Advance Optimization Methods for NOx Reduction and Boiler Optimization

Neural Networks and Beyond

NOx Roundtable
Charlotte, North Carolina
January 23-24, 2006

NeuCo
Generating Value®

Industry Challenges

- Asset life extended far beyond designed life
- Systems getting more complex
- Unit operations beyond design conditions
- Margins slimmer, markets more demanding
- Brain-drain is rampant

Traditional Tools

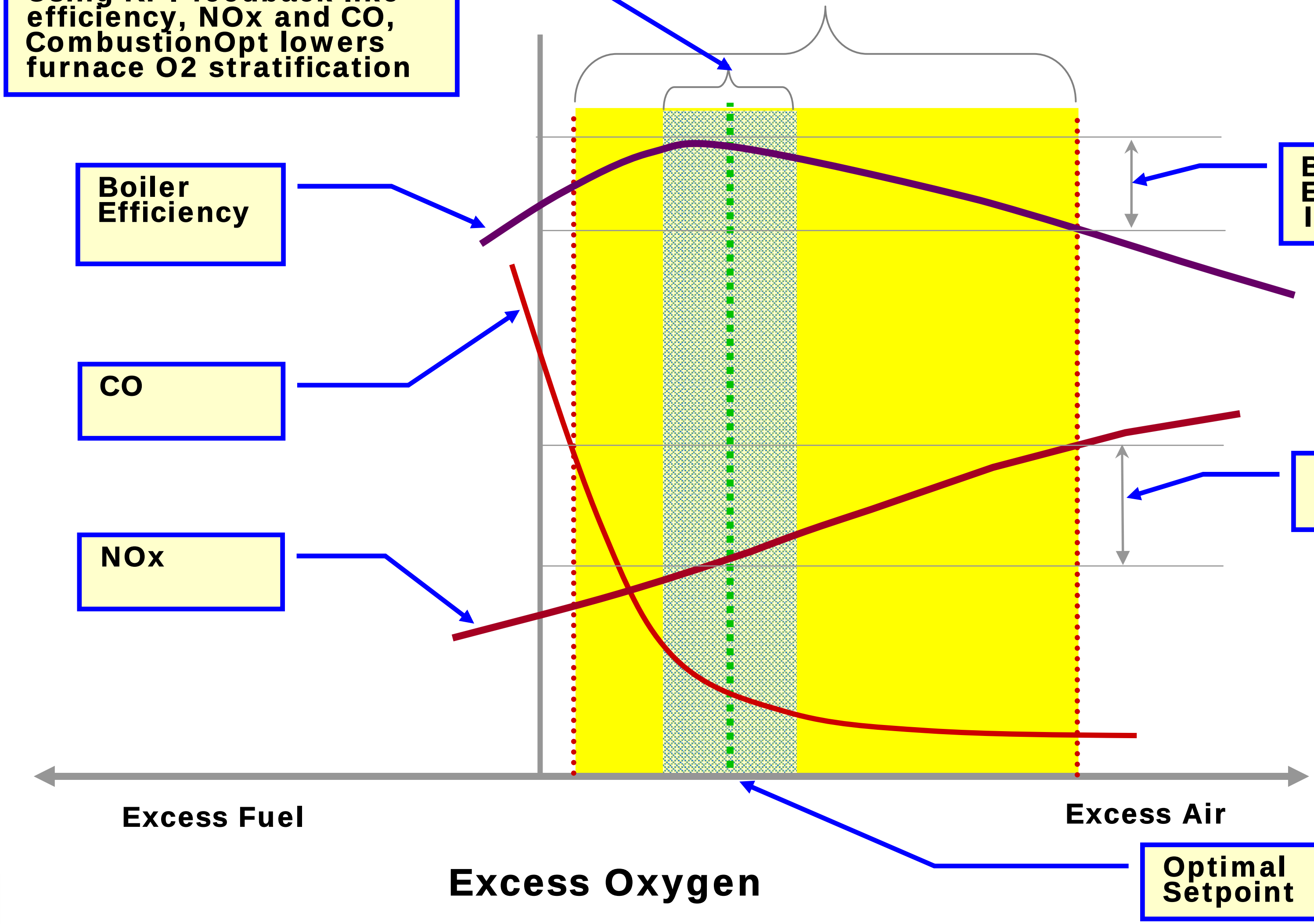
- Systems:
  - Instrumentation and Controls
  - Performance Monitoring
  - Advanced Sensors and Detectors
- Infrastructures:
  - Enterprise Resource Planning (ERP) Systems
  - Computerized Maintenance Management Systems (CMMS)
  - Historians and Portals
- Methodologies:
  - Six Sigma
  - Key Performance Indicators (KPI)
  - Earned Value Analysis (EVA)

Gaps

- Data
  - Too much of it and most of it is redundant
- Information
  - Lacks context and any understanding of implications
- Knowledge
  - Too late or too coarse-grained to be useful

Closing the gaps requires ***real-time analytics*****!**

Combustion Optimization



Using KPI feedback like efficiency, NOx and CO, CombustionOpt lowers furnace O2 stratification

Typical operating range

Boiler Efficiency

Boiler Efficiency Increase

CO

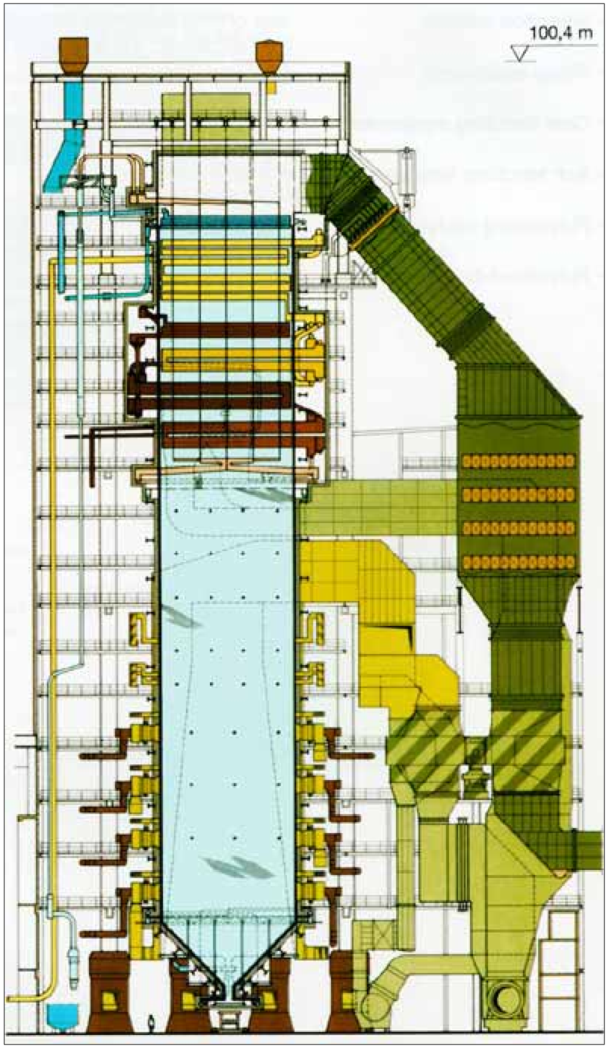
NOx

NOx Reduction

Optimal Setpoint

Benefits of Neural Network Combustion Optimization

- Lower NOx (5-25%) with 15% average
- Improved heat rate (0.25-1.5%)
- Better control of CO, LOI, and opacity
- Enhanced operator performance and more consistent operations
- Higher availability through advanced diagnostics
- Lower post-combustion operating costs
- Capital preservation (potential avoidance of SCR or SNCR)



The Evolution of Combustion Optimization Installations

- 1st Gen – Early 1980's
  - Design of Experiments in Advisory
  - 80+ Installed, None Still Running
- 2nd Gen – Early 1990's
  - Neural in Open-Loop ("Advisory" systems)
  - 40+ Installed, Few Still Running
- 3rd Gen –Mid 1990's
  - Neural in Closed-Loop
  - 40+ Installed, Half Still Running
- 4th Gen – Late 1990's
  - Neural Closed-Loop with On-Line Learning
  - 40+ Installed, All Still Running
- 5th Gen – Current
  - Multiple optimizers using different methods for different problems
  - Integration of the optimizers with one another and business objectives
  - Being currently demonstrated at several plants

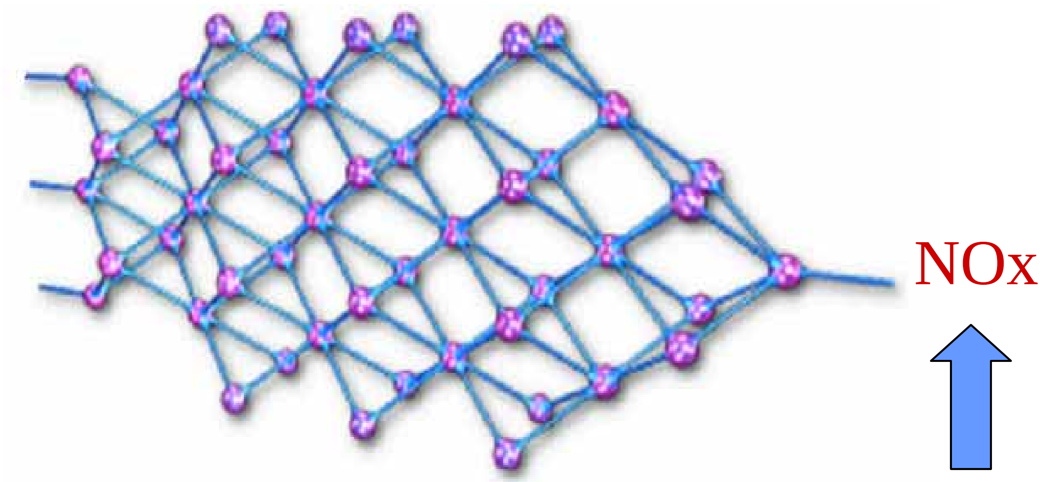
Neural Network-Based Represents State-of-the-Art Combustion Optimization

- Insufficient direct feedback to control the combustion process better through conventional DCS methodology
- Highly non-linear and complex processes
- Process changes continuously based on burners, damper and mill issues
- Normal power plant equipment degradation and maintenance cycles and associated process changes
- Fuel changes, blending and fluctuations
- Changing and seasonal environmental regulations

What is a Neural Network?

- Mathematical system that receives real-time operating data (inputs) and empirically learns through experience or experiment
- What is learned is the interrelationships between the input values and the objective function or goal
- Mathematical system emulates human's ability to recognize patterns and learn relationships from information received from input sensors
  - Biological NN: sight, hearing, touch, smell, & taste for human objectives
  - Artificial NN: state/manipulated variables for boiler performance objectives

Neural Networks As Applied to Combustion Optimization



Excess O_2

Ambient Conditions

Secondary Air Biases

Feeder Biases

Primary Air Biases

NOx

Controllable and
Non-Controllable Parameters (state variables)

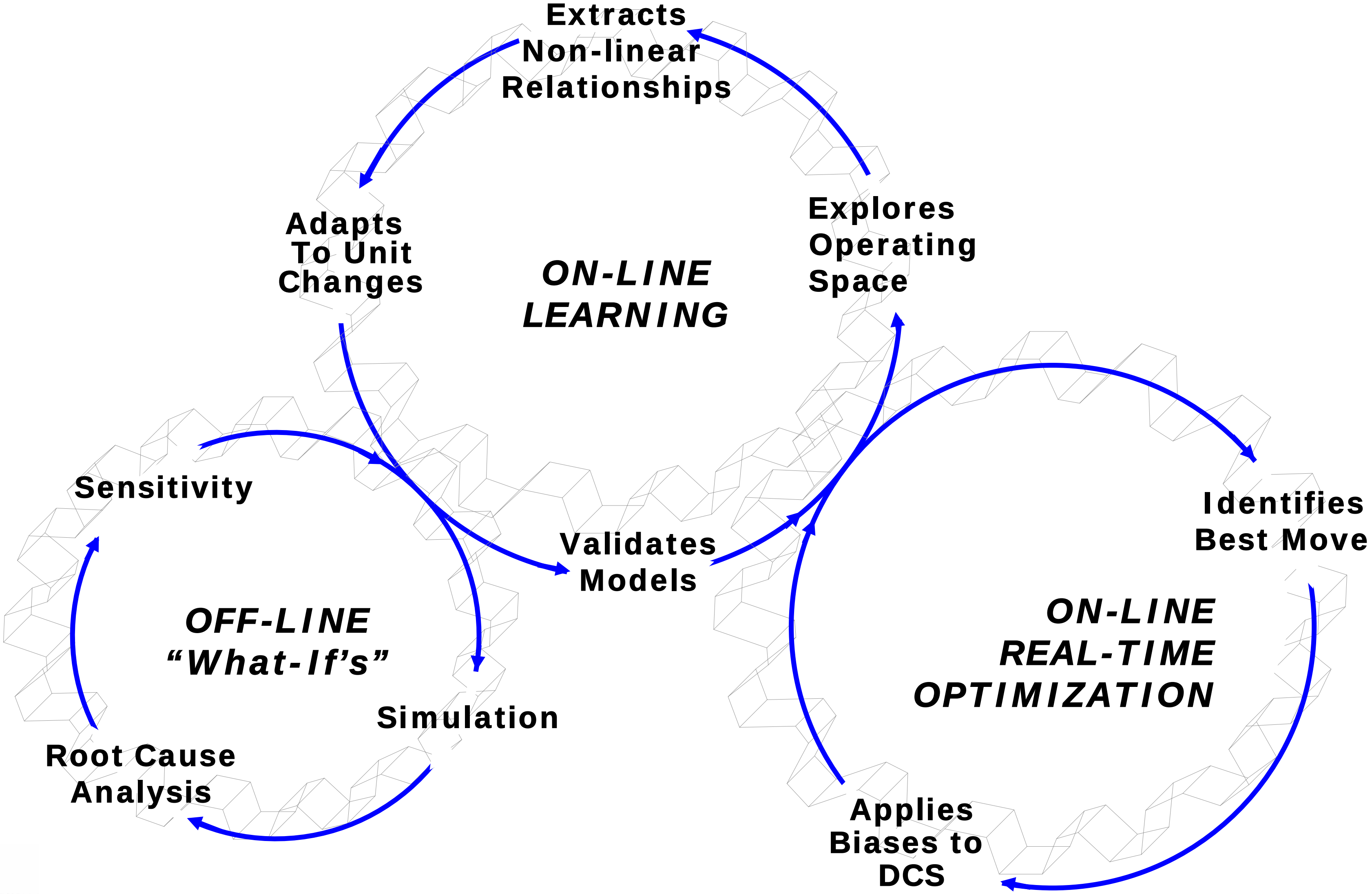
Objective

NOx depends upon (O_2, Ambient Conditions, Biases, etc…..)

How Does a Neural Network Train?

- Internal parameters (weights) are adjusted to minimize the error between actual data and the model predictions
- During training phase, error is calculated at each point in time and connection weights at each node adjusted using back propagation
- As the model's experience builds, so does model accuracy
- Statistical model validation is crucial for overcoming intrinsic ANN susceptibility to local minima/maxima

How On-line Learning Works



Extracts Non-linear Relationships

Adapts To Unit Changes

ON-LINE LEARNING

Explores Operating Space

Sensitivity

Validates Models

Identifies Best Move

OFF-LINE “What-If’s”

Simulation

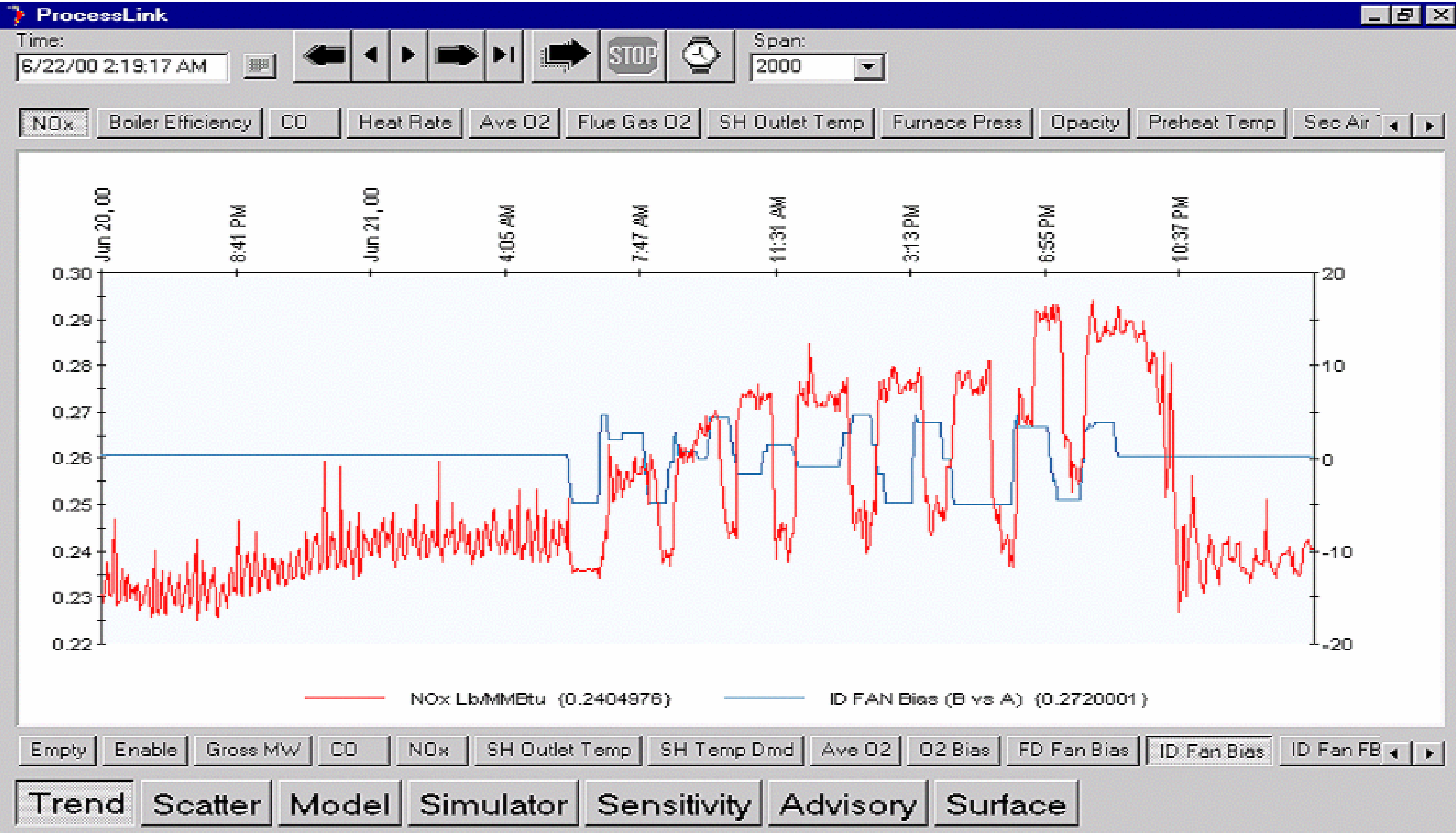
ON-LINE REAL-TIME OPTIMIZATION

Root Cause Analysis

Applies Biases to DCS

Automated Parametric Testing

Cause and Effect Relationships – Effect of ID Fan Bias (Blue) on NOx (Red)



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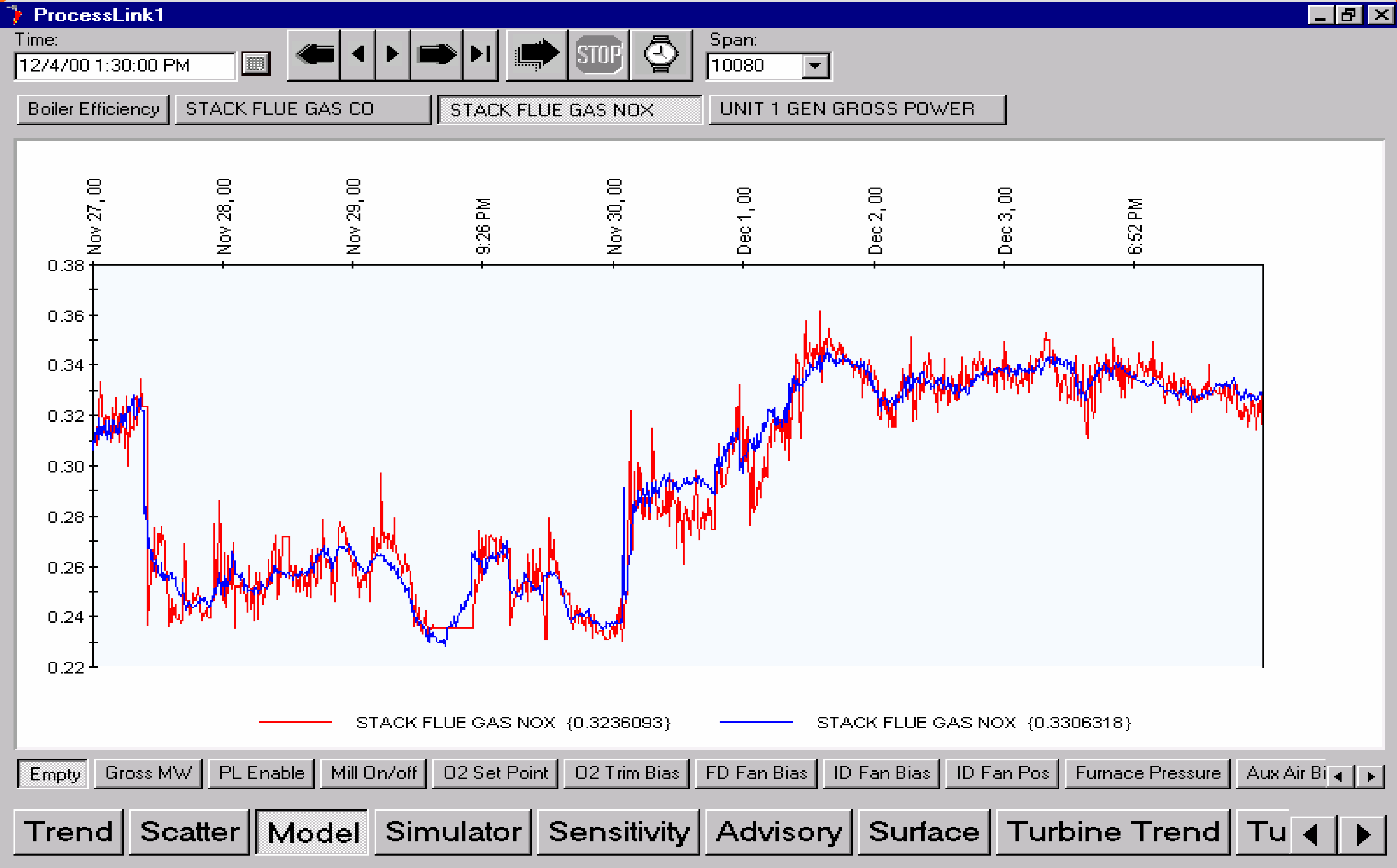
Neural Network Model Development

Data Visualization indicates model accuracy



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🟥 STACK FLUE GAS NOX (0.3236093)

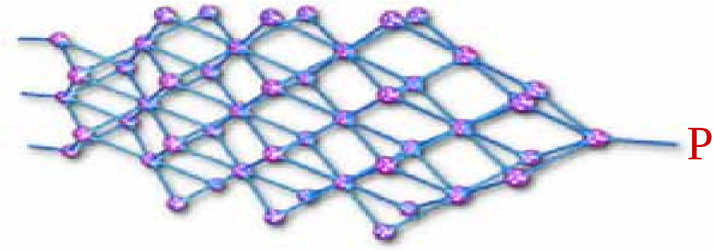
🟦 STACK FLUE GAS NOX (0.3306318)

Neural Networks are Adaptive and Update Themselves Automatically

- Neural Nets continually update their regression coefficients (weights) using the most recent plant data

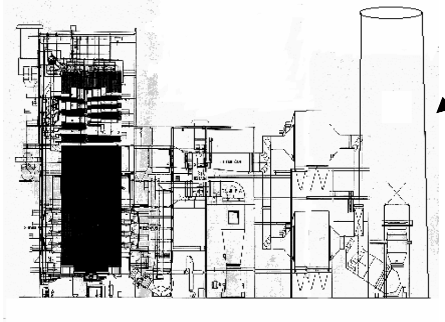
Model

Boiler state variables
Ambient Conditions
MVs (biases & trims)



Predicted NOx

Plant

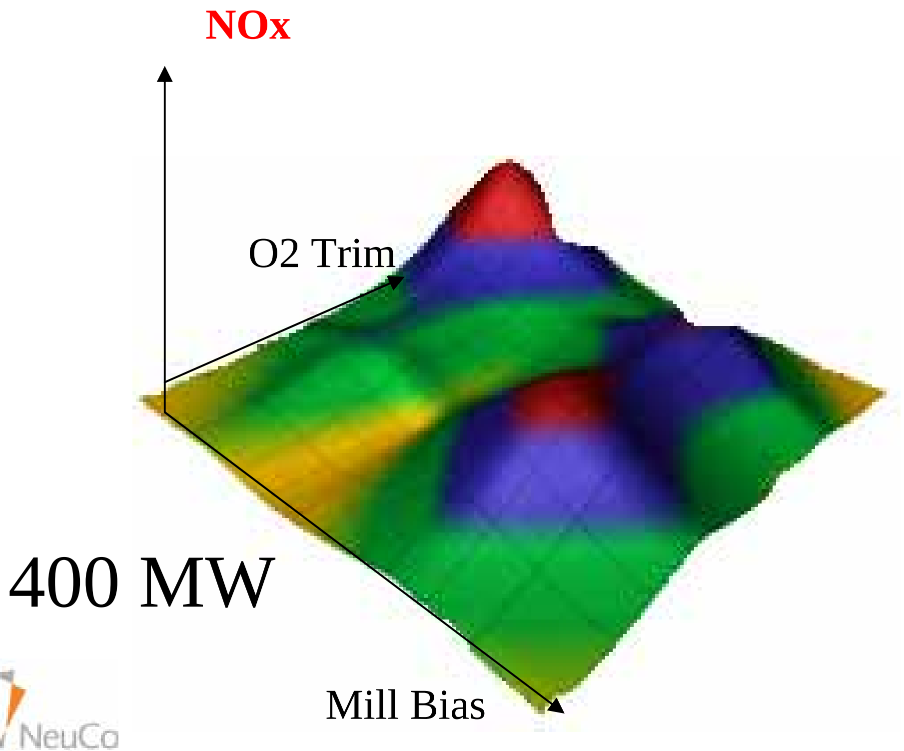


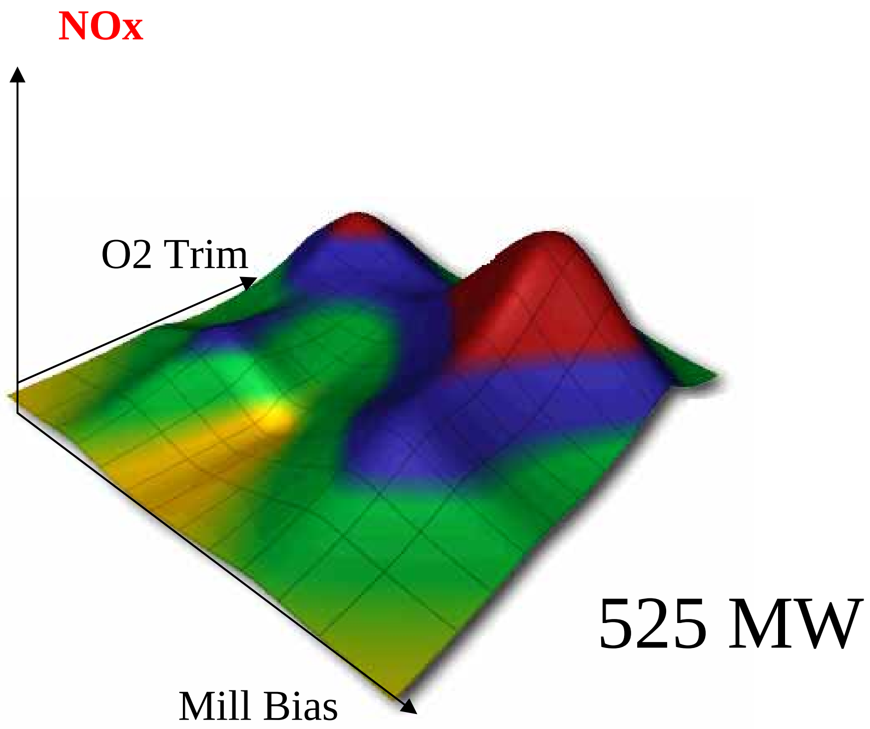
Actual NOx from CEMS

Error = Actual NOx – Predicted NOx

Combustion Optimization Response Surfaces

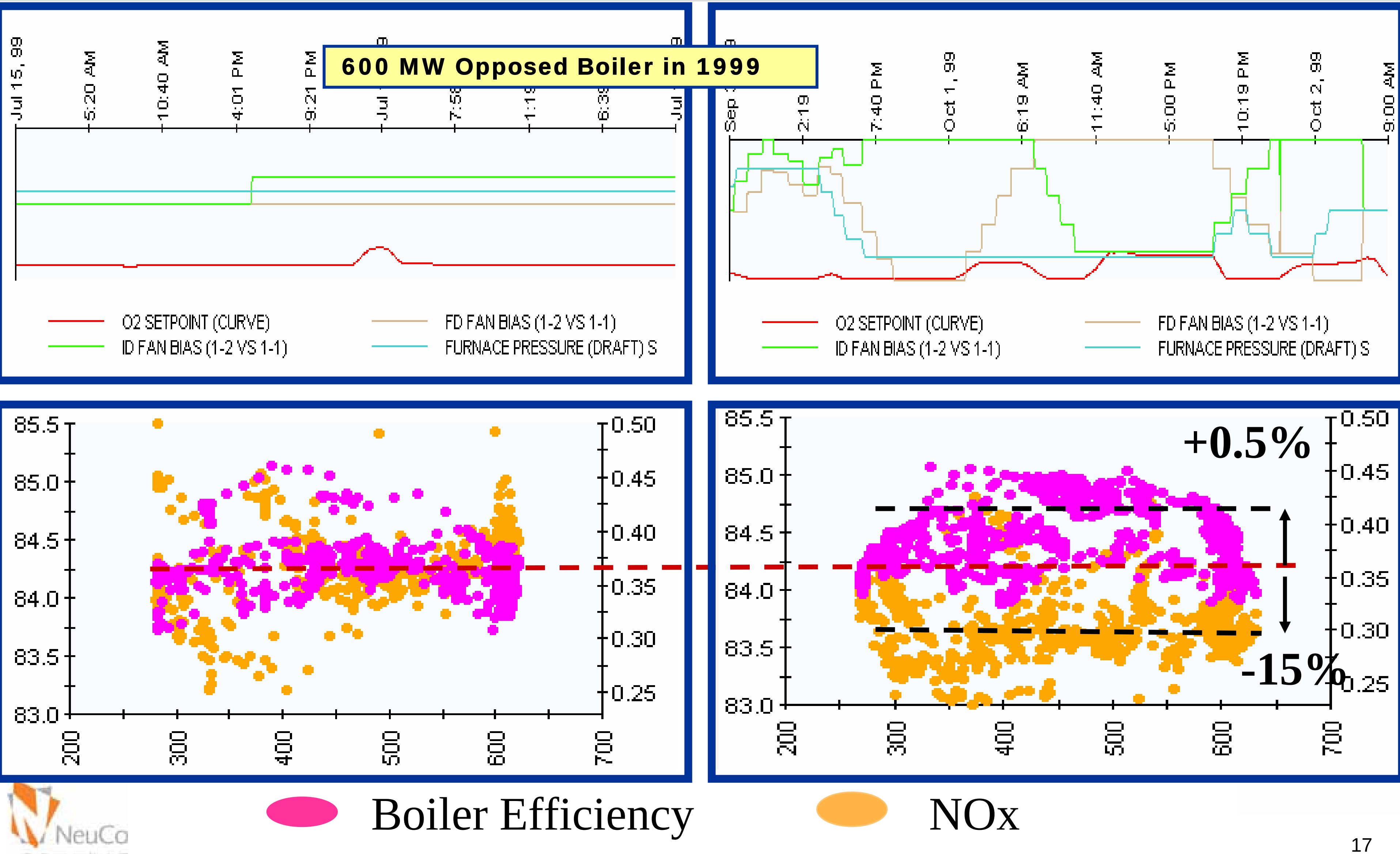
- Typical system has 20-40 inputs to predict each objective (NOx, Efficiency, etc)
- Complex relationships – Output varies with time and input changes
- Example – Effects of Mill Biases and O2 varies as load changes



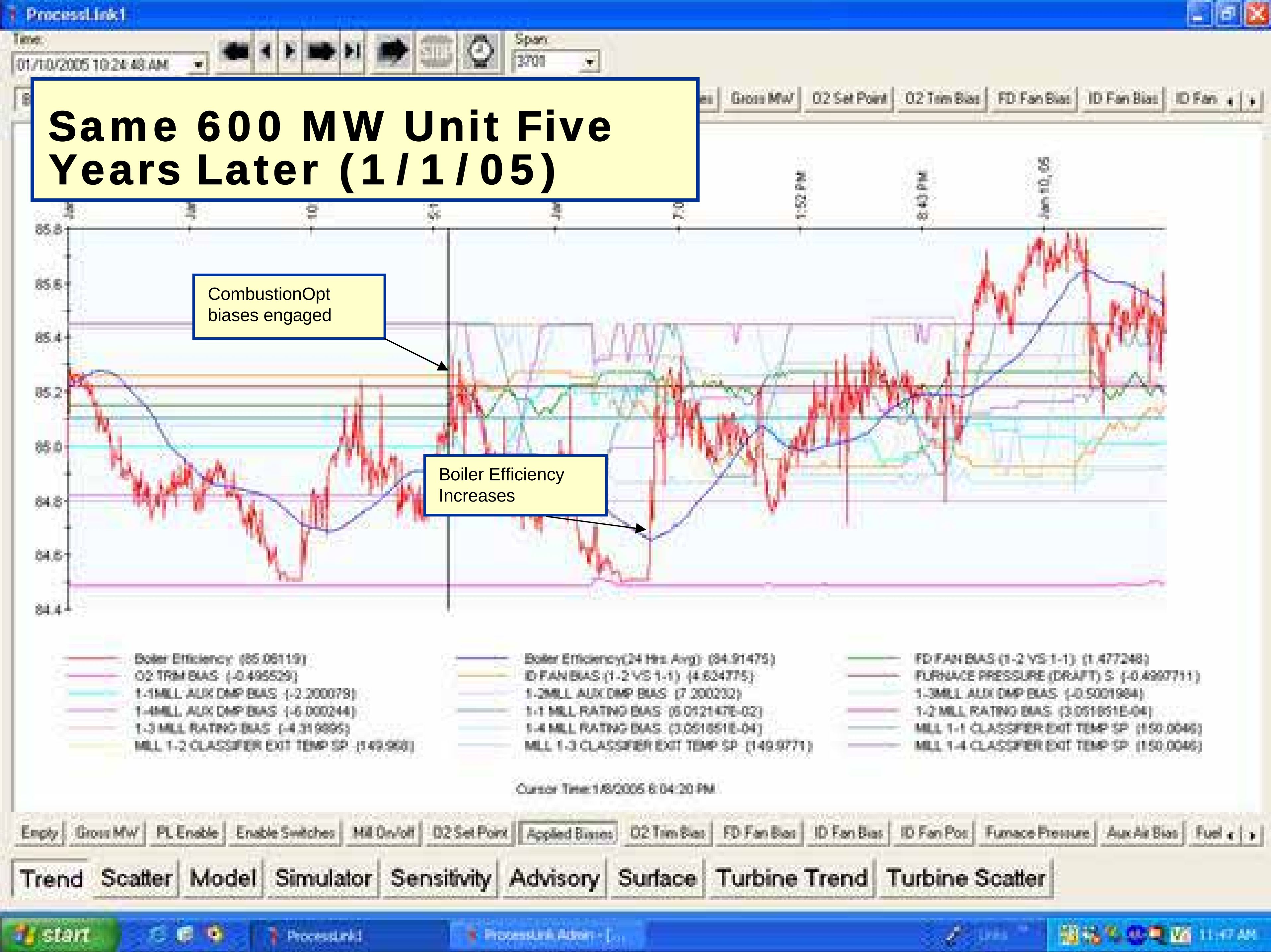


Example of NOx and Efficiency Improvement

600 MW Opposed Boiler in 1999



Same 600 MW Unit Five Years Later (1/1/05)



CombustionOpt biases engaged

Boiler Efficiency Increases

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Boiler Efficiency (85.06119)
O2 TRIM BIAS (-0.496529)
1-1MILL AUX DMP BIAS (-2.200078)
1-4MILL AUX DMP BIAS (-6.000244)
1-3 MILL RATING BIAS (-4.319895)
MILL 1-2 CLASSIFIER EXIT TEMP SP (149.968)
Boiler Efficiency(24 Hrs Avg) (84.91475)
ID FAN BIAS (1-2 VS 1-1) (4.624775)
1-2MILL AUX DMP BIAS (7.200232)
1-1 MILL RATING BIAS (6.012147E-02)
1-4 MILL RATING BIAS (3.051851E-04)
MILL 1-3 CLASSIFIER EXIT TEMP SP (149.9771)
FD FAN BIAS (1-2 VS 1-1) (1.477248)
FURNACE PRESSURE (DRAFT) S (-0.4997711)
1-3MILL AUX DMP BIAS (-0.5001984)
1-2 MILL RATING BIAS (3.051851E-04)
MILL 1-1 CLASSIFIER EXIT TEMP SP (150.0046)
MILL 1-4 CLASSIFIER EXIT TEMP SP (150.0046)

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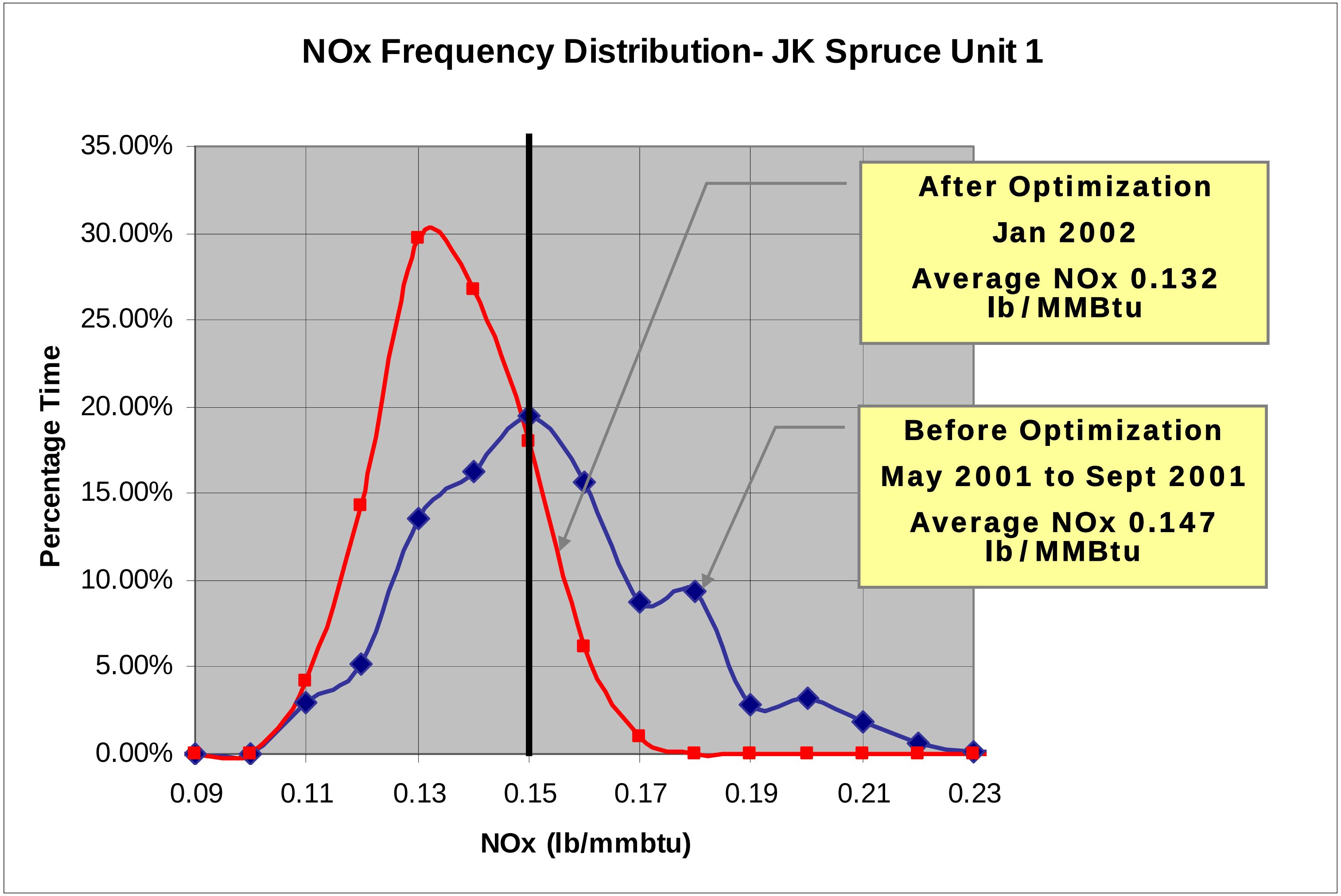
Effects of Combustion Optimization on 600 MW Coal-Fired Tangential Boiler


NOx Frequency Distribution- JK Spruce Unit 1

After Optimization

Jan 2002

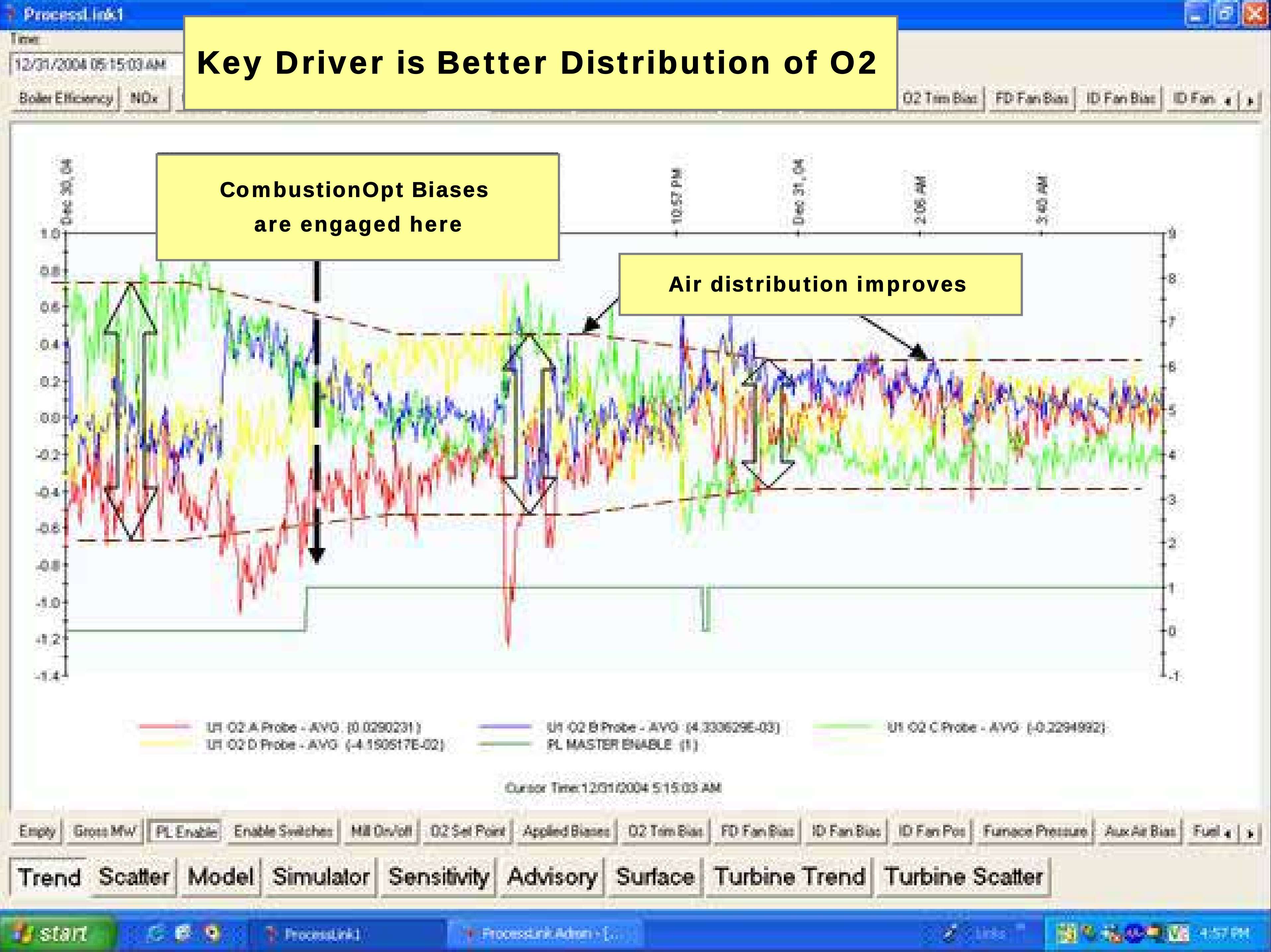
Average NOx 0.132 lb / MMBtu

Before Optimization

May 2001 to Sept 2001

Average NOx 0.147 lb / MMBtu

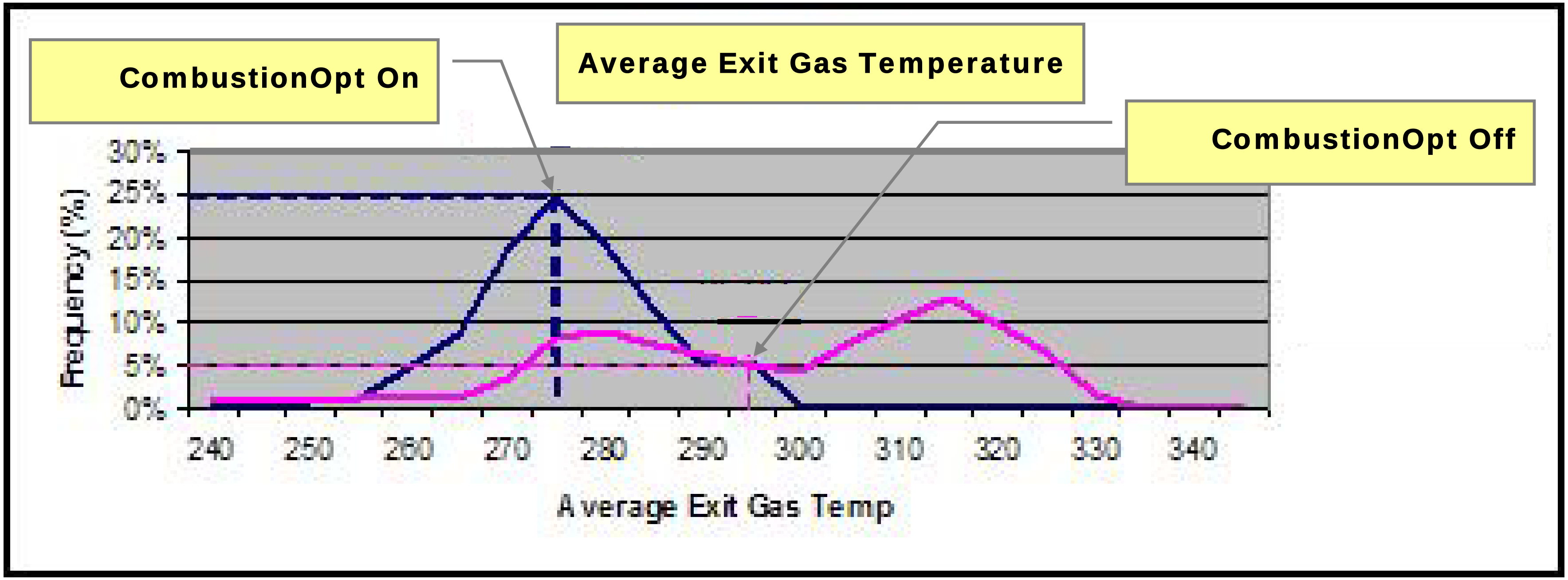
Key Driver is Better Distribution of O2



CombustionOpt Biases are engaged here

Air distribution improves

Temperatures Affect NOx & Efficiency

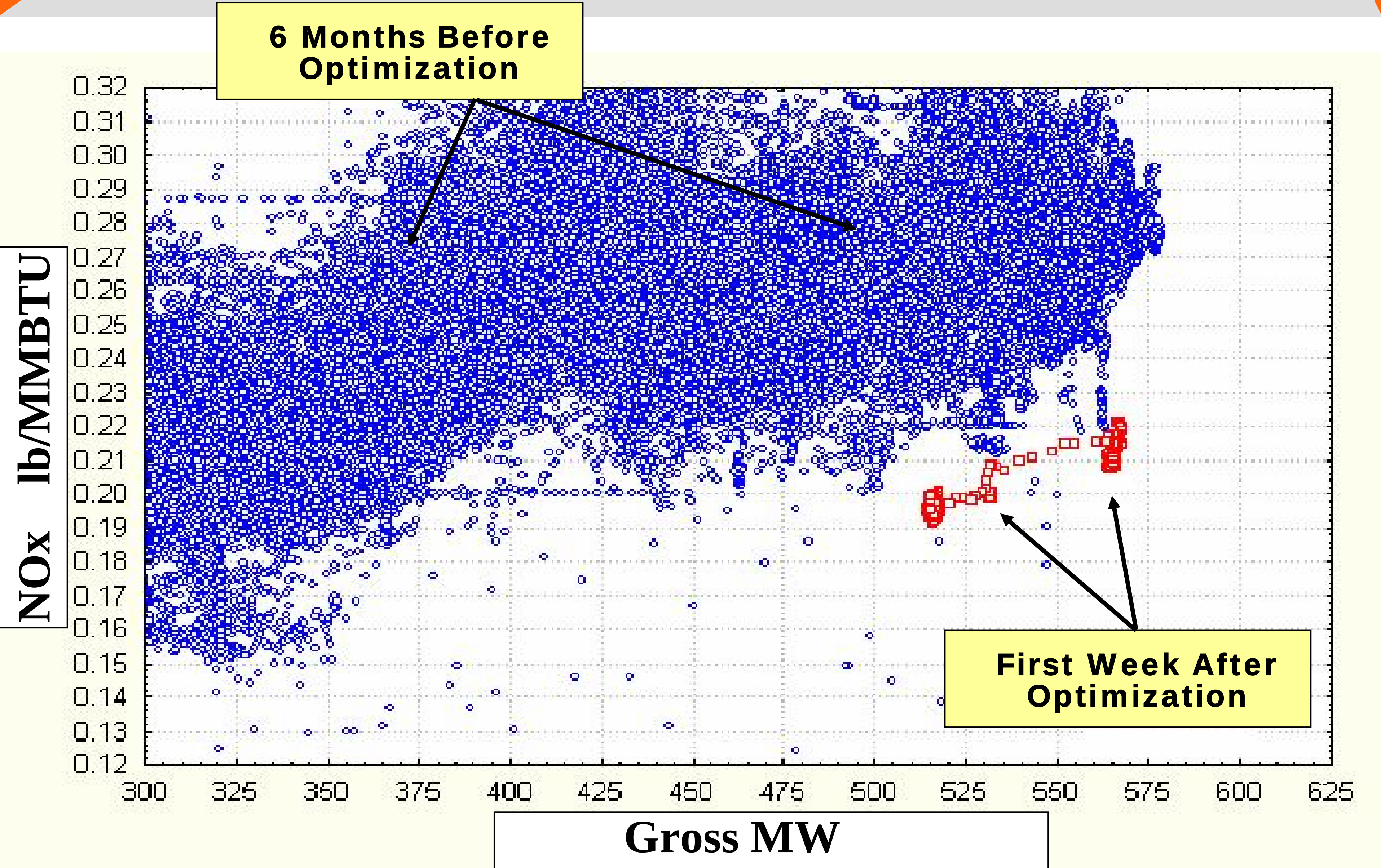


CombustionOpt On

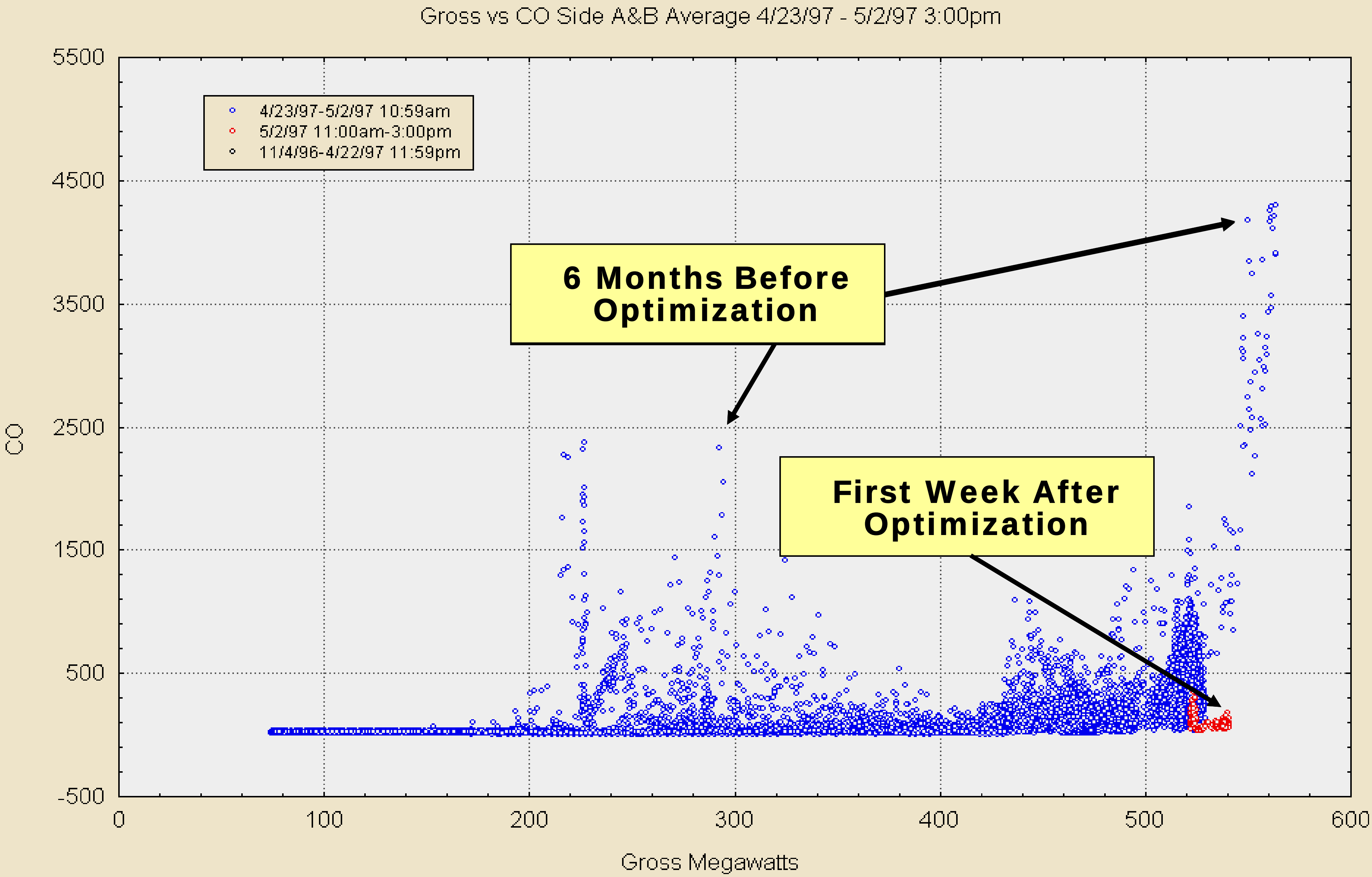
Average Exit Gas Temperature

CombustionOpt Off

Impacts on NOx for 600 MW Oil/Gas-Fired Opposed Boiler



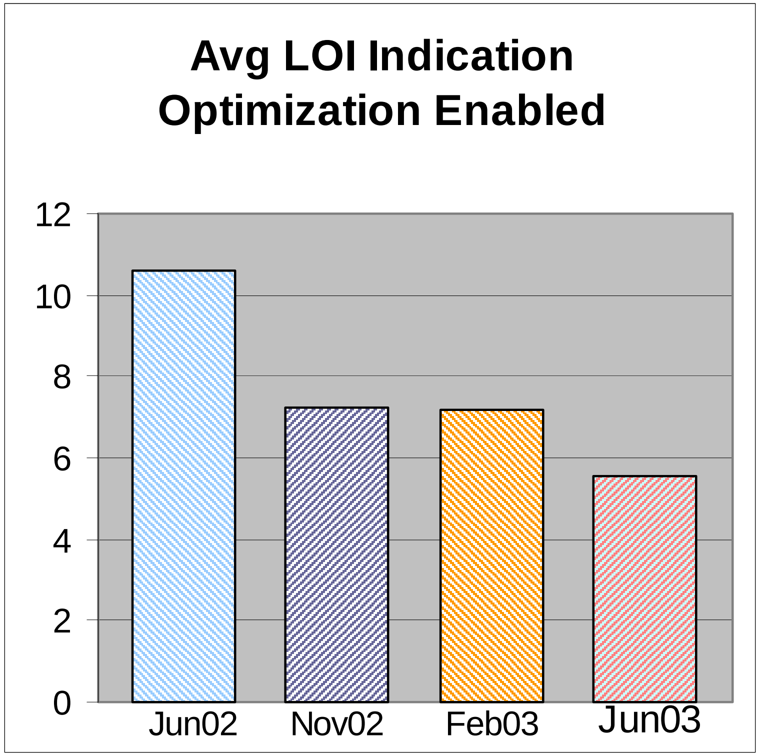
Impacts of Combustion Optimization on CO on Same Boiler Over Same Period

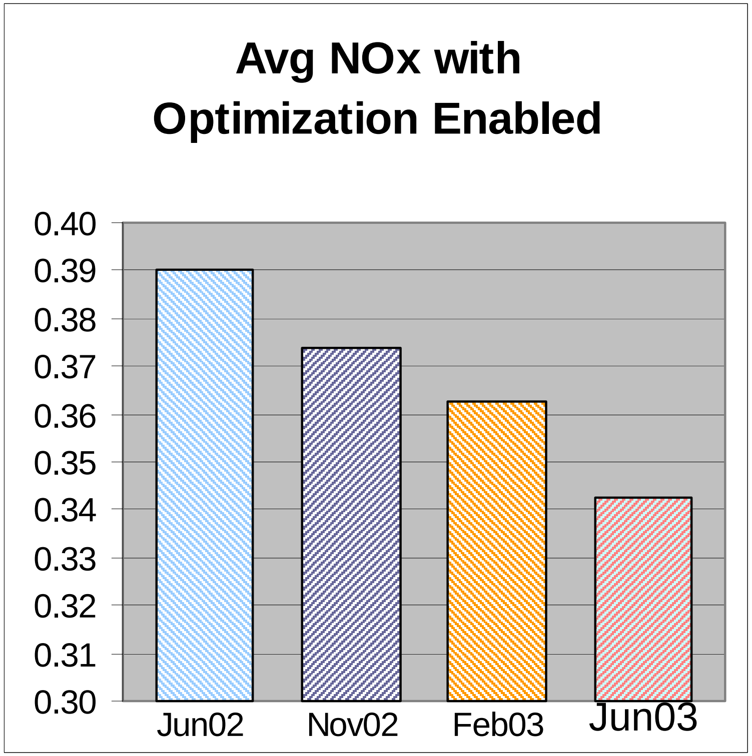


6 Months Before Optimization

First Week After Optimization

Increasing LOI & NOx Reduction over One Year with In-Situ LOI Indicators





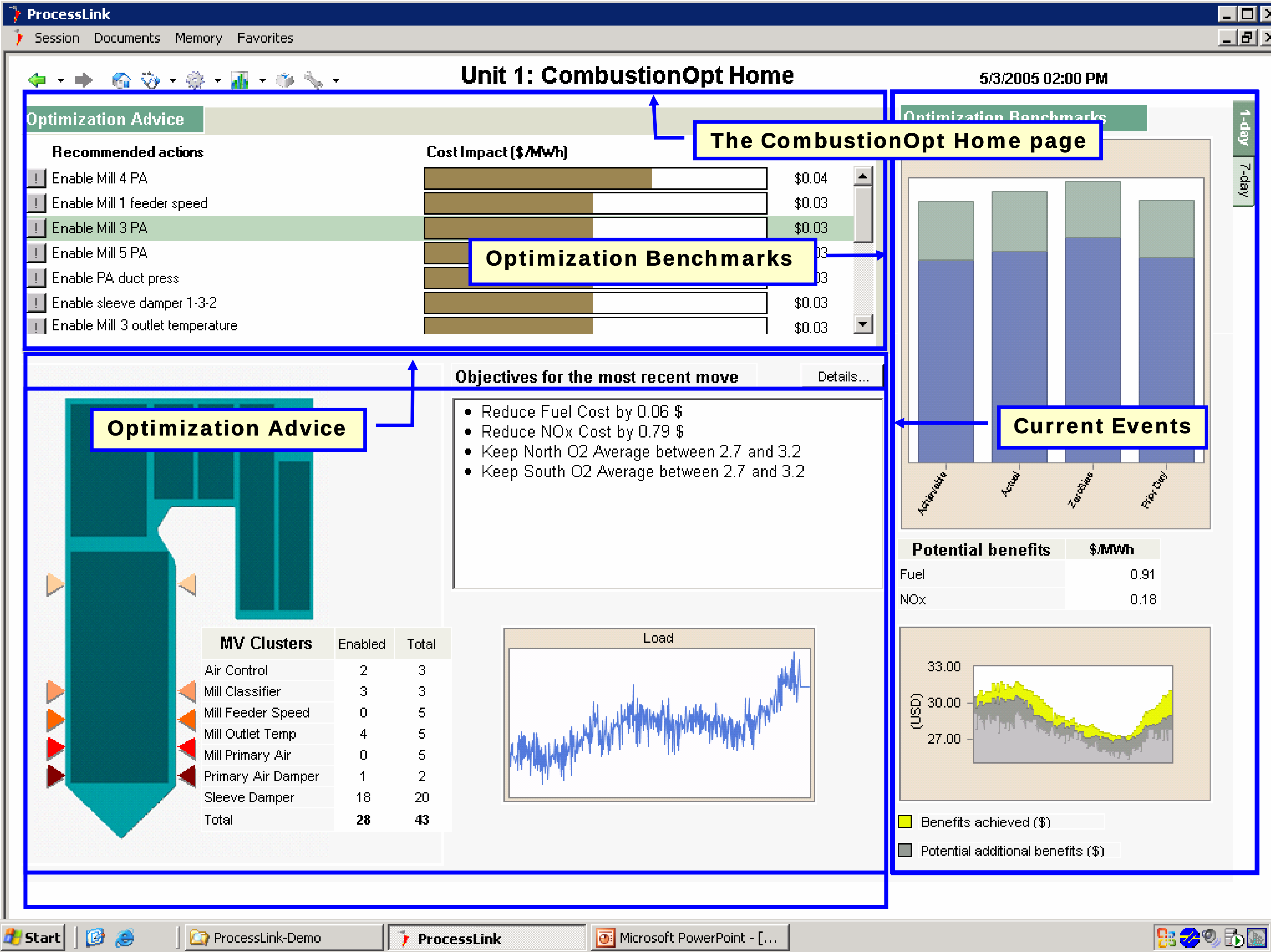
Recent Advances in Combustion Optimization

In recent year some newer techniques have evolved:

- Committees of models
- Automated design of experiments for normal operating conditions and AGC
- Easier means of implementing plant constraints in the optimization search
- Easier means of implementing objective profiles
- Improvements in data visualization
- Easier means of interfacing with DCS readily adopted

Key Recent Advances

- On-Line Learning
- Monetized tradeoffs between objectives
- Condition-based Optimization Profiles
- Scripting for any set of condition-based rules known to improve unit performance and/or avoid undesirable conditions
- Enhanced dynamic and discrete modeling enhancements



Unit 1: CombustionOpt Home

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The CombustionOpt Home page

Optimization Advice

Optimization Benchmarks

Current Events

Optimization Advice

Recommended actions	Cost Impact ($/MWh)
! Enable Mill 4 PA	$0.04
! Enable Mill 1 feeder speed	$0.03
! Enable Mill 3 PA	$0.03
! Enable Mill 5 PA	03
! Enable PA duct press	03
! Enable sleeve damper 1-3-2	$0.03
! Enable Mill 3 outlet temperature	$0.03

Objectives for the most recent move

- Reduce Fuel Cost by 0.06 $
- Reduce NOx Cost by 0.79 $
- Keep North O2 Average between 2.7 and 3.2
- Keep South O2 Average between 2.7 and 3.2

MV Clusters	Enabled	Total
Air Control	2	3
Mill Classifier	3	3
Mill Feeder Speed	0	5
Mill Outlet Temp	4	5
Mill Primary Air	0	5
Primary Air Damper	1	2
Sleeve Damper	18	20
Total	**28**	**43**

Optimization Benchmarks

Potential benefits	$/MWh
Fuel	0.91
NOx	0.18

🟨 Benefits achieved ($)

▨ Potential additional benefits ($)

Enhanced Dynamic and Discrete Modeling

- Both dynamic and discrete modeling techniques needed
- These capabilities needed to better address a variety of operating challenges:
  - Faster ramping
  - Burners and mills out-of-service
  - Anticipated changes in operating conditions
- Scripting functionality and a rules engine bolster these capabilities
- Greater flexibility and use of mathematical methods best suited to different problems provide a broader arsenal of tools to address combustion challenges

Monetized Objective Prioritization

- Important (where possible) to prioritizes objectives and manage tradeoffs between them based on their monetary value
- Models of physical units (lb/mmBtu, Btu/kWh, etc.) require knowledge of process changes over time
- Costs of these units, however, are imposed externally by markets/contracts
- Physical units and monetary value address separately but brought together to prioritize and trades-off objectives

Combustion / SCR Optimization Challenges

- Must avoid problems associated with sub-stoichiometric combustion
  - Waterwall corrosion
  - Slagging
  - Increased LOI
- Exploit available fuel and air measurements
- SCRs increasingly operate year-round
- No automated control over AIG
- NH3 instrumentation can be useful
- Objectives vary depending on market conditions

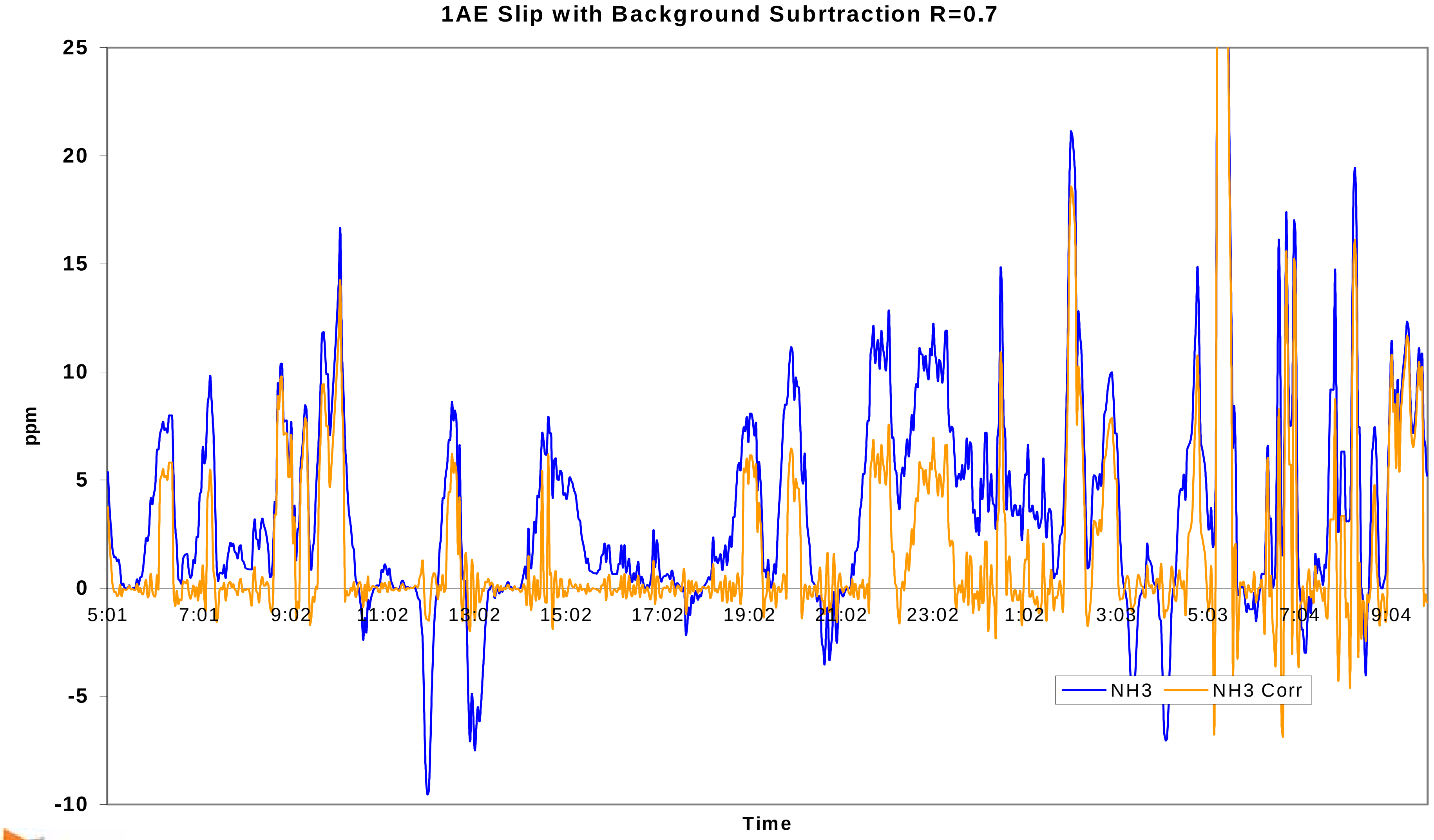
New On-Line Signals Becoming Available

- Flame scanner signals
- Tune-able Diode Laser NH3 Signals
- New In-furnace TDL measurements

On-Line NH_3 Signal for Closed-Loop Optimization: CCPI Project at Baldwin

- Unisearch LASIR TDL Slip analyzer with 4 single traverse light paths on each unit, two per SCR section, just downstream of the SCR, above the air pre-heater.
- Installed 9/13/2004, began collecting data.
- Initial data showed surprisingly frequent and high levels of slip.
- Recent SCR Off base-lining has shown that some of the indicated slip frequency and magnitude is suspicious.
- The data collected were analyzed with the neural modeling available through CombustionOpt.
- Slip was successfully modeled as a function of CombustionOpt fuel and air bias variables.
- Work with Unisearch is on-going.

NH3 Slip at Baldwin 1 9/19 – 9/20



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NH3 Slip Model with Closed-Loop Fuel and Air Biases as Inputs

NH3 Slip Model Captures Trends but Attenuates Spikes

NH3 SLIP 1A2 NW {2.604985}

NH3 SLIP 1A2 NW (Grouped) Predictor {4.258342}

GROSS GENERATION {449.271}

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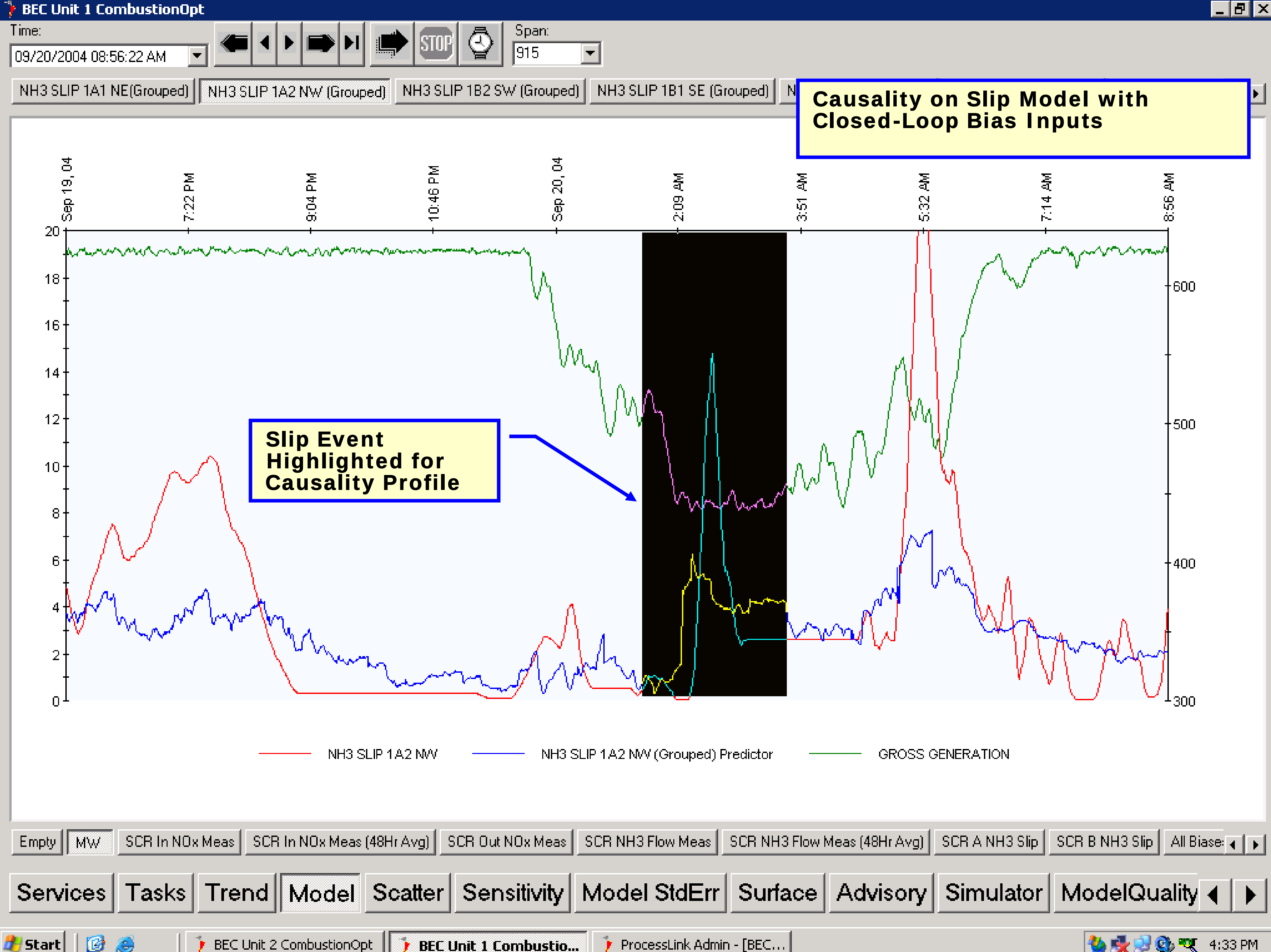

Causality on Slip Model with Closed-Loop Bias Inputs

Slip Event Highlighted for Causality Profile

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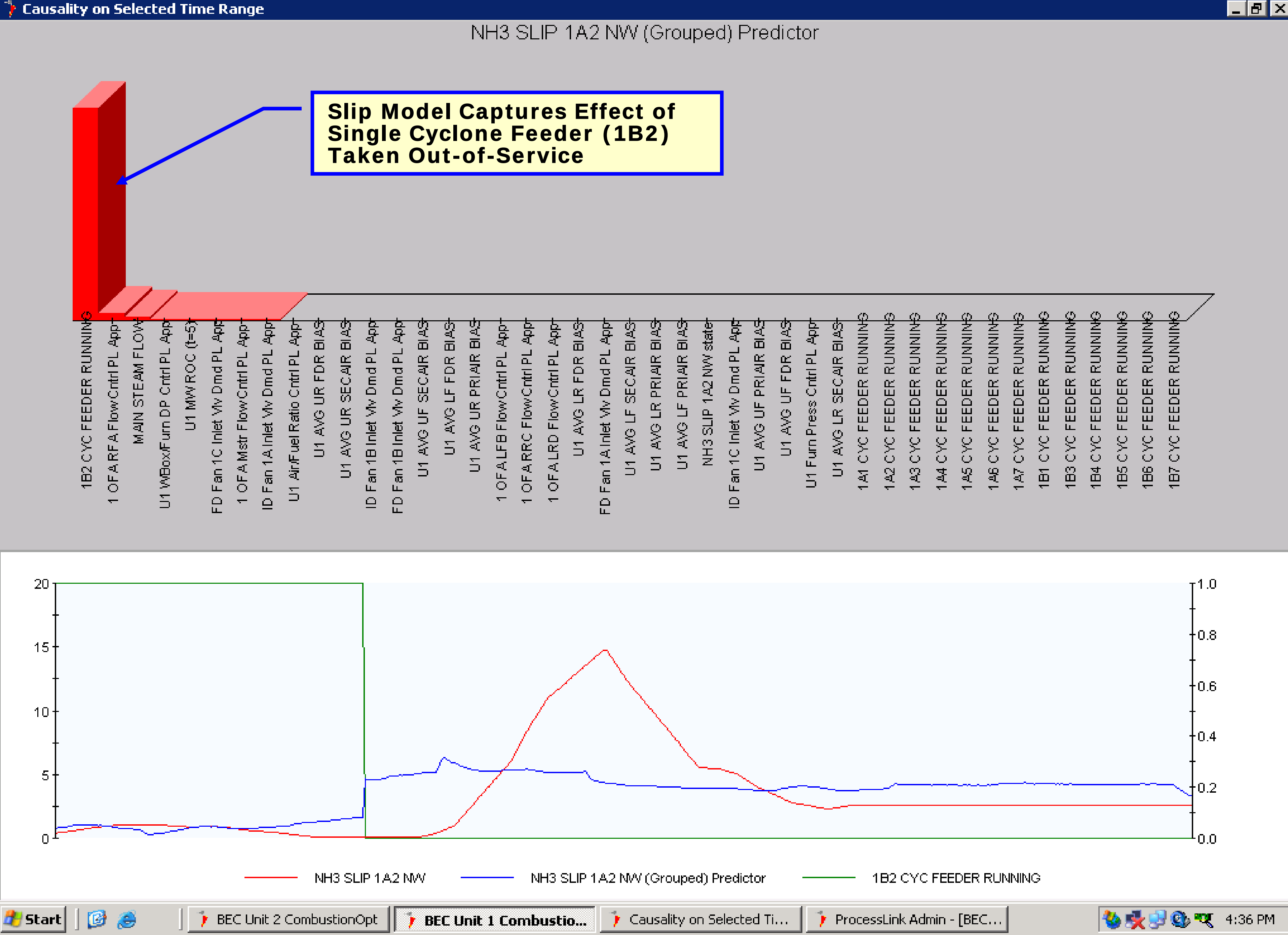
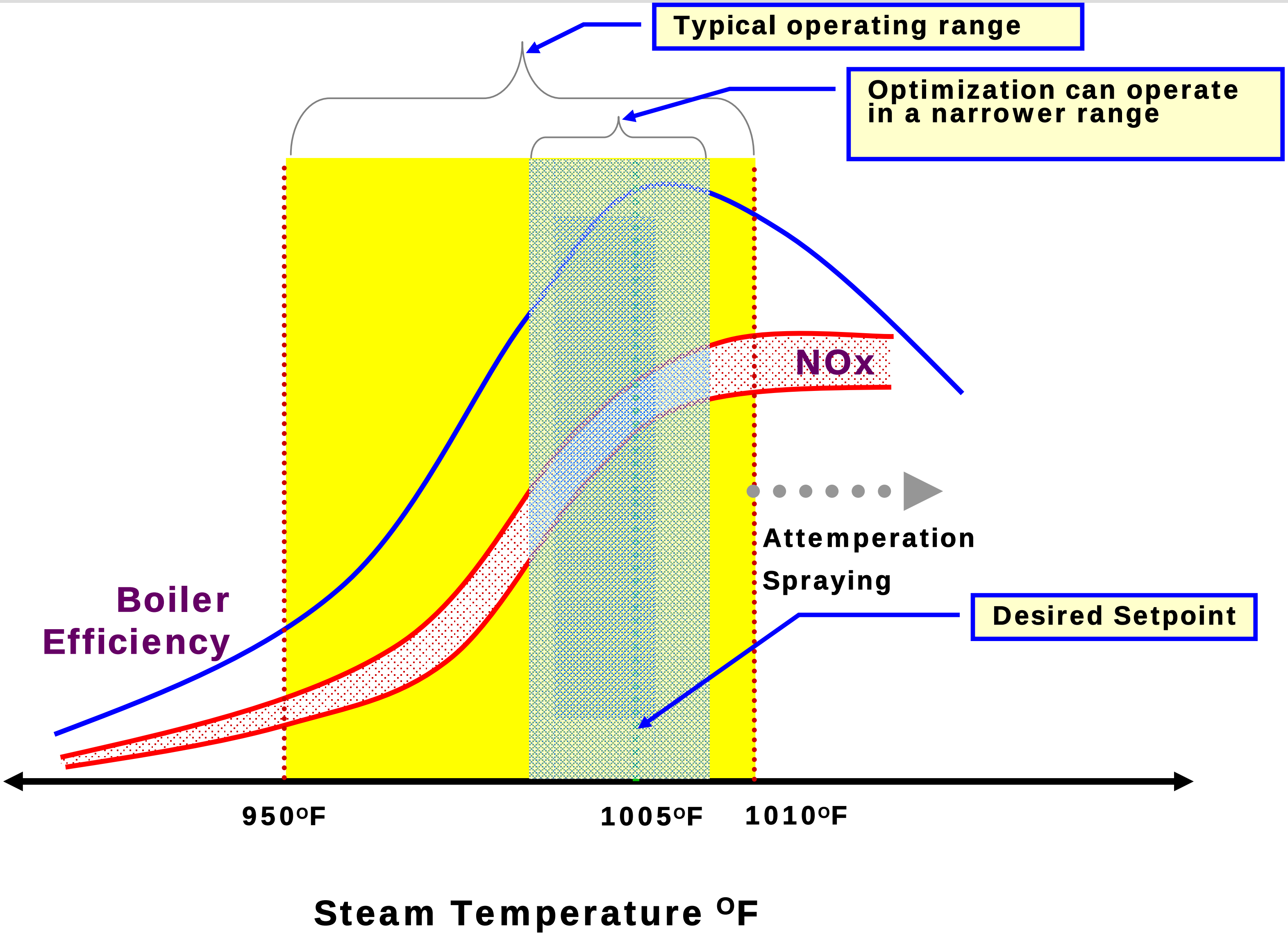


Slip Model Captures Effect of Single Cyclone Feeder (1B2) Taken Out-of-Service

TDL Technology for In-Furnace Measurement of Key Combustion Constituents

- Same telecommunications-derived TDL technology has been adapted for in-furnace signals indication CO, O_2, CO_2, $H2_0$ and temps
- Molecular measurements are temperature compensated
- Over $50 million invested
- Complementarities with combustion optimization will be demonstrated at PRRP Rawhide
- Follow-on demonstration to demonstrated at CPS San Antonio Deely Unit 2

Optimization of Boiler Cleaning



Why Optimize Soot Cleaning?

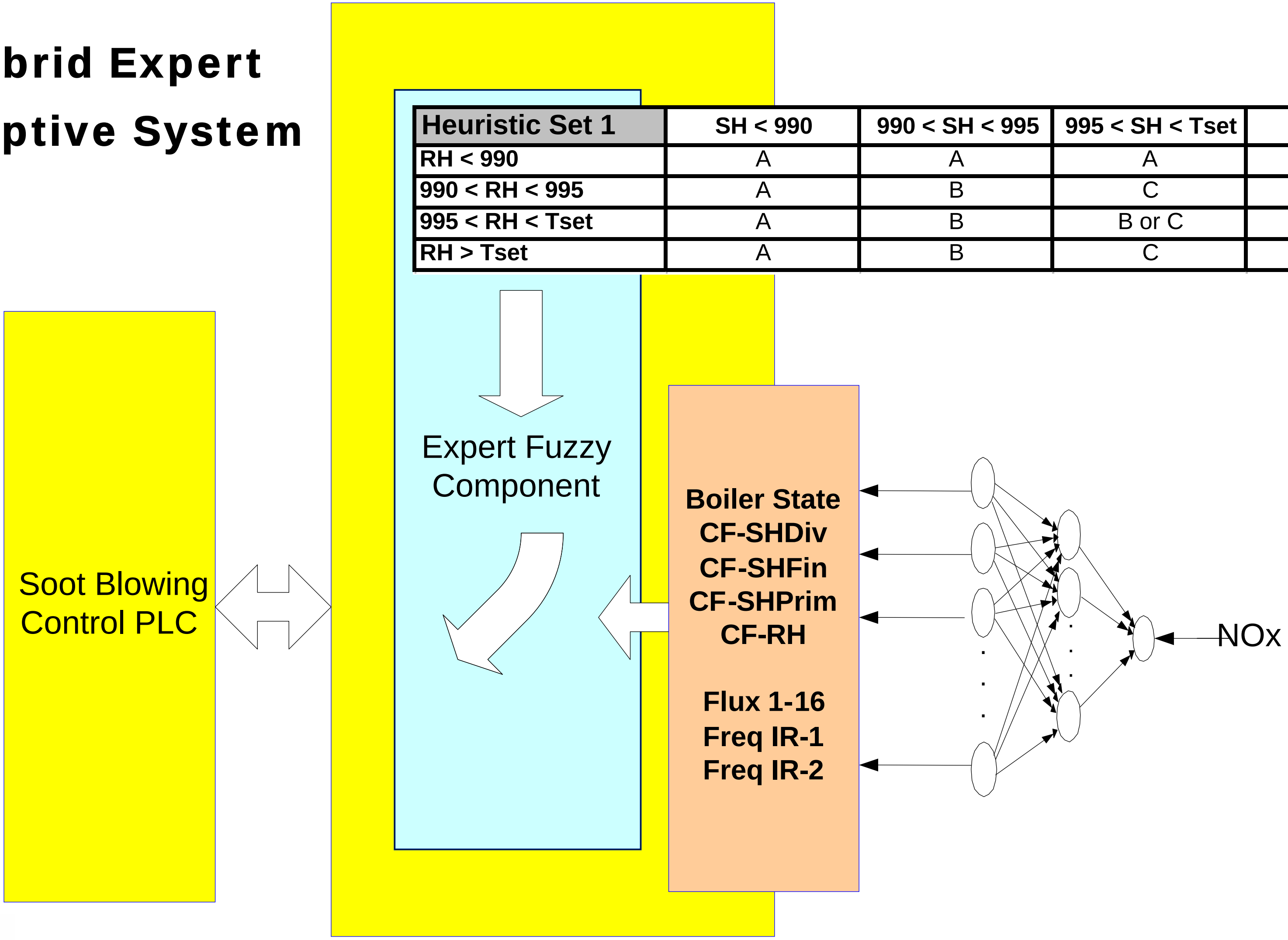
- Cleaning actions (or lack thereof) affect many plant parameters:
  - Slagging/fouling impacts heat transferability
  - Capacity: Steam and gas temperatures, spray flows, differential pressures, fan limits
  - Performance: Boiler efficiency, heat rate
  - Emissions: NOx, Opacity, LOI, CO
  - Availability/Reliability: Waterwall/tube longevity, EFOR, equipment wear-and-tear
- Operational complexities:
  - Fuel and equipment variations
  - SCR/SNCR systems
  - LOI control objectives
- Bottom line economic impact - $$$$

Optimal Boiler Cleaning

- Optimizes boiler cleaning based on unit-specific objectives:
  - Improves emissions control (NOx, opacity, CO)
  - Improves Heat Rate including Reheat & Superheat steam temperature control
  - Balances tradeoffs between furnace/backpass absorption
  - Reduces O&M costs by avoiding unnecessary boiler cleaning actions and reducing tube wear and thermal stressing
  - Compensates for off-design fuels and operations
  - Leverages existing soot cleaning instrumentation, models, equipment and control systems

How it Works

Hybrid Expert Adaptive System

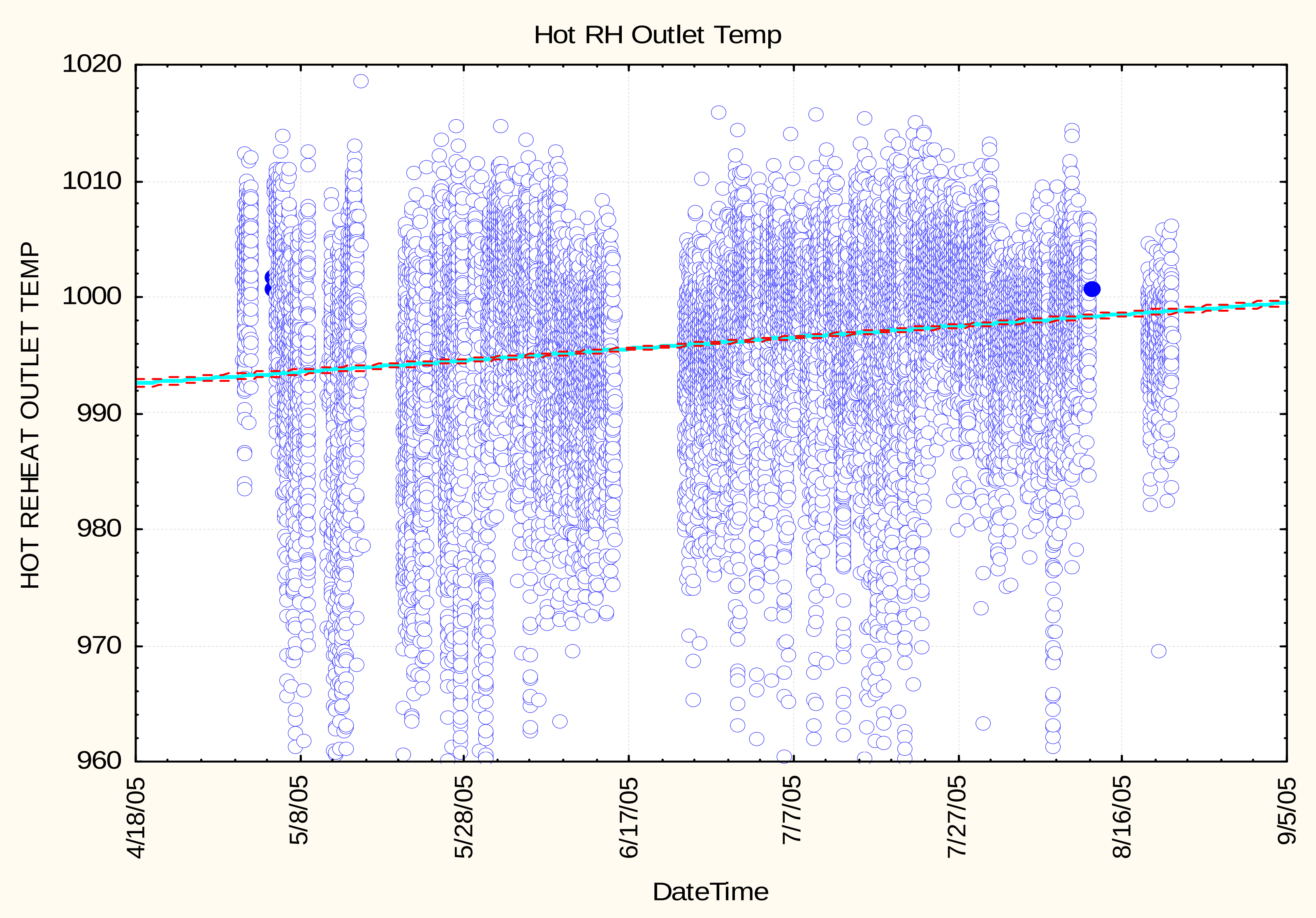


Heuristic Set 1	SH < 990	990 < SH < 995	995 < SH < Tset	SH > Tset
RH < 990	A	A	A	A
990 < RH < 995	A	B	C	C
995 < RH < Tset	A	B	B or C	C
RH > Tset	A	B	C	B or C

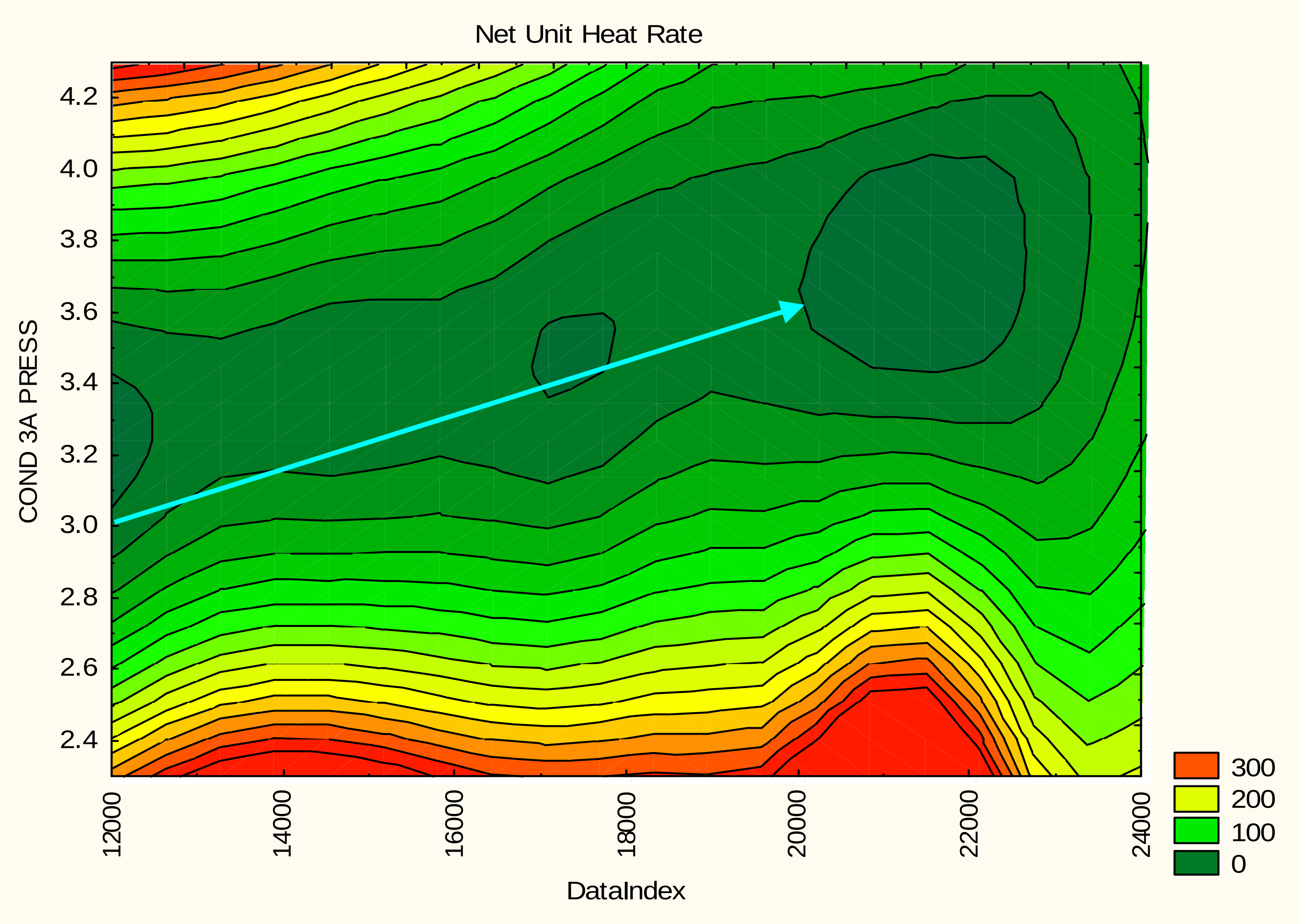
SootOpt at Baldwin Unit 3

- 630 MW, Base-Loaded, T-Fired
- SOFA, Low NOx Burners
- High variability in PRB coal
- Heat Flux Sensors and Water Cannons
- ASI PLC-based SB control system with locally intelligent controls
- PrecisionClean and standard IK’s in convection pass
- Also thermocouples and FEGT
- Prevailing sootblowing guidelines:
  - ISB preset flux targets in the furnace, operators intervene
  - Operator initiated in the convection pass

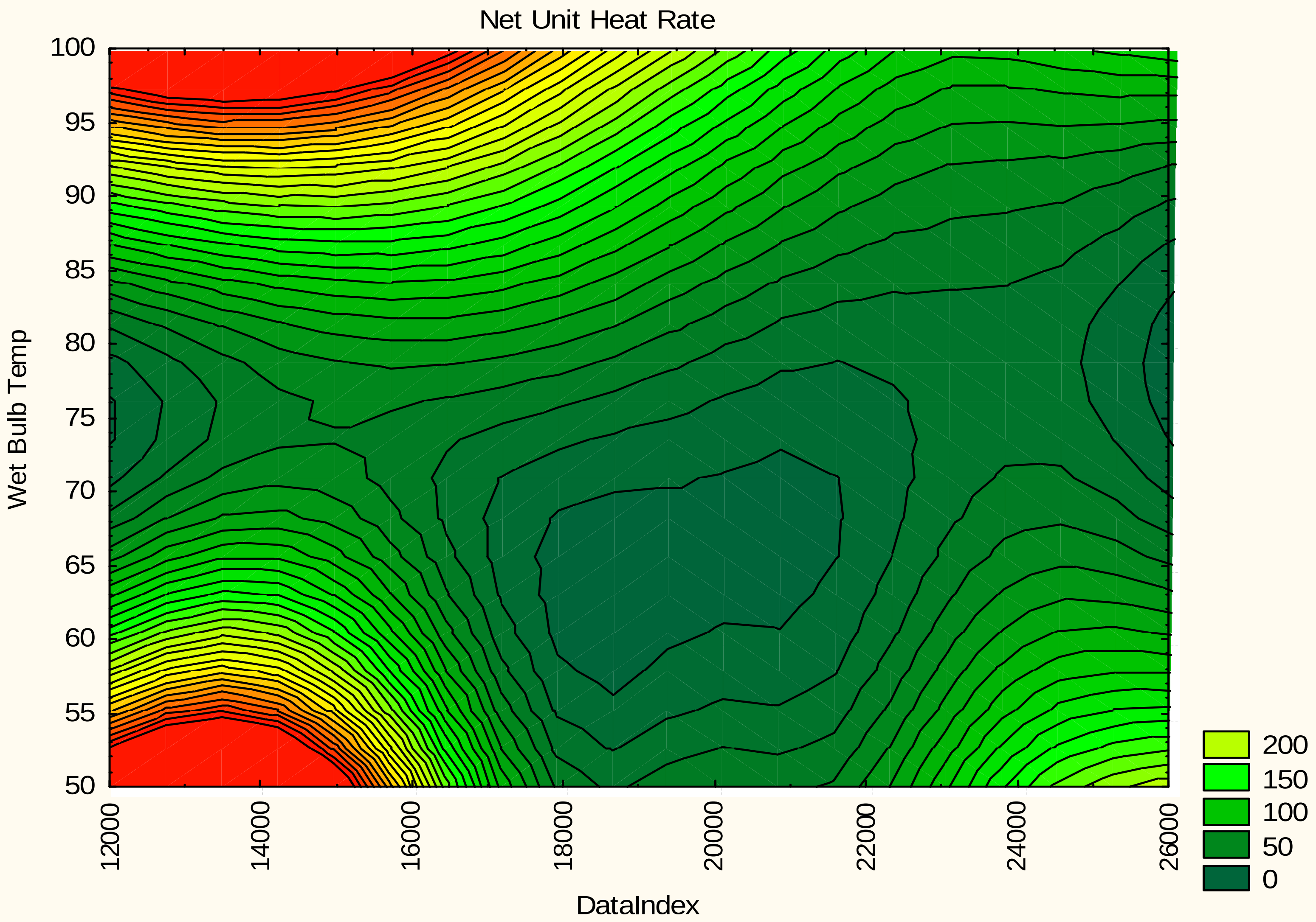
RH Temps


Hot RH Outlet Temp
HOT REHEAT OUTLET TEMP
1020
1010
1000
990
980
970
960
4/18/05
5/8/05
5/28/05
6/17/05
7/7/05
7/27/05
8/16/05
9/5/05
DateTime

Heat Rate vs Cond Press over Time



Heat Rate vs Wet Bulb over Time



Action-Oriented Performance Optimization

- Identifies, analyses & takes or recommends actions to alleviate immediately controllable efficiency and capacity losses
- Single online model for performance monitoring & predictive simulations
- Uses actual data to determine realistically achievable efficiency & capacity targets and their impacts
- Distinguishes between actions that are immediately controllable vs. those that require an outage or de-rate
- Key Building Block for Availability Optimization

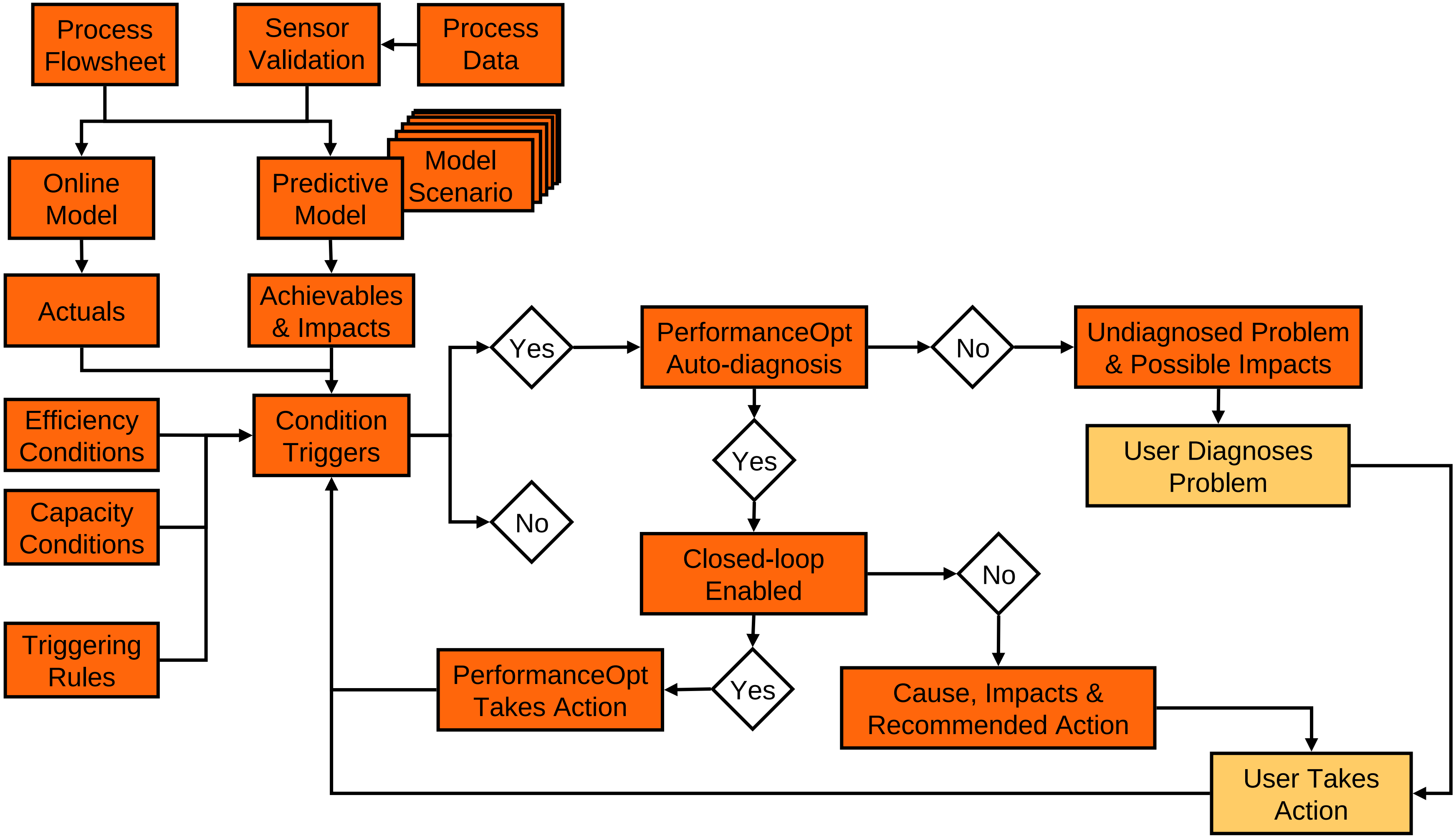
What's Needed for Action-Oriented Performance Optimization?

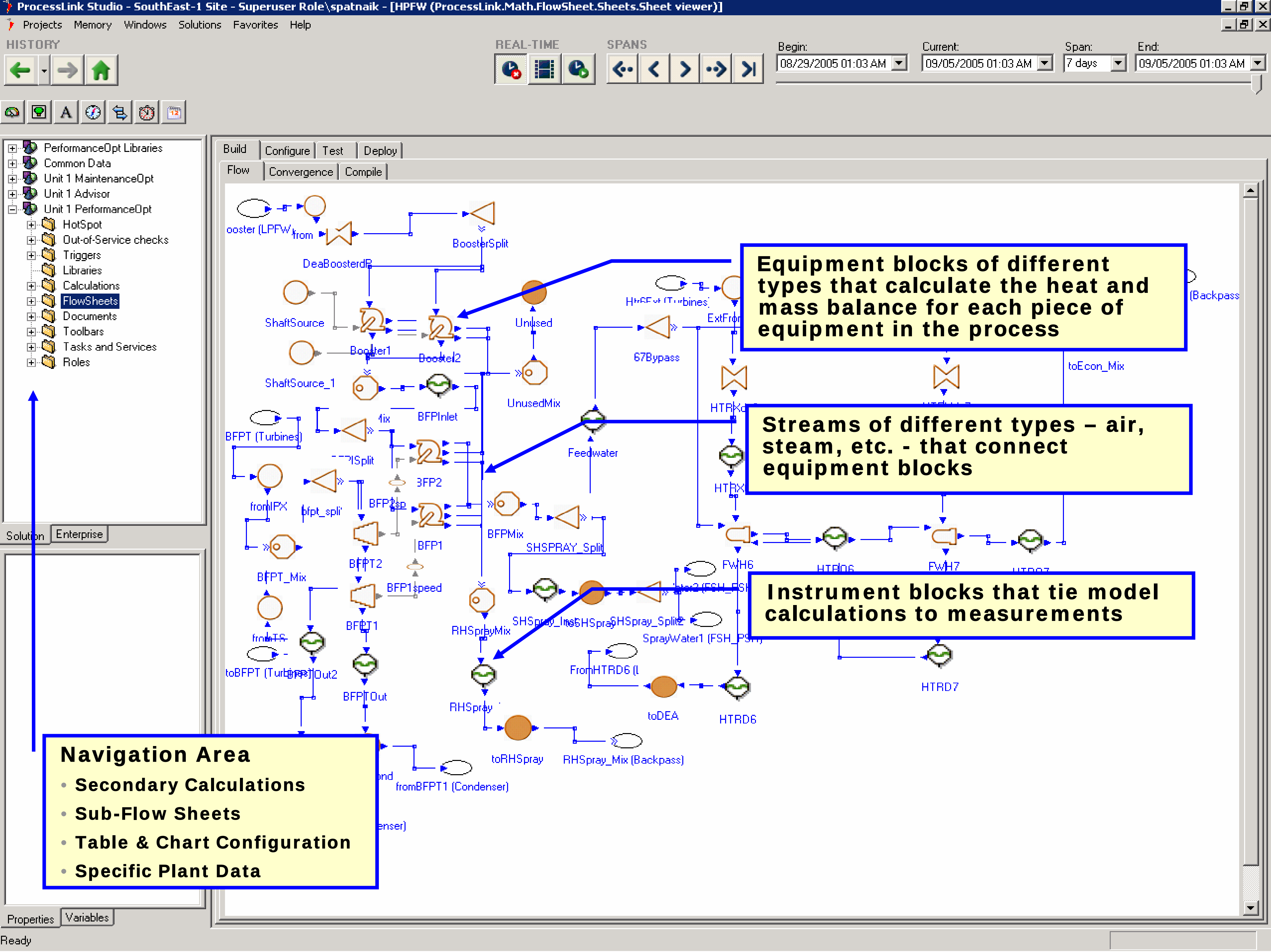
- Beyond controllable losses
  - Additionally identifies equipment/system problems at a much smaller grain-size i.e. closer to the source
    - Air Heater leakage
    - ID Fan amps
    - Feedwater Heater TTD
- Beyond performance curves and design data
  - Problems detected based on "achievable" values as opposed to "design" values
  - Helps differentiate between failed sensors and real process problems
  - Provides actionable advice for some of the problems it identifies

How Effective Performance Optimization is Accomplished

- Integrated boiler and steam cycle model
  - Rigorous mass and energy balance
  - Sophisticated sensor validation mechanisms
- Simultaneous, real-time on-line and what-if simulations
- Continuous determination of deviations from achievable
  - Achievable values based on current plant conditions
- Accurate model-based estimation of capacity as well as efficiency benefits

Performance Optimization Workflow





Equipment blocks of different types that calculate the heat and mass balance for each piece of equipment in the process

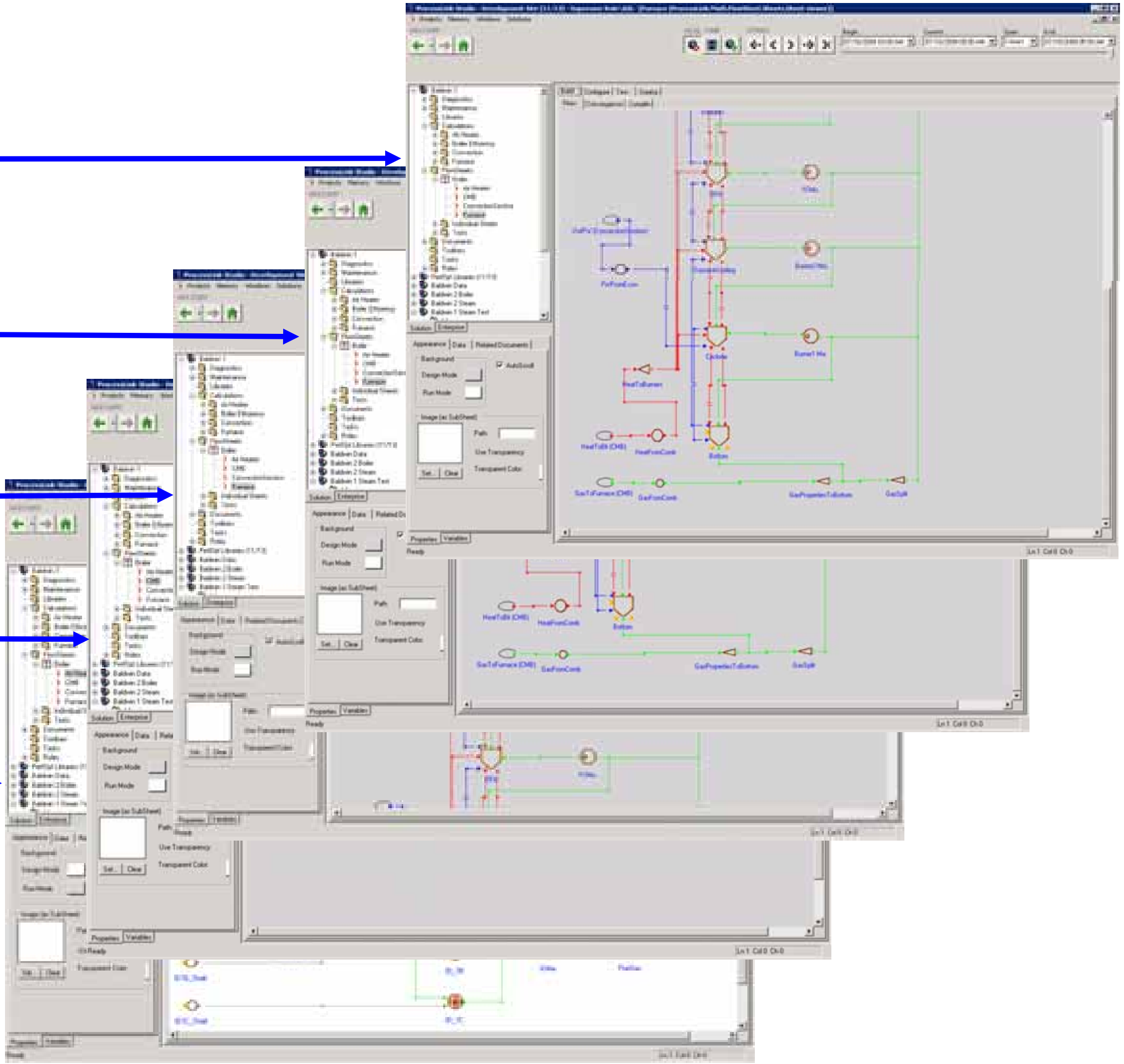
Streams of different types – air, steam, etc. - that connect equipment blocks

Instrument blocks that tie model calculations to measurements

Navigation Area

- Secondary Calculations
- Sub-Flow Sheets
- Table & Chart Configuration
- Specific Plant Data

Fundamental Building Block
1st Principle Models - Boiler



Boiler Convection Section

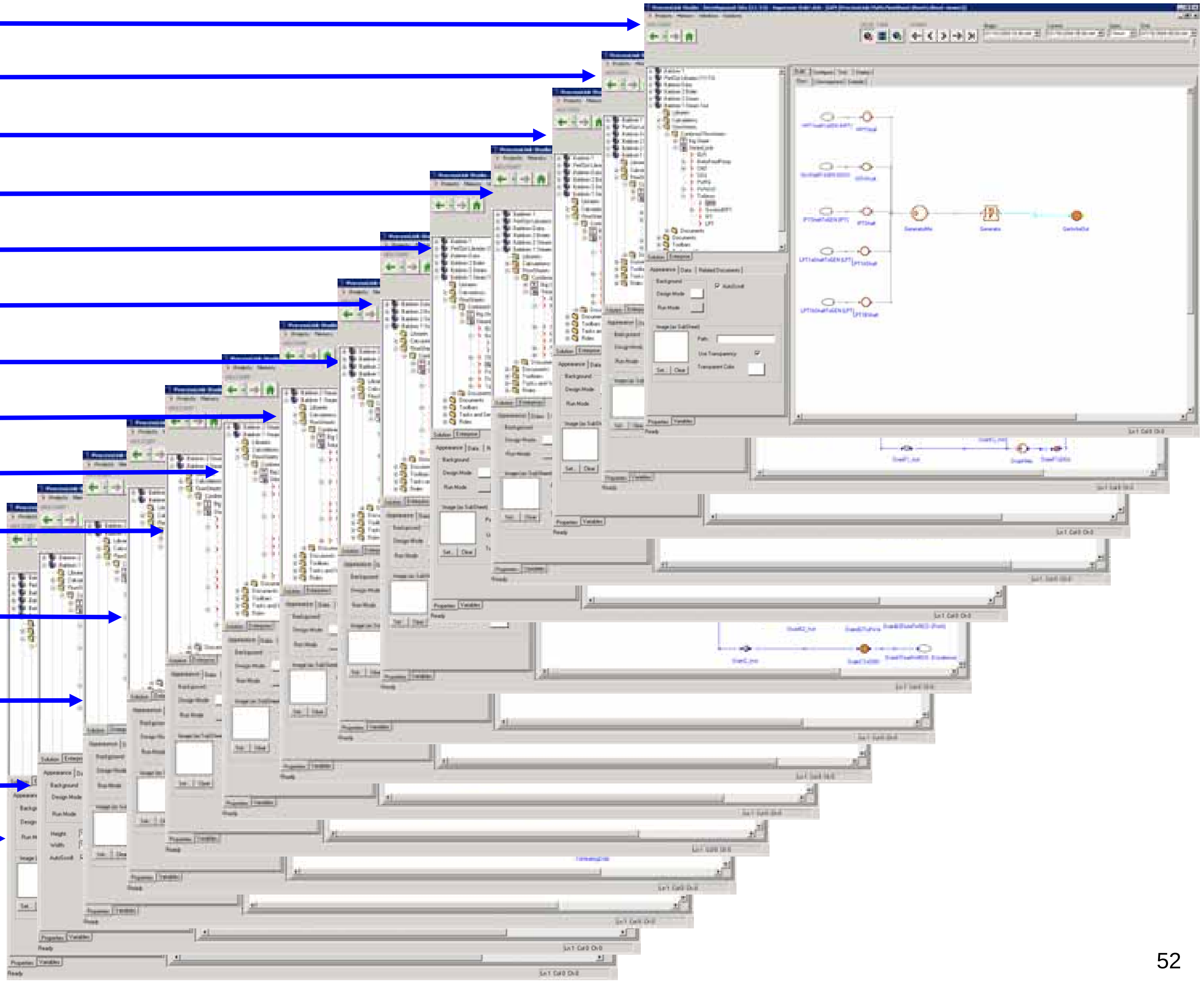
Boiler Furnace (Bottom)

Boiler Furnace (Top)

Boiler Combustor

Boiler Air Heater

Fundamental Building Block
1st Principle Models - Steam



- Generator
- FW HP Heater
- BFW Turbine
- BF Pump
- Dearator
- Feed Water Htr B
- Feed Water Htr A
- Condenser Pumps
- Condenser
- Low Pressure Turbine
- Intermediate Pressure Turbine
- High Pressure Turbine
- Turbine Governor
- Boiler

What's Needed for Plant Optimization

- **Enterprise Data Management**
  - Integrate from any source
  - Validate and replace if necessary
  - Aggregate and manage calculations
- **Hybrid Modeling Methods**
  - First-Principles**: When you know the math, write it**
  - Rule-Based**: When experts have key knowledge, capture it**
  - Machine Learning**: When not understood, learn it**
- **Integrated Optimization Engine**
  - Coordinate local decisions based on global impact
- **Action-Centric Portals**
  - Present actionable knowledge to the person that can act on it when it something can still be done, while allowing the user to drill-down all of the details upon which the knowledge is based