REINHOLD ENVIRONMENTAL Ltd.

2019 NOx-Combustion-CCR Round Table Presentation

February 11 & 12, 2019, in Salt Lake City, Utah / Hosted by PacifiCorp

Advanced Sensing and Control

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For Energy and Environmental Solutions

REACTION ENGINEERING INTERNATIONAL

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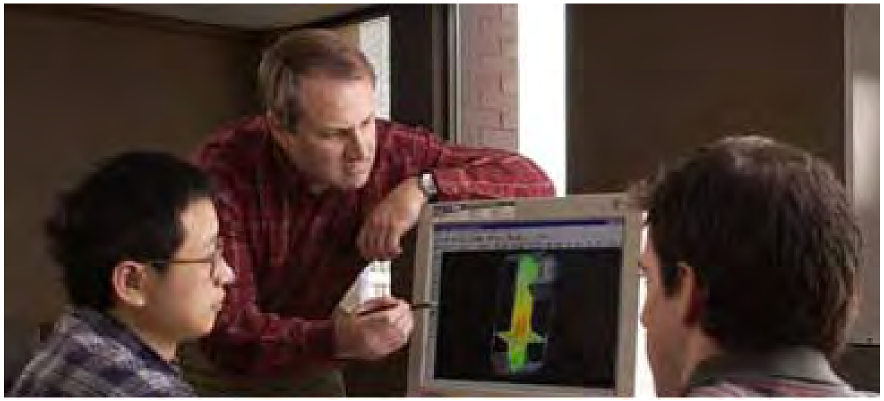
Reaction Engineering International

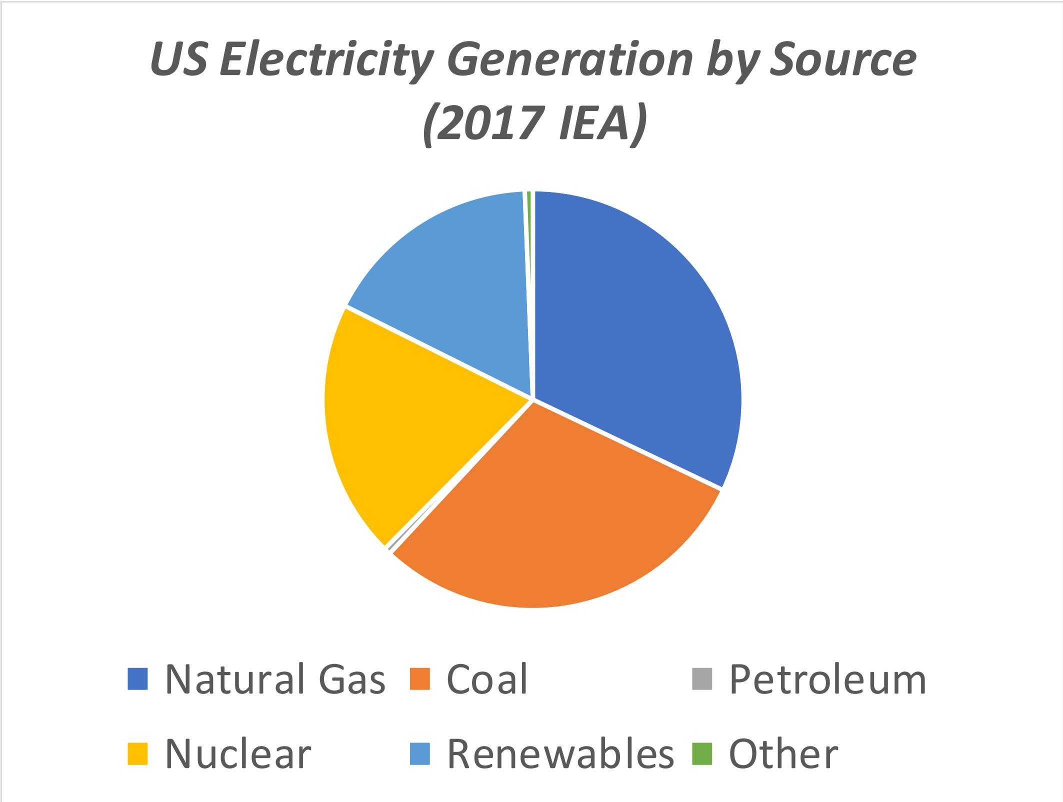
Privately held consulting firm recognized for independent analysis and evaluations involving a range of industrial combustion applications



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

Coal Based Power Generation

- Coal remains a significant Fraction of US Energy Supply
- Security – not dependent on real-time fuel delivery
- Low Cost Electricity
- Reliability – diverse fuel mix
- Improvements to reliability and efficiency are more cost-effective than building new plants



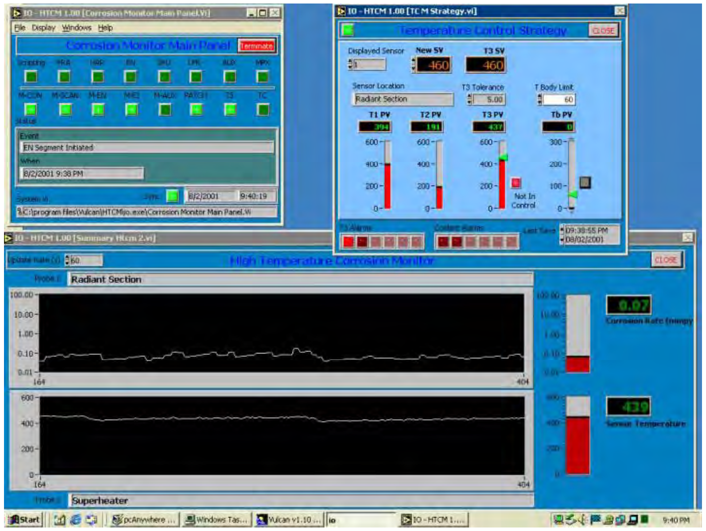
Coal Based Power Generation

Opportunity for Improvements to Reliability and Efficiency

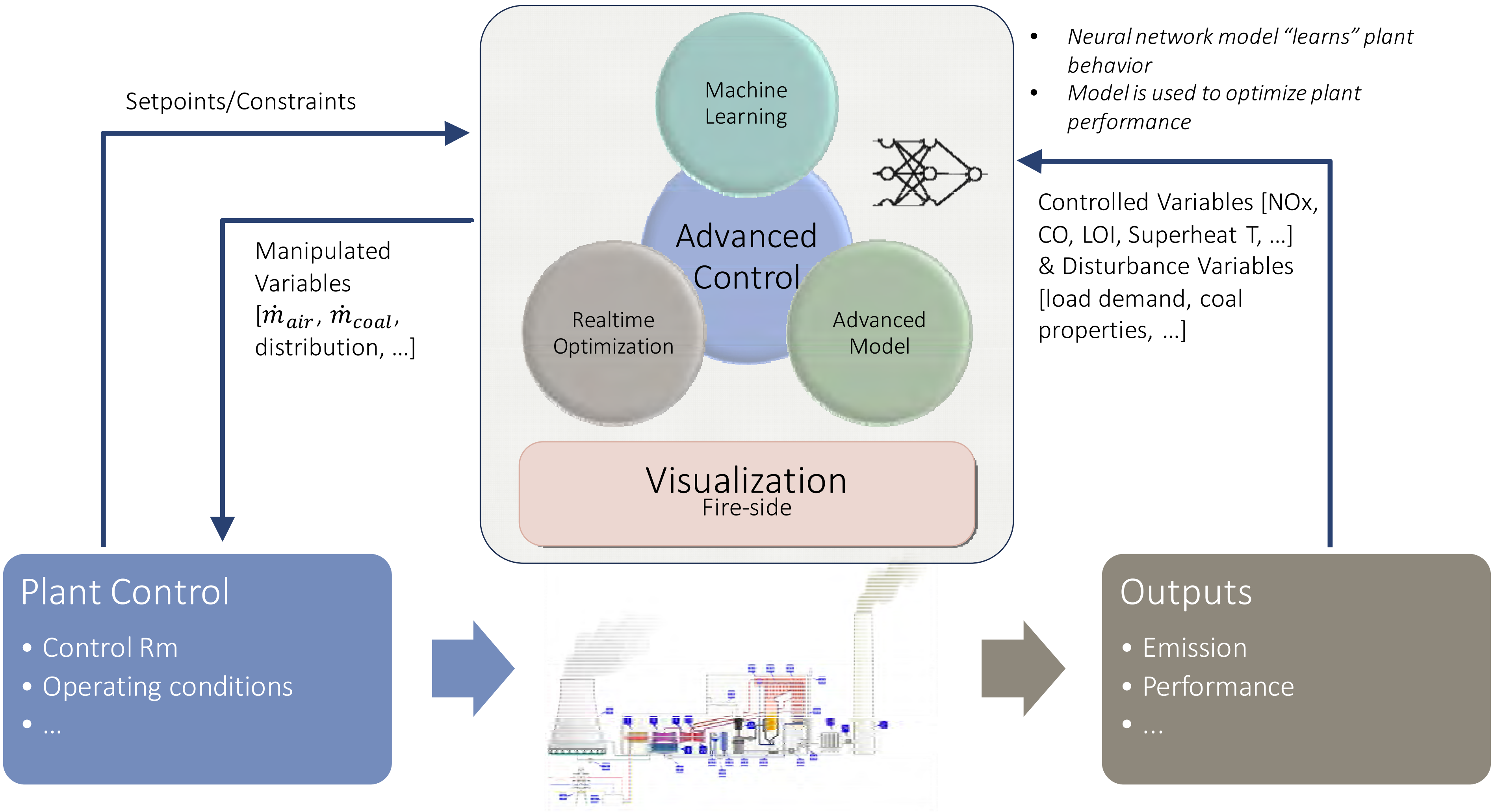
- Minimization of steam tube failures
- Sootblower / cleaning optimization (minimize erosion and fouling and reduce operator involvement)
- Combustion optimization for low emissions
- Management of thermal transients and low load operation
- Mitigate thermal fatigue associated with transient operation and use of aggressive coals

Condition Based Monitoring

- Maintenance philosophy that actively monitors health condition
- Monitor and predict condition before damage occurs
- Maximize availability and generating capacity
- Increase efficiency/reduce emissions/reduce cost
- Integration in Advanced Control System



Advanced Control



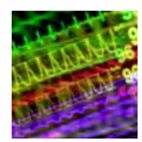
Plant Digitalization for Optimization

- Data quality control
- Advanced model
  - CFD
  - Reduced order model
- Monitoring system
  - Real-time data
- Advanced control
  - Non-linear, dynamic, machine learning model
  - Model predictive control
  - Real time optimization

Data Quality Control

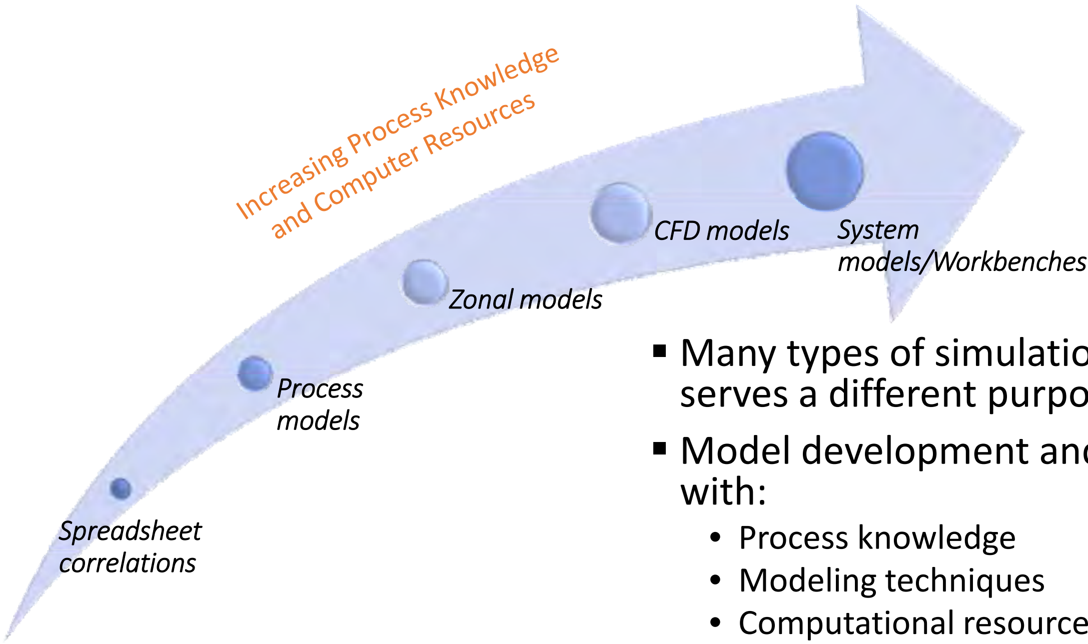
Advanced Model

Monitoring System



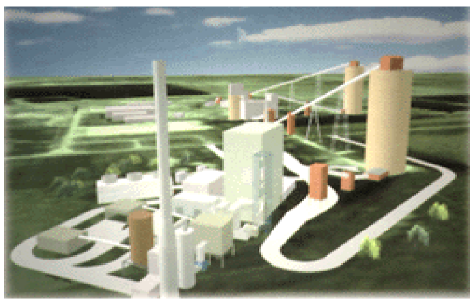
Advanced Control

Modeling Options



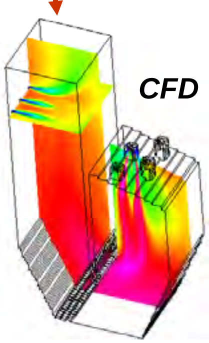
- Many types of simulation tools – each serves a different purpose
- Model development and use are correlated with:
  - Process knowledge
  - Modeling techniques
  - Computational resources
  - Benefit/value

Plant Simulation – Vision 21 Program

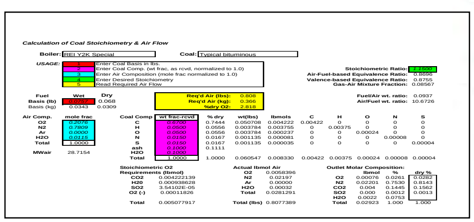


- Develop and demonstrate software framework for virtual simulation of energyplex – "Digital Twin"
- Hierarchy of models
- Fully integrated, interactive simulation environment

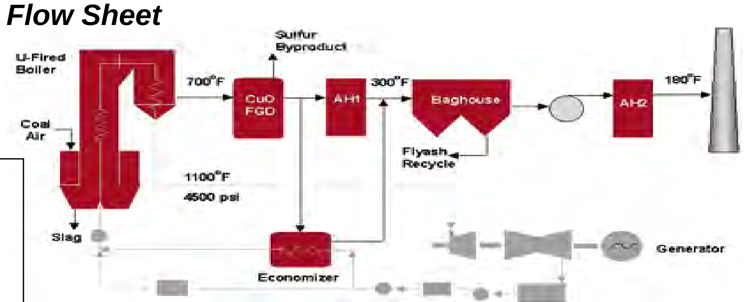
CFD



Spread Sheet

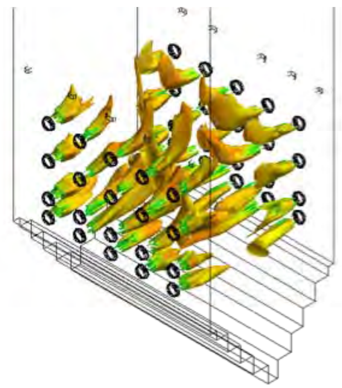


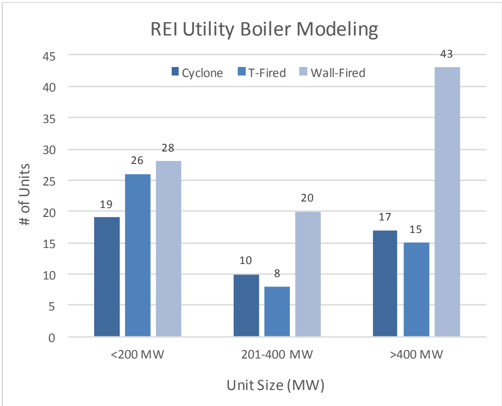
Flow Sheet



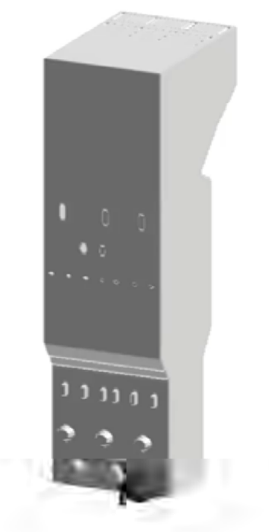
Boiler Models – “Digital Twin”

- >200 Utility Boilers Modeled (>70,000 MW of Capacity)
- Cyclone, Wall, Roof, Turbo & T-fired
- Coal, Oil, Gas, Biomass, Petcoke, TDF, Blends, Oxygen
- Stokers, OTSGs, Fluidized Beds, HRSGs
- Equipment and Process Design/Evaluation
- Impacts on performance, emissions, and balance of plant



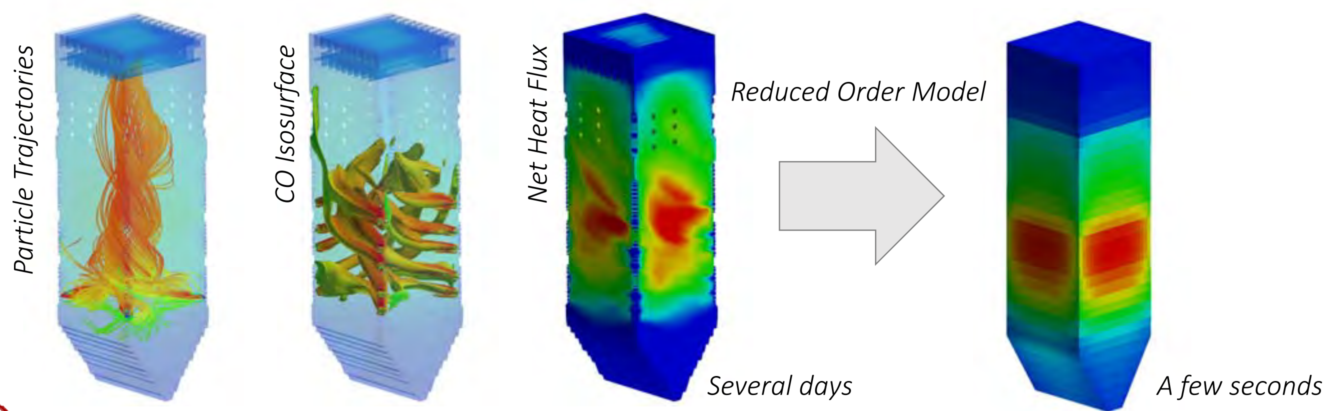


Combustion and Post-Combustion Control



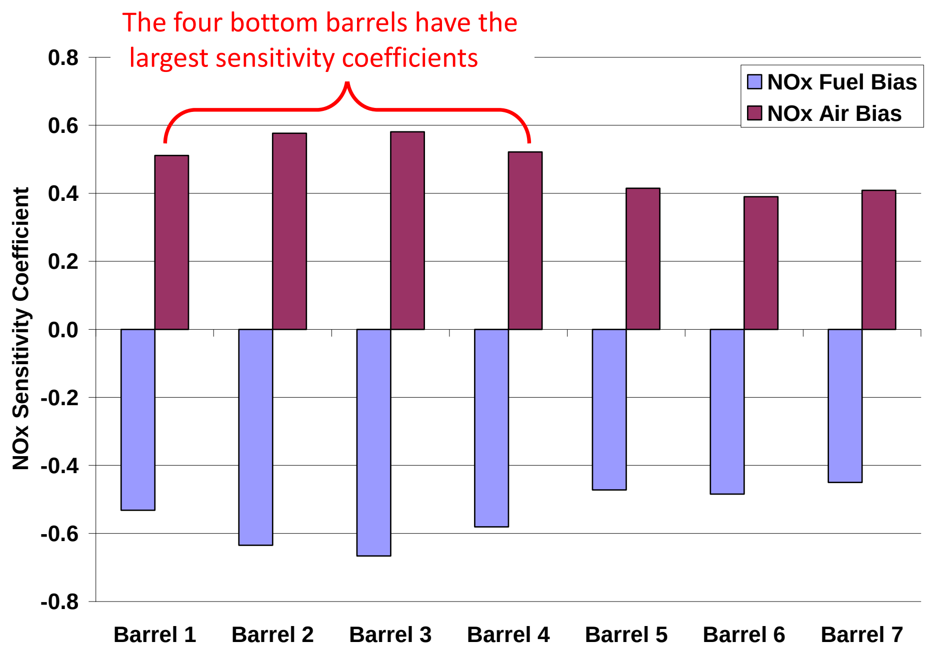
Reduced Order Models

- Tuned to CFD results
- ROM developed for fast calculation of the key parameters within model predictive control
- Visualization of the key results to demonstrate operation sensitivity



Burner Flow Control Sensitivity Project

NOx Sensitivity Coefficients

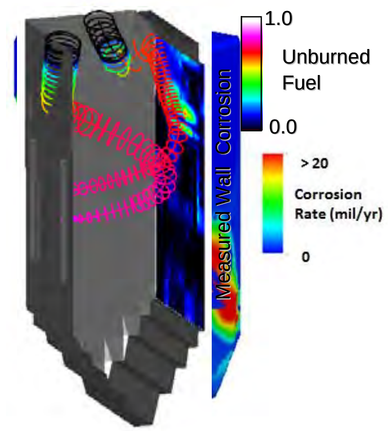


Burner Flow Control Sensitivity Project

Overall Conclusions

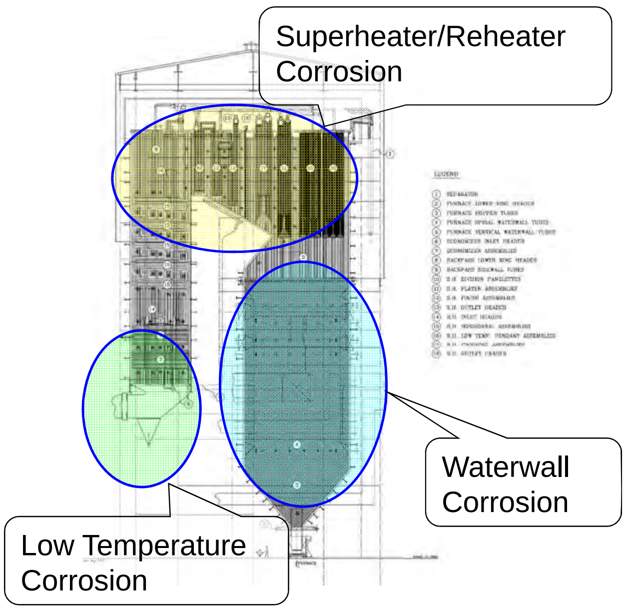
- For all cases studied, balanced air and fuel is not optimum
- SA distribution has larger impact on NOx and UBC than fuel distribution
- SCs for UBC in ash are larger than those for NOx
- OFA design/operation at least as important in reducing NOx emissions as burner to burner balancing
- Cyclone unit showed largest NOx sensitivity to SA flow, 600 MW T-Fired unit showed the least
- PA control is significantly more important than fuel flow control in opposed wall unit, for UBC control

Coal-Fired Boiler Corrosion



- **Efforts focused on impacts of firing system modifications, fuel changes, additive utilization, and operational optimization**
- **CFD-based modeling**
  - Correlation-based approach resulting from collaborations with EPRI and KEPRI
  - Integrated with REI's CFD software
- **Real-time monitoring**
  - Initially motivated by desire to validate modeling tools
  - Adaptation of an electrochemical approach in a collaborative effort with Corrosion Management (UK)

Coal Boiler Corrosion

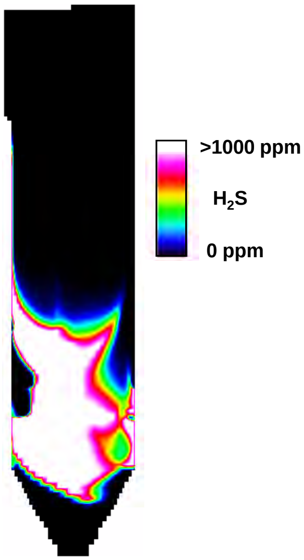


- High temperature corrosion of waterwalls
- High temperature corrosion of superheater/reheater
- Low temperature corrosion of economizer
- Low temperature corrosion of air preheater

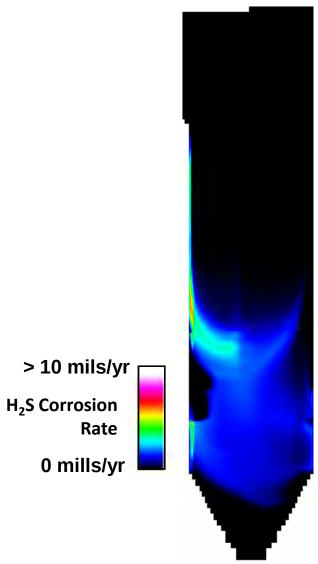
Corrosion Mechanisms and Modeling

- **Mechanisms**
  - **Tube wall interaction with gaseous phase constituents**
    - **Under oxidizing conditions metal loss is very slow and a protective Fe_3O_4 scale forms**
    - **Under reducing conditions, reducing sulfur species or fuel chlorine may disrupt the protective scale and metal loss occurs**
  - **Tube wall interaction with deposit**
    - **Pyrite (FeS_2) in coal is converted to FeS**
    - **Metal loss may occur in areas where unoxidized material, especially FeS, is deposited**
  - **Highest wastage rates are due to tube wall interaction with chlorine and FeS deposits – up to 100 mil/yr or more**
- **Modeling**
  - **Development of advanced corrosion correlations (models) for three corrosion mechanisms**
    - **Gas phase attack by reduced sulfur species such as H_2S**
    - **Deposition of unreacted fuel and resulting sulfur-based attack**
    - **Chlorine-based attack**
  - **Incorporation of these correlations into two-phase, reacting CFD code**
  - **Validation of the correlations through pilot-scale tests and CFD simulations**

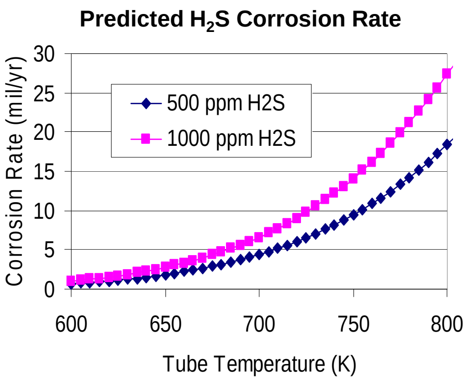
Predicted H_2S Corrosion



Predicted Side Wall H_2S Concentration

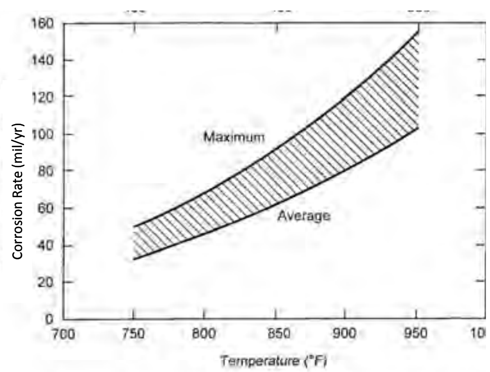


Predicted Side Wall H_2S Corrosion Rate

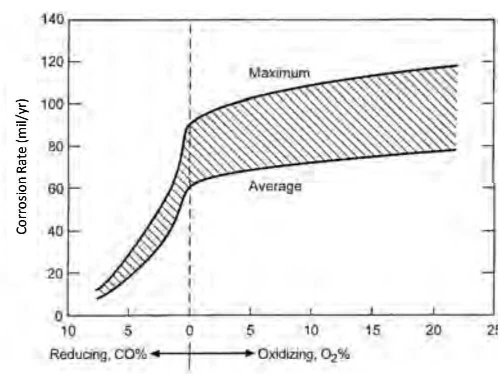


- H_2S corrosion alone cannot account for observed high corrosion rates (up to ~100 mil/yr), even at T_{tube} = 750 K

EPRI Experimental Work



Corrosion rate under FeS deposit as a function of temperature in a 1% O_2 environment.



Corrosion rate under FeS deposit as a function of gas O_2 and CO content at 450°C.

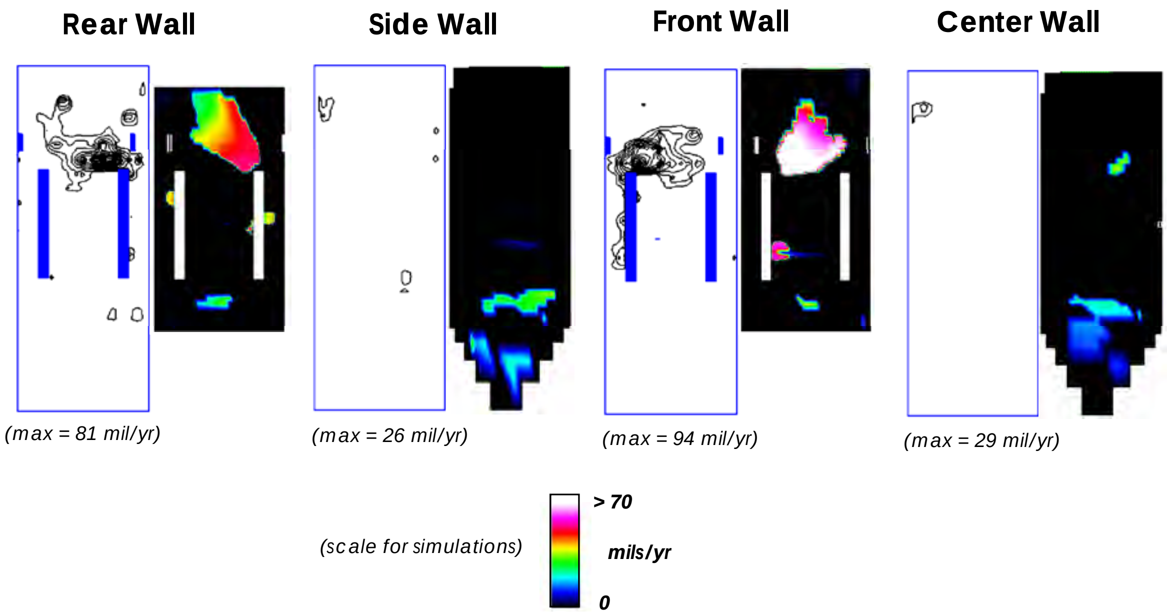
EPRI experimental work for metal under an FeS layer:

- Very high corrosion rates may occur
- Corrosion rates increase with temperature
- Corrosion rates are highest under oxidizing or mildly reducing conditions

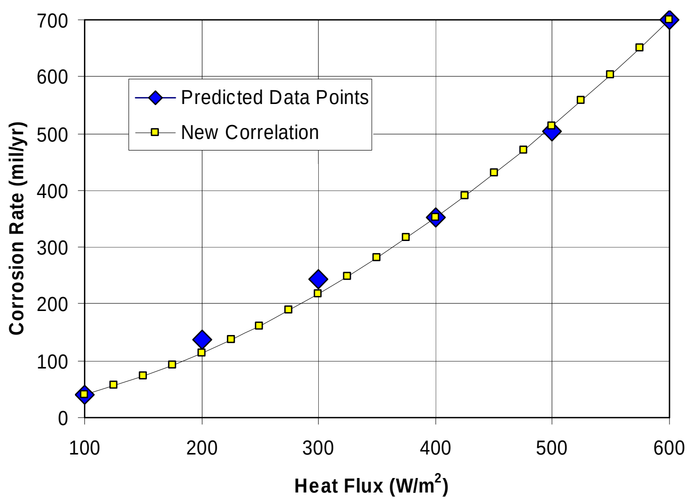
Corrosion Due to Deposition of FeS & Carbon

- Corrosion may occur where unoxidized FeS and coal are deposited
- Deposit based corrosion is associated with a high fraction of unoxidized material in deposit, high tube temperatures, high heat flux
- Experimental evidence indicates that the highest corrosion rates occur when unoxidized deposits are exposed to oxidizing flue gas

Validation Using Plant UT Data



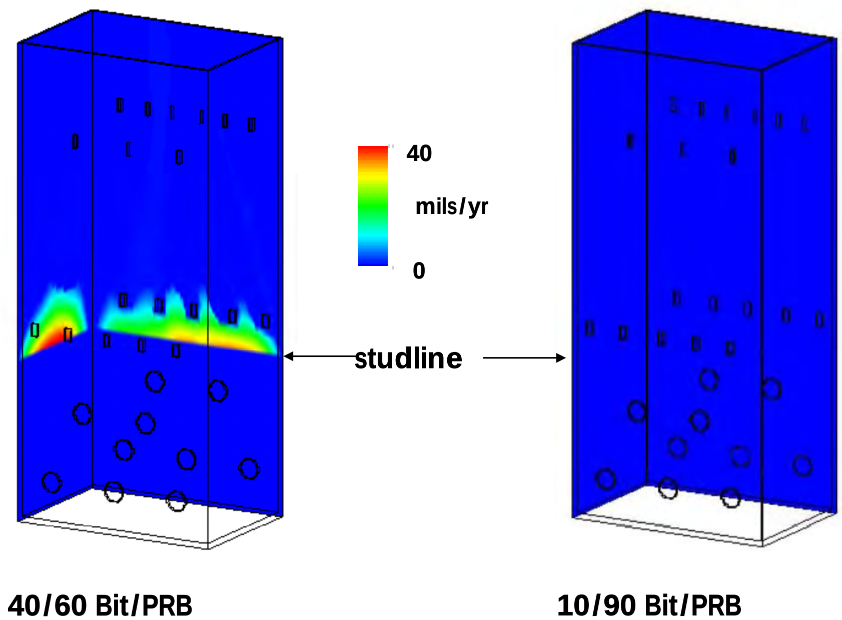
Chlorine Corrosion Correlation Tuning



Chlorine corrosion correlation vs. predicted data points of Davis et al (2000)

- New correlation predicted chlorine corrosion rate is comparable to the experimentally verified predictions of Davis et al (2002)

Cyclone-fired Boiler Chlorine Corrosion



- CFD predictions showed that chlorine based corrosion could be mitigated by keeping Cl content of blend < 0.1%
- Actual boiler operation showed tube failures immediately above the studline with 0.17% Cl in blend

Waterwall Corrosion in Coal Fired Boilers

- Gas phase H_2S Corrosion

$$CR_{H2S} = a \cdot f_1(T_m) \cdot f_2(Cr\%) \cdot f_3(H_2S) + b$$

- Deposition of Unoxidized Material

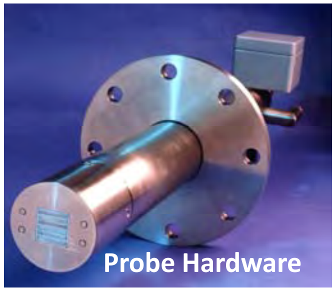
$$CR_{dep} = a \cdot f_1(dep) \cdot f_2(Stoichiometry) \cdot f_3(T_m) + b$$

- Chlorine-based Corrosion

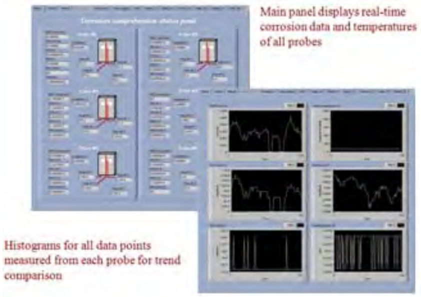
$$CR_{Cl} = a \cdot f_1(\%Cl) \cdot f_2(HeatFlux) \cdot f_3(T_m) + b$$

Corrosion Monitoring

EN Corrosion Monitoring

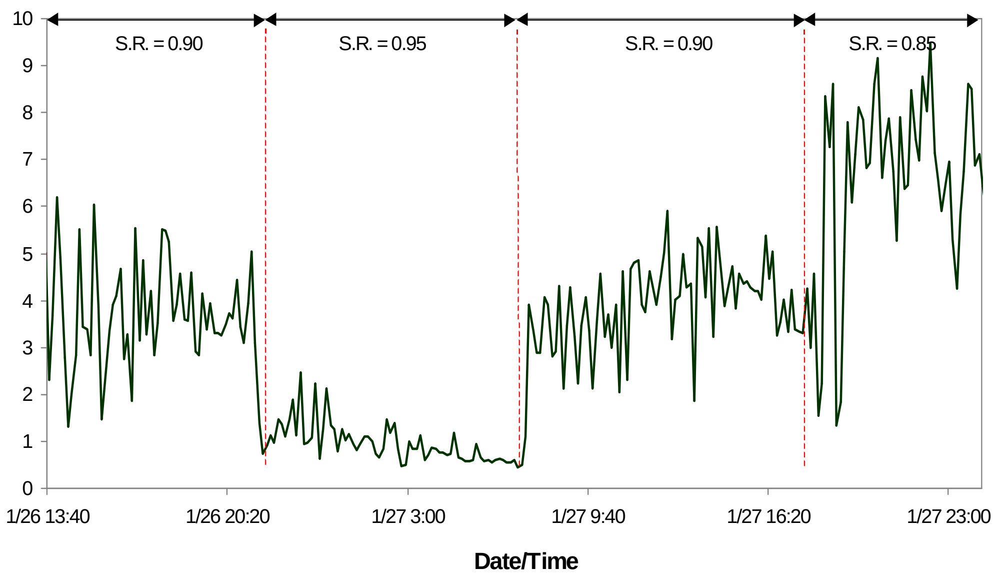


Data Acquisition

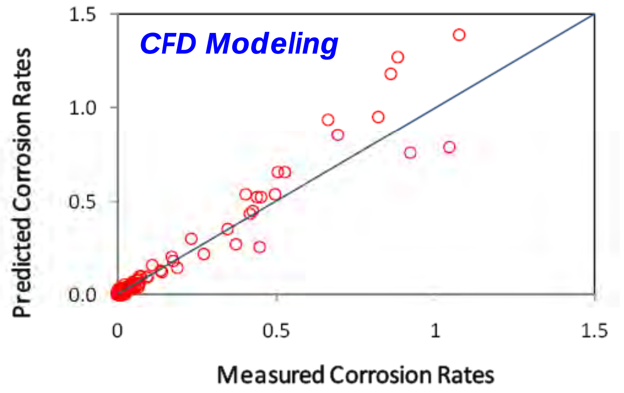


- 20 year collaboration with Dr. William Cox (Corrosion Management)
- EN Technology
- Advantages
  - Sensitive and Instantaneous response allowing real time measurement
  - Direct indication of corrosion
  - Quantitative measurement
  - Response can be related to corrosion mechanism, with aid of modeling
- Disadvantages
  - Quantity of data
  - Complexity of installation

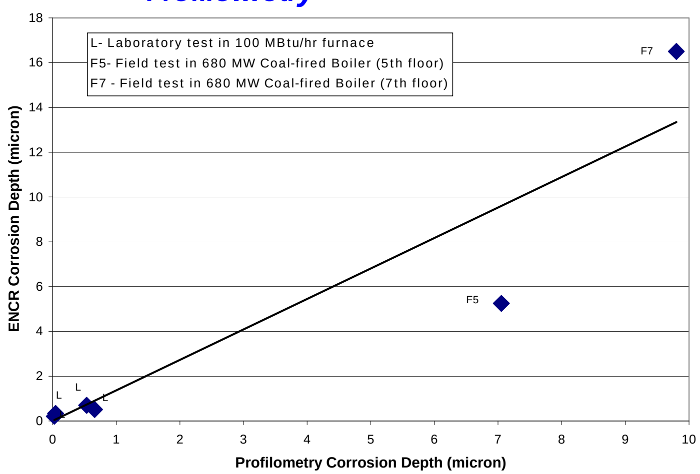
Response of corrosion sensors to step changes in SR at UofU's U-furnace

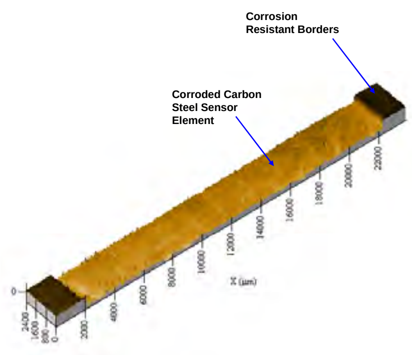


Quantitative Validation

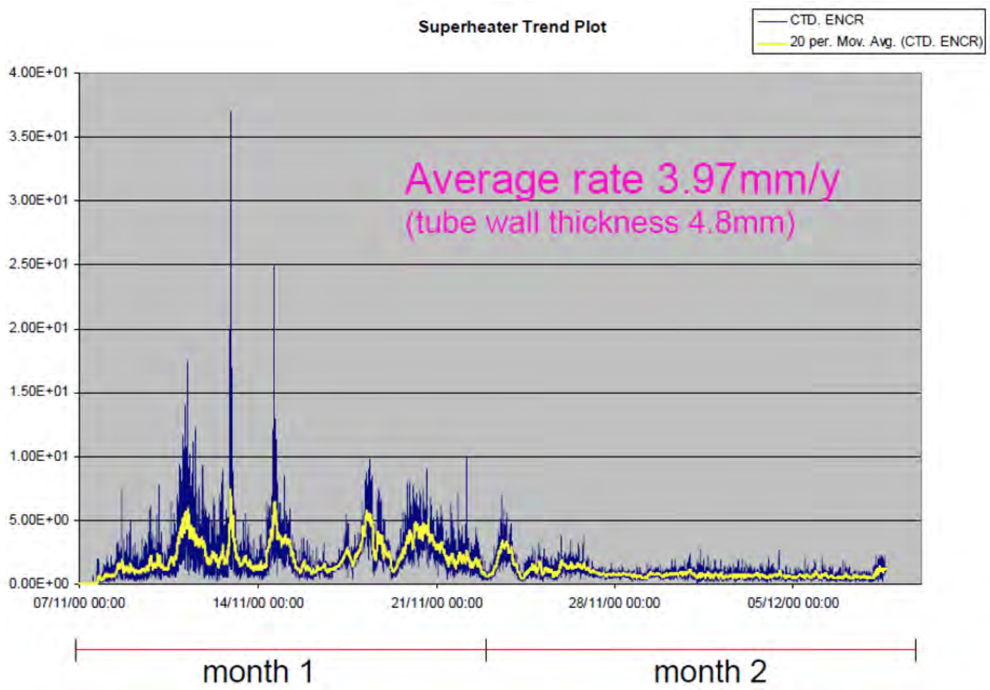


Profilometry



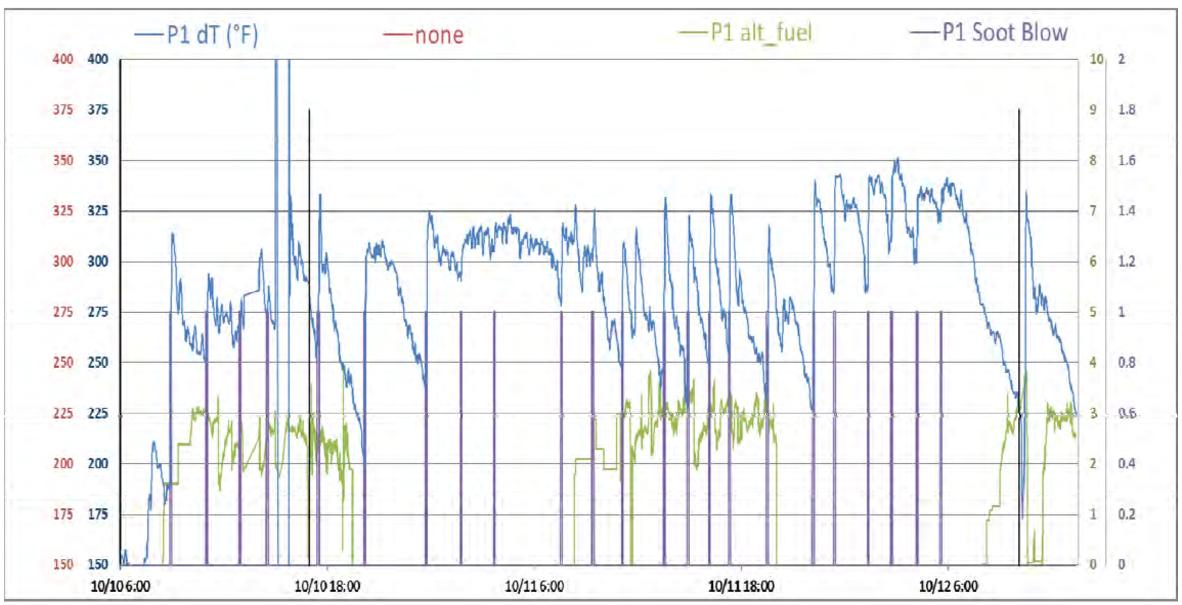


Superheater Corrosion



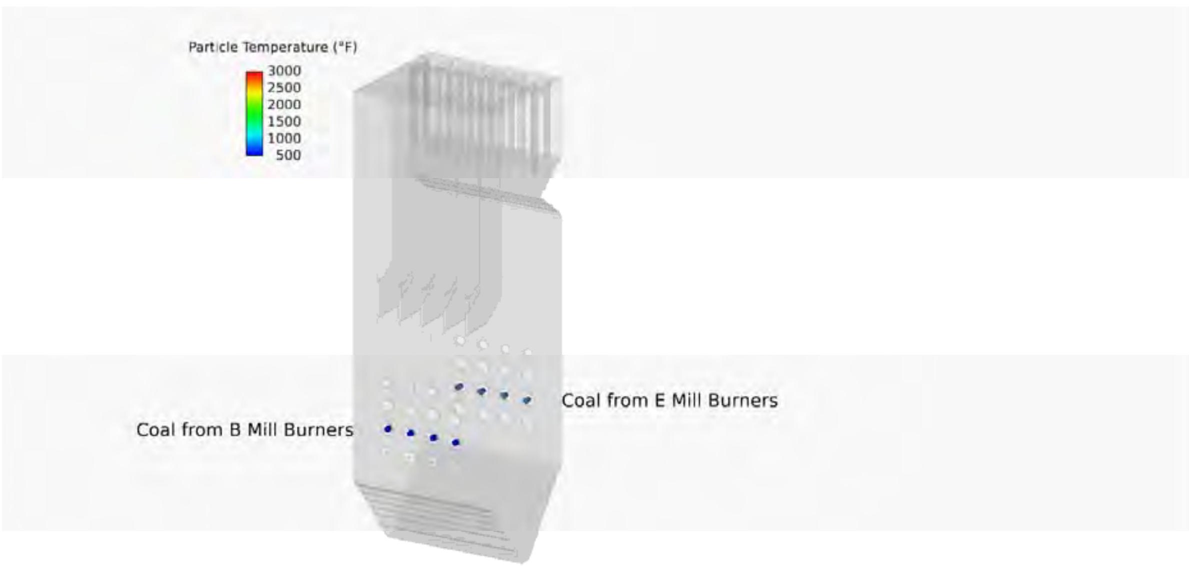
Fouling/Slagging Monitoring and Modeling

Effects of co-firing (green) and soot blowing on deposition on probe surfaces



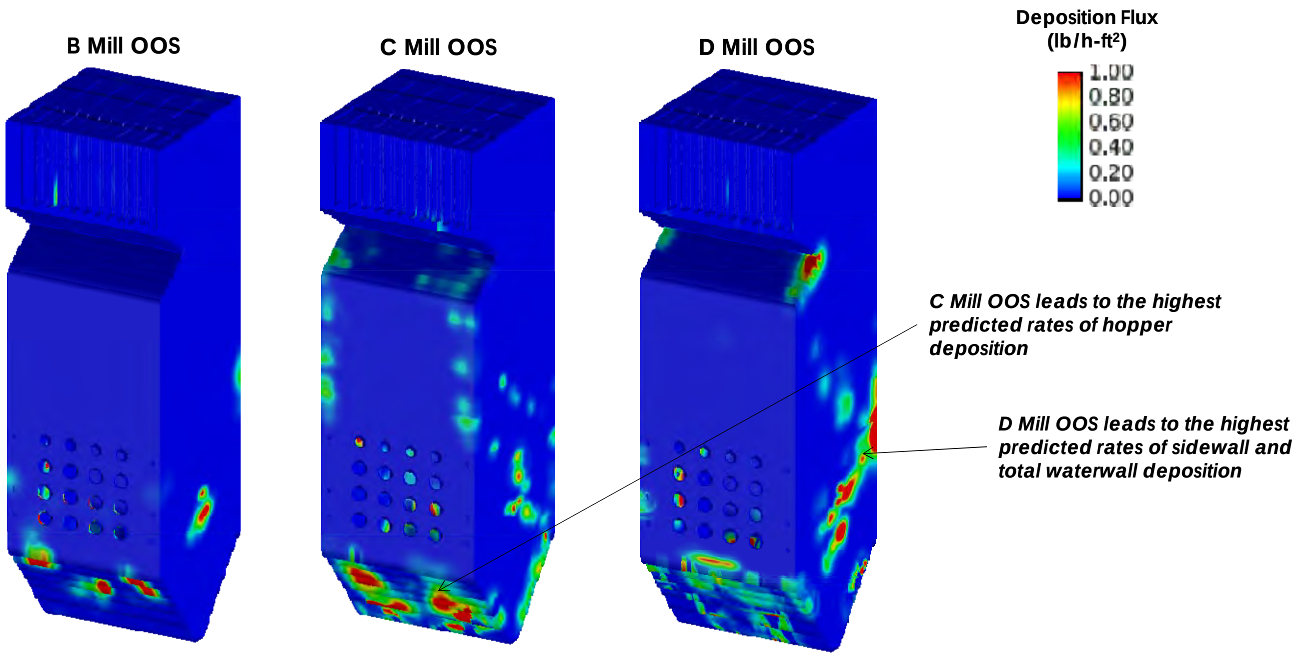
Coal Particle Trajectories

Effects of Mill OOS



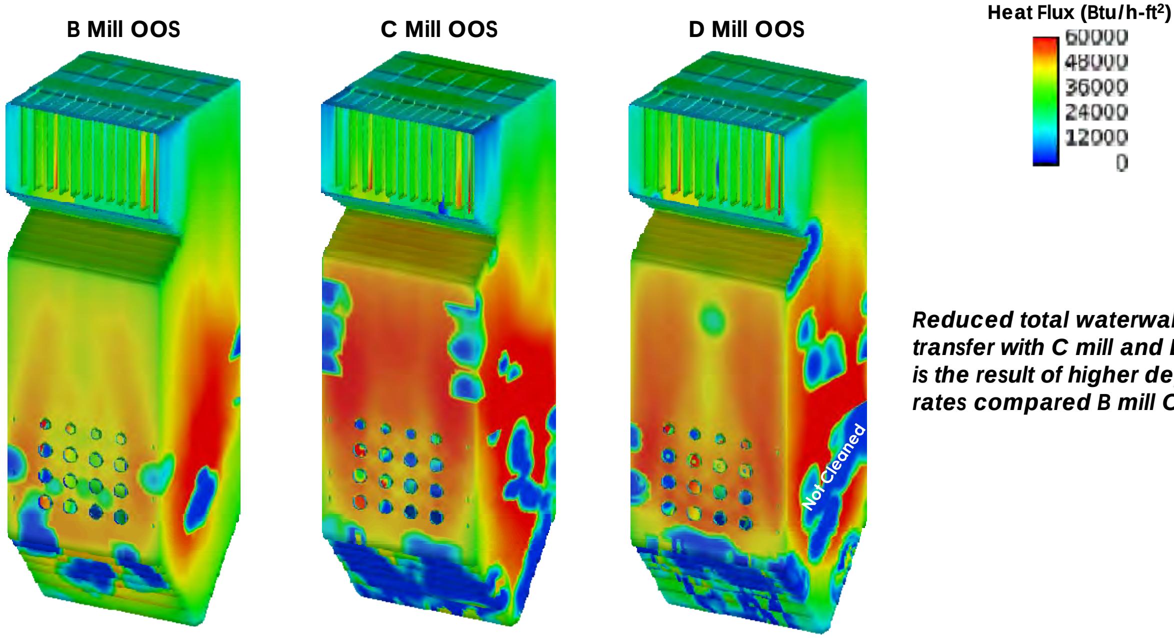
Particulate Deposition Flux

Effects of Mill Configuration



Net Heat Flux

Effects of Mill Configuration



Reduced total waterwall heat transfer with C mill and D mill OOS is the result of higher deposition rates compared B mill OOS

Office of Fossil Energy

Energy Department Selects Additional Advanced Combustion Projects to Receive $3.3M

AUGUST 9, 2018

BEPC Leland Olds Station
ND Lignite

2. *Combustion Performance and Emissions Optimization through Integration of a Miniaturized High-Temperature Multi-Process Monitoring System* – **Reaction Engineering International** (Murray, UT) will design, prototype, and demonstrate a monitoring system for boiler condition management. The key objectives are to miniaturize the design; combine quantitative heat flux, deposition rate, relative surface temperature, and metal wastage measurements into a single sensor; and integrate monitoring output with a plant distributed control system (DCS). The project will culminate with a demonstration and characterization of corrosion, deposition, heat flux, and temperature at multiple locations within a full-scale pulverized coal-fired power plant.

PacifiCorp Hunter Plant
Bituminous Coal

3. *Development of Miniaturized High-Temperature Multi-Process Monitoring System* – **Reaction Engineering International** (Murray, UT) will design, prototype, and demonstrate a miniaturized monitoring system, which can provide a real-time indication of tube surface conditions at key locations in a coal combustion boiler. The prototype system will be tested in pilot-scale combustion environments, and advanced profilometry techniques will validate accuracy of the resulting corrosion data. The project will culminate with a system-level demonstration of the miniaturized, self-regulating sensors at a full-scale pulverized-coal-fired plant.

Basin Electric Power Cooperative
Leland Olds Station

BASIN ELECTRIC POWER COOPERATIVE
A Touchstone Energy® Cooperative

Jamey Backus, Plant Manager

- Located near Stanton, North Dakota
- Two lignite-fired units with total generating capacity 669 MW
  - Unit 1 – 222 MW opposed wall-fired PC
  - Unit 2 – 447 MW opposed wall-fired cyclone

PacifiCorp – Hunter Plant

PACIFICORP

- Located near Caste Dale, Utah
- Three units with total generating capacity 1,320 MW

Project Objectives

- Primary objective: Develop and demonstrate a miniaturized high temperature multi-process* monitoring system that can provide a real-time indication of boiler condition in a full-scale lignite-fired boiler

*metal loss rates, heat flux, metal surface temperature, ash deposit thickness and ash deposition

- Specific objectives
  - Miniaturize sensor design for easy installation in a boiler without waterwall structure change or long shut-down
  - Design sensor body to avoid active temperature maintenance for sensor elements
  - Re-design the signal conditioning unit to increase resolution
  - Implement the signal acquisition, signal processing, and wireless data communication module onto a single electronic board to reduce cost and power consumption
  - Develop quantitative correlations for heat flux and deposition rate based on the existing data
  - Validate the correlations and the system in a pilot-scale combustor and demonstrate in a full-scale lignite-firing utility power plant
  - Develop and implement logic algorithms for the plant DCS to improve boiler energy efficiency, soot blowing, and NOx emissions by automated control of boiler operations

Summary

- Coal is expected to remain a significant contributor to US power generation for the next decade
- Coal boilers are required to ramp more regularly to accommodate inherent variability in renewable generation sources
- Transient operation presents challenges to boiler performance and maintenance
- Condition Based Monitoring (CBM) provides a key role to maintain/improve unit reliability and efficiency
- CBM requires integration with advanced process control systems to realize potential for optimization
- New R&D programs are in place to demonstrate practical use of a miniaturized MPMS for real-time CBM and combustion optimization

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