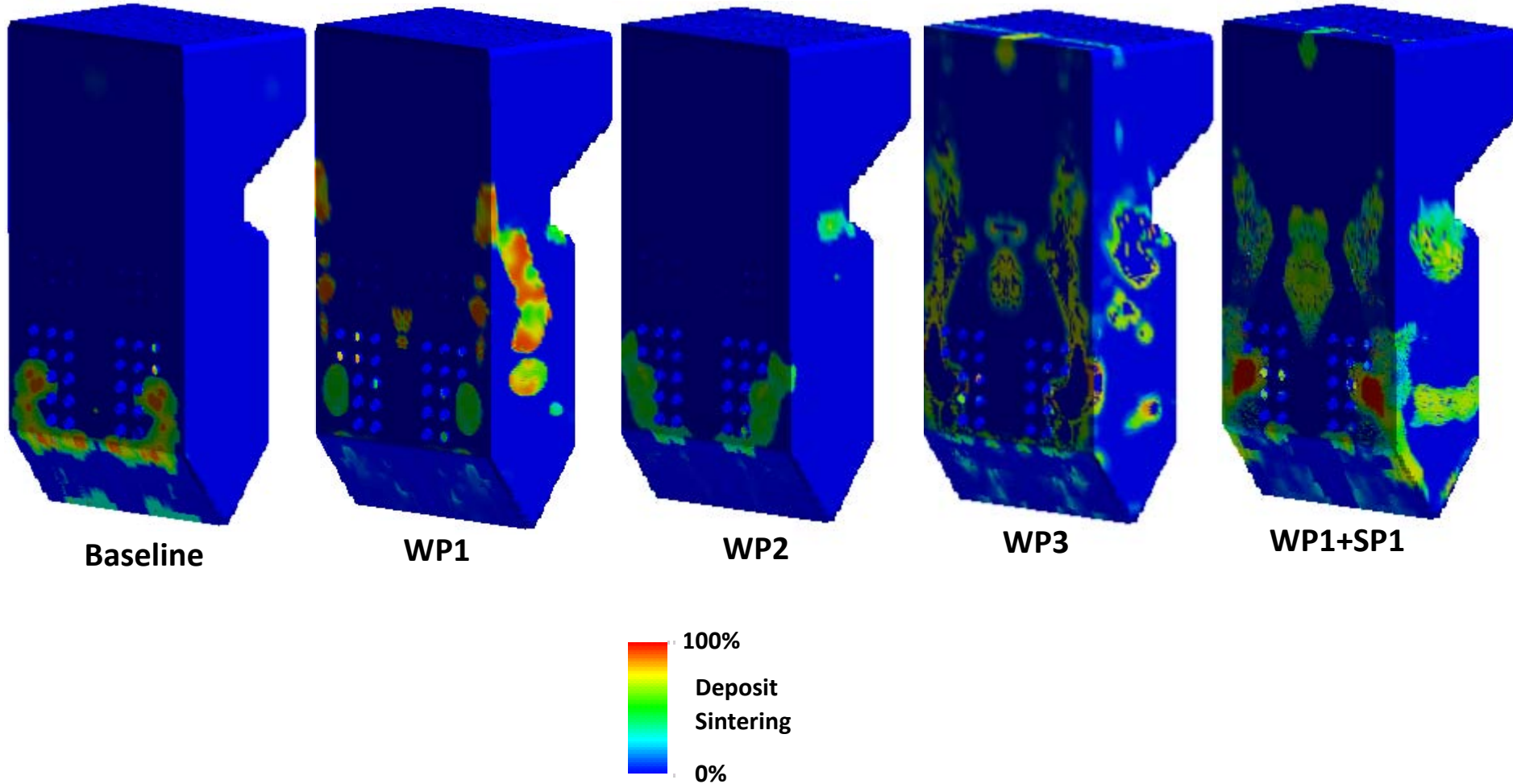
WP2

WP3

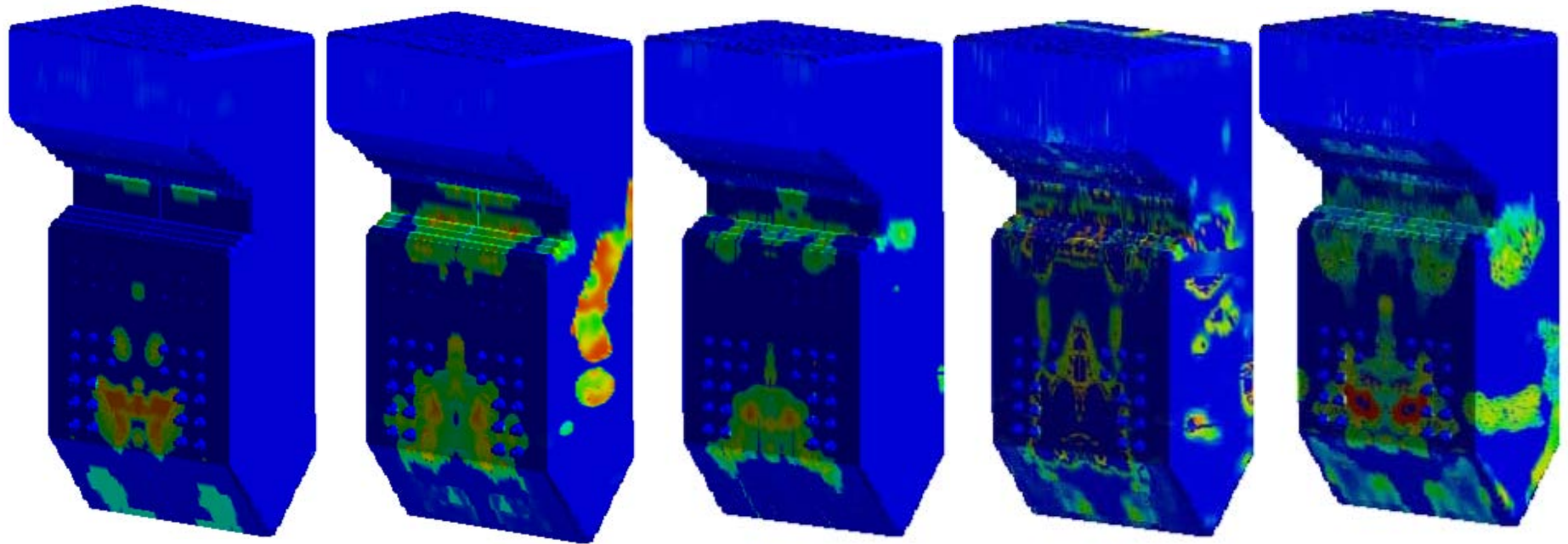
WP1+SP1



Deposit Sintering Extent After Four Hours



Deposit Sintering Extent After Four Hours



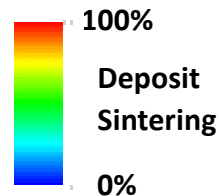
Baseline

WP1

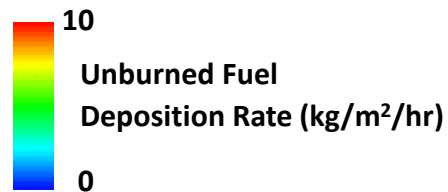
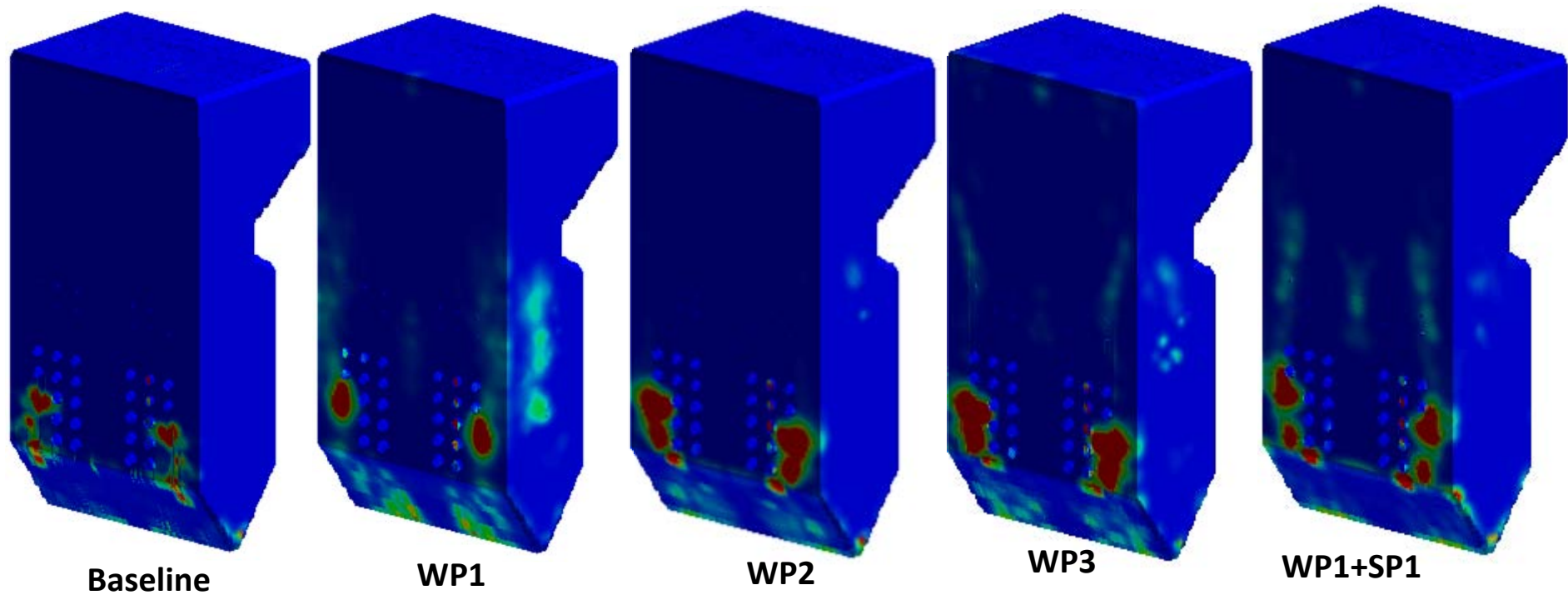
WP2

WP3

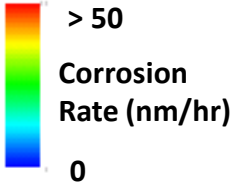
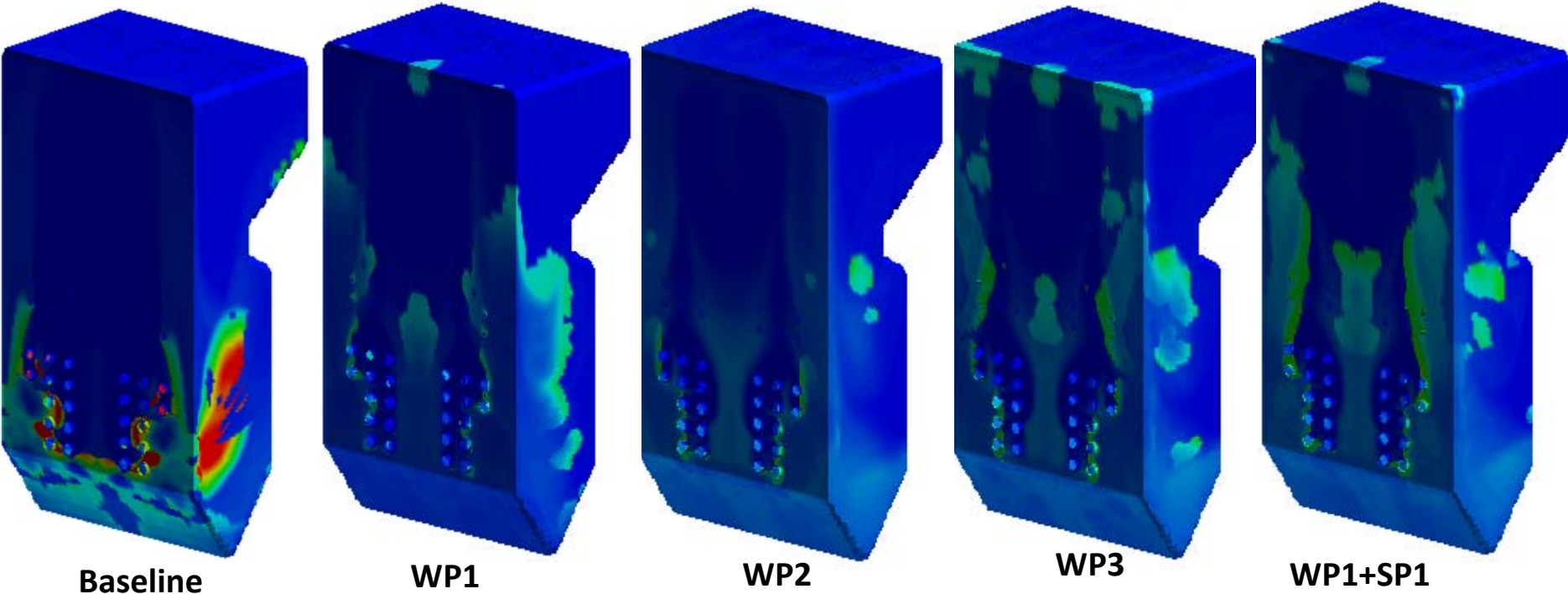
WP1+SP1



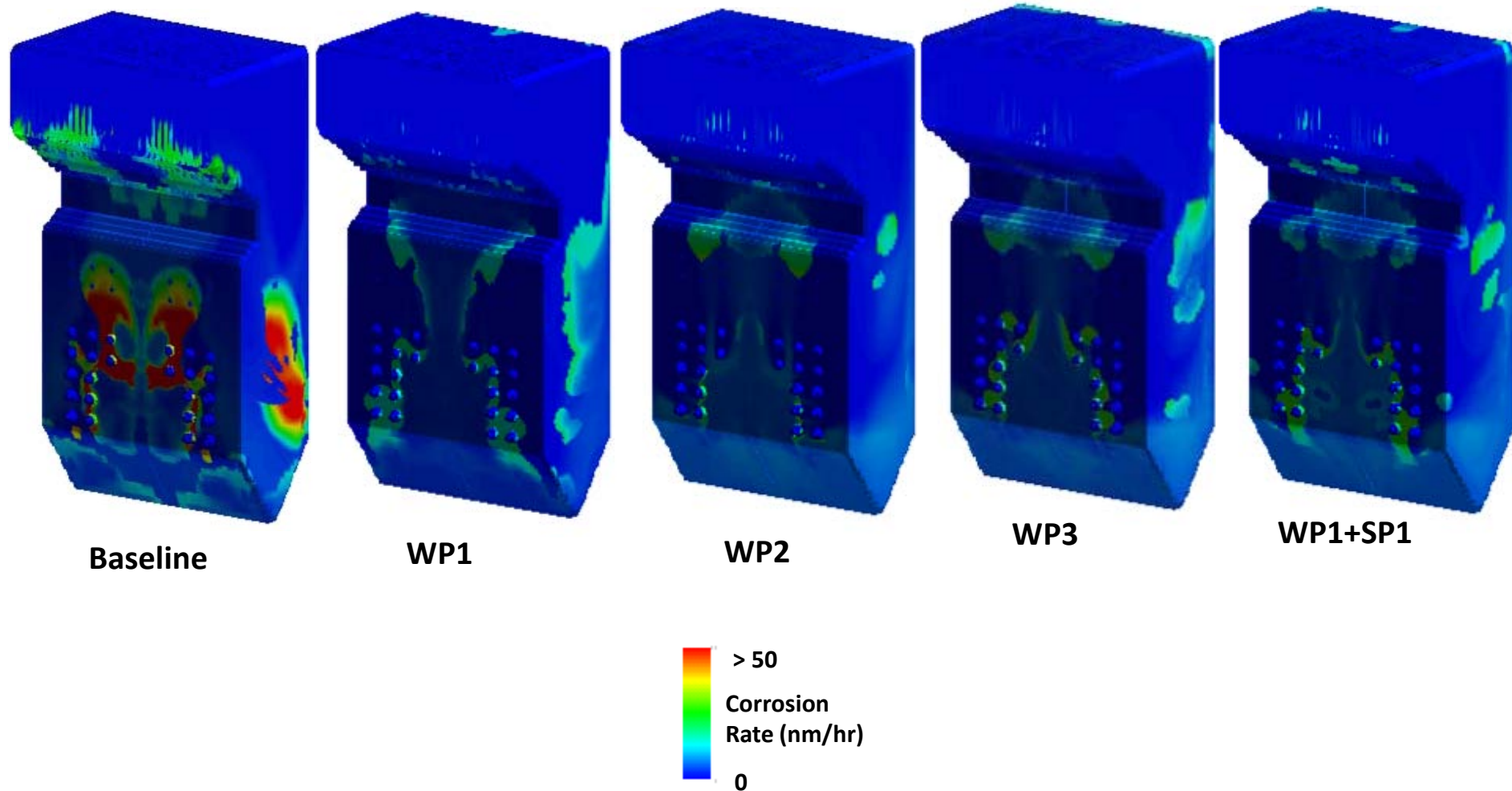
Unburned Fuel Deposition Rate



Total Corrosion Rate

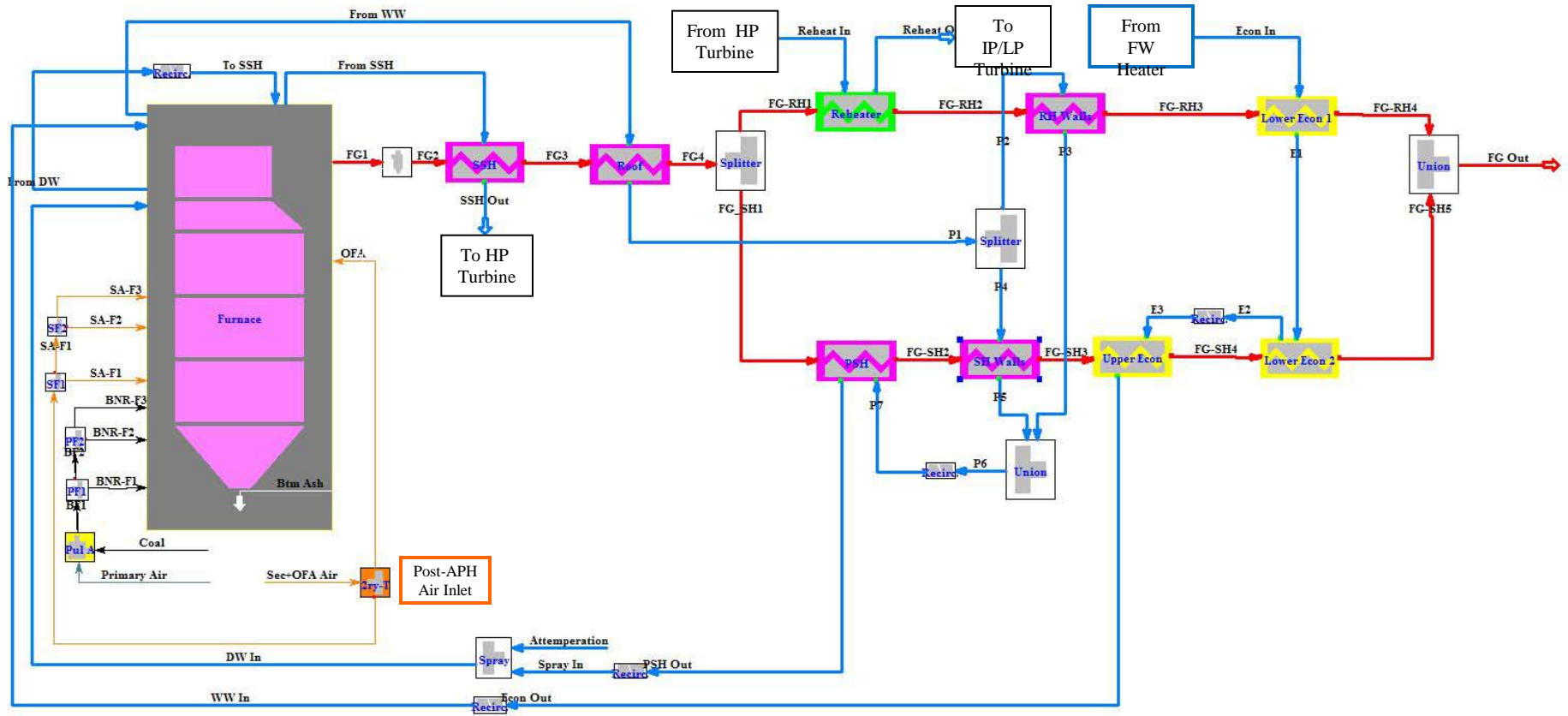


Total Corrosion Rate



Steam Gen Expert

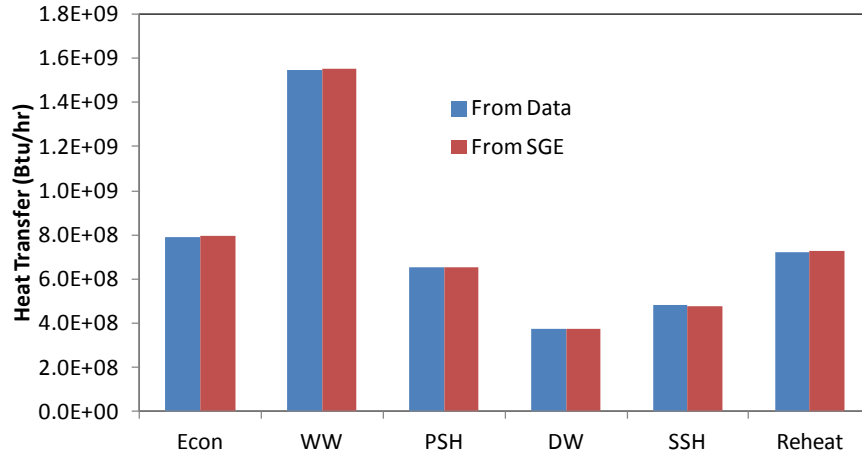
- Heat Balance



SGE Coupled with CFD

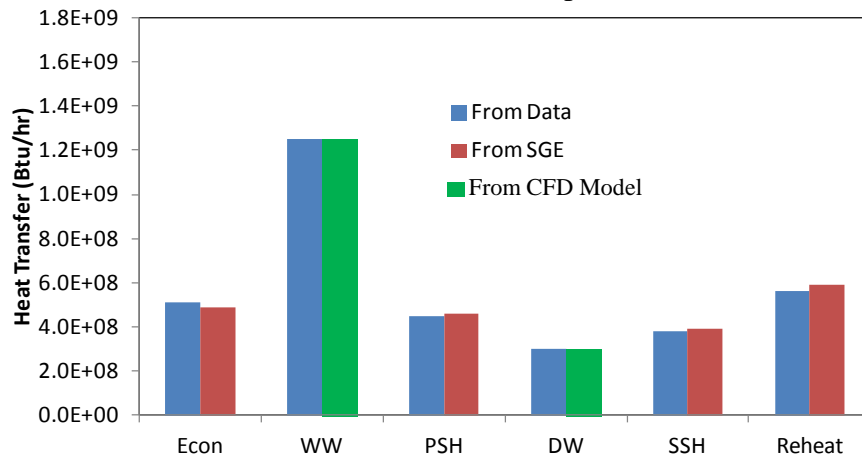
-Tune for Baseline Conditions

VVO

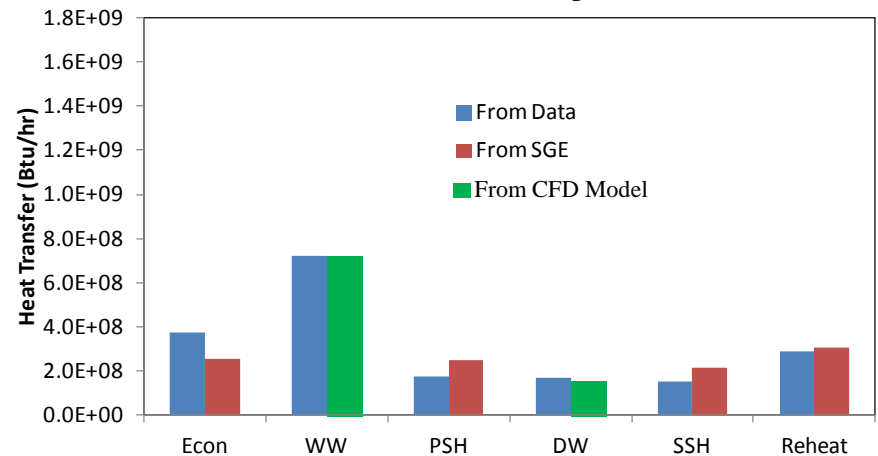


75% and 35% loading predictions improved when using CFD model results for radiant furnace water wall (WW) and division wall (DW)

75% w/ CFD input



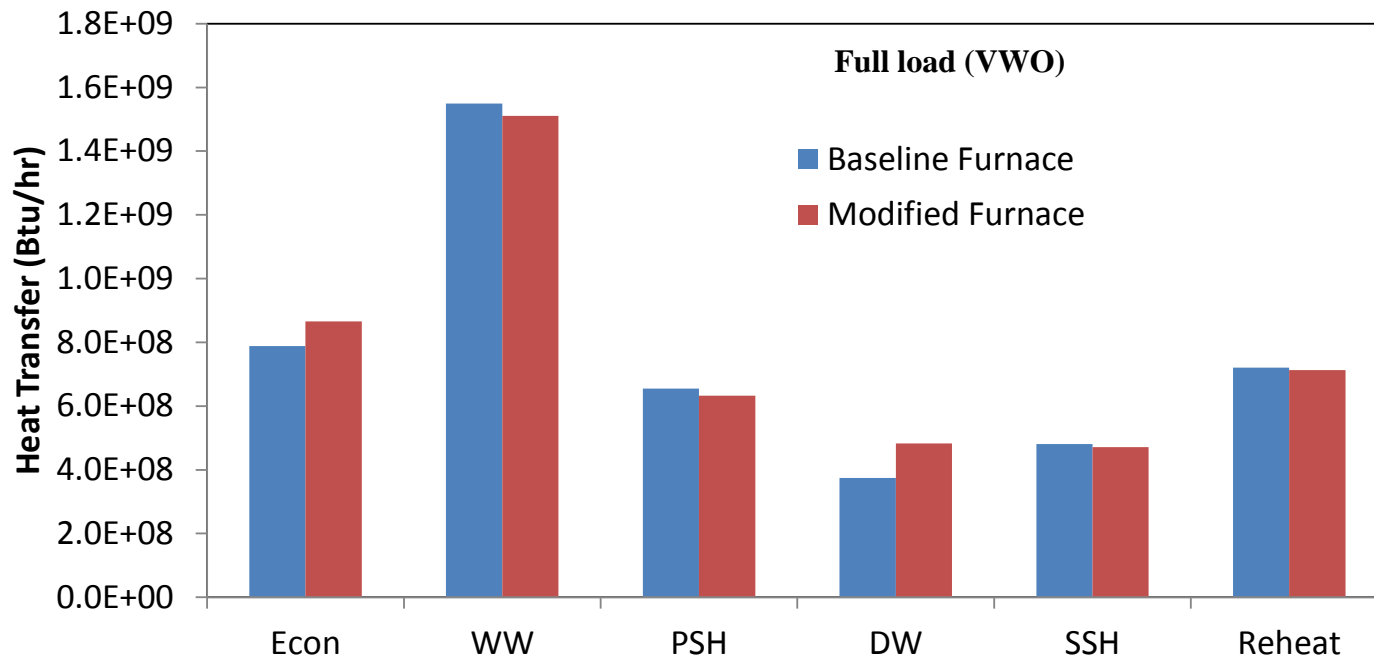
35% w/ CFD input



Evaluation of Boiler Modifications

→ Changes:

- ◆ Expanded surface area of division walls in radiant boiler
- ◆ Additional soot blowers
- ◆ Addition of a modular external economizer



Results of Modifications

- Increase in division wall (DW) and economizer heat transfer; slight decrease in waterwall (WW), primary superheat (PSH), and reheat (RH) heat transfer rates

	Baseline	Mod 2
Spray Flow (kpph) ¹	45	123.4 ¹
Boiler Exit Temp (F)	823	829 ²
Air Heater Inlet Temp (F)	823	774 ³

¹ maintain 1005 °F HP turbine inlet temperature w/ higher DW

² no change to existing economizer

³ additional heat removed by external economizer

Summary and Conclusions

→ Computational Tools

- ◆ Detailed models for describing mineral matter transformation, ash deposit build-up and sintering are available
- ◆ These models have been implemented in a CFD framework and applied to multiple full-scale coal-fired boilers resulting in predictions that are qualitatively accurate
- ◆ Simulations have been carried out with a pseudo-transient approach
- ◆ Extension of this approach to biomass co-firing has also been completed and further evaluations are in process
- ◆ CFD simulations in the radiant furnace have been coupled with a process model (SGE) for coupled FG/steam calculations
- ◆ SGE combined with radiant furnace CFD can be used to efficiently evaluate impacts of radiant furnace slagging, cleaning, and radiant or convective pass heat transfer surface modifications

Summary and Conclusions

→ Ash Behavior: Coal-only vs Biomass/Coal

- ◆ Deposition patterns/rates, sintering extent, and corrosion rates can vary extensively as a function of biomass source
- ◆ Ash management can range from very similar to significantly more challenging