Development of Miniaturized High Temperature Multi-Process Monitoring System

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NATIONAL ENERGY TECHNOLOGY LABORATORY

2021 Spring Project Review

For Energy and Environmental Solutions

REACTION ENGINEERING INTERNATIONAL

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Agenda

- Project Overview
- Technical Discussion
  - *m*MPMS Description & Development
  - Full-scale Demonstration
    - Plant Operation
    - Data from full-scale demonstration
- Next steps

Reaction Engineering International

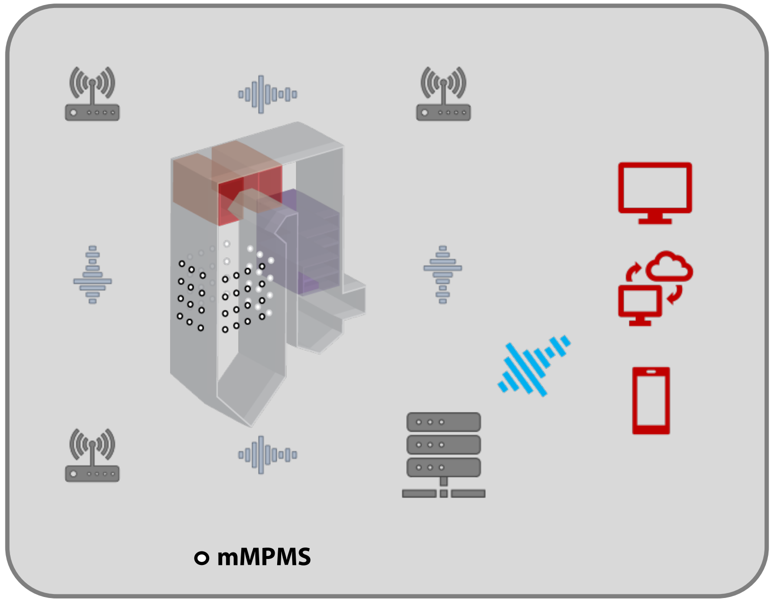
- Founded 1990 with Strong University and Specialist Affiliations
- Managed more than 40 government R&D projects in the past 15 years
- Has both management experience and technical expertise in the combustion and gasification related R&D programs
- Expertise
    - Combustion, Gasification, Fuel Conversion & Pollutant Emissions
    - Unique, Proprietary Modeling Capabilities & Tools
    - Laboratory and Field Testing
    - Specialized Equipment & Controls

Project Objective

- Develop and demonstrate a miniaturized high temperature multi-process* monitoring system that can provide a real-time indication of boiler condition in a **bituminous coal-fired full-scale boiler**
- Develop control logic to help reduce or manage **tube wastage under low NOx and load cycling operating conditions**

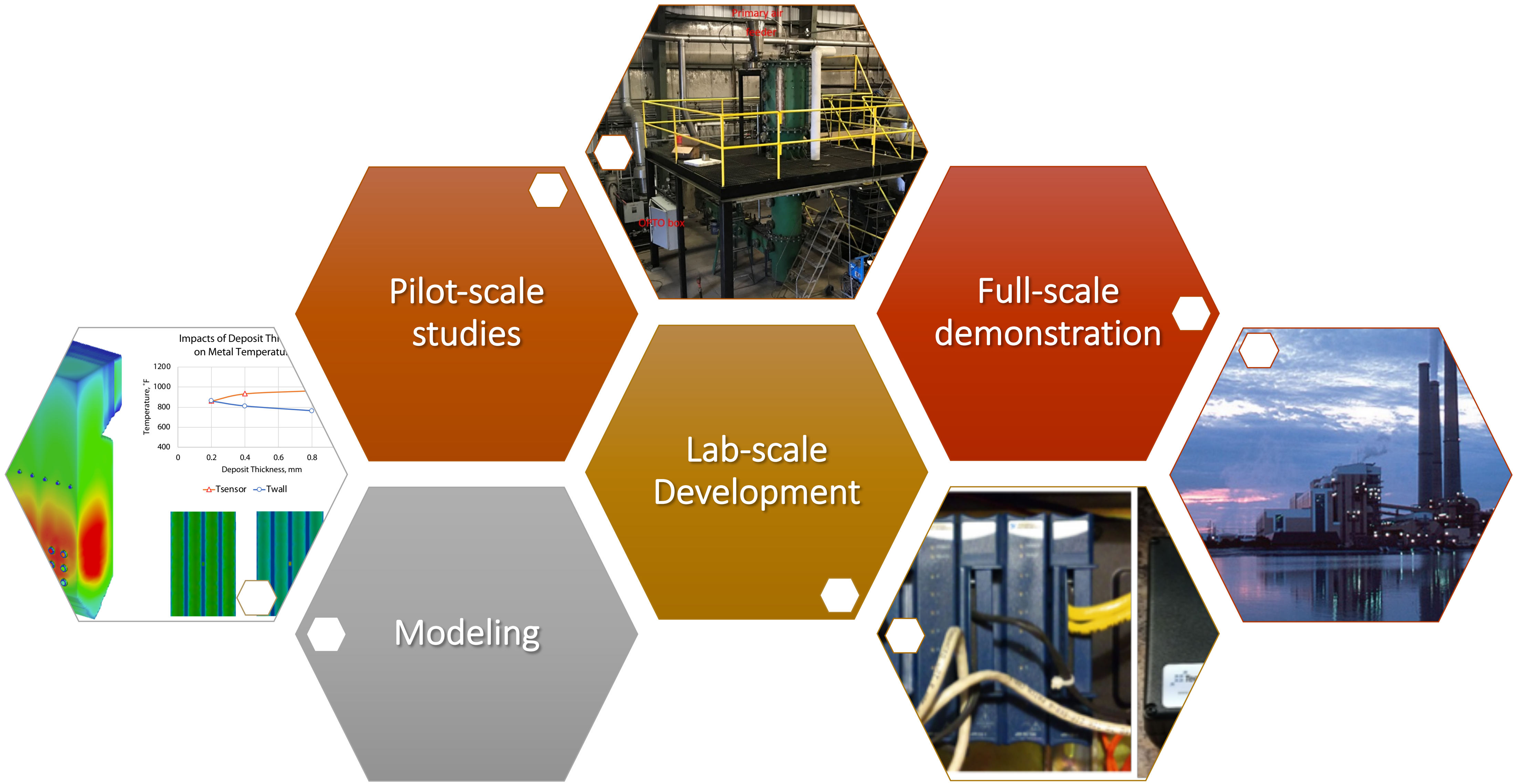
**metal wastage, heat flux, metal surface temperature, ash deposit thickness and ash deposition rate*

Conceptual Schematic of Boiler Condition Monitoring using mMPMS



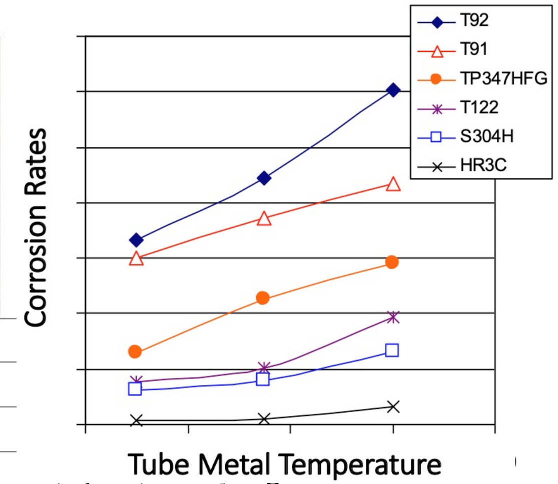
miniaturized **M**ulti-**P**rocess **M**onitoring **S**ystem

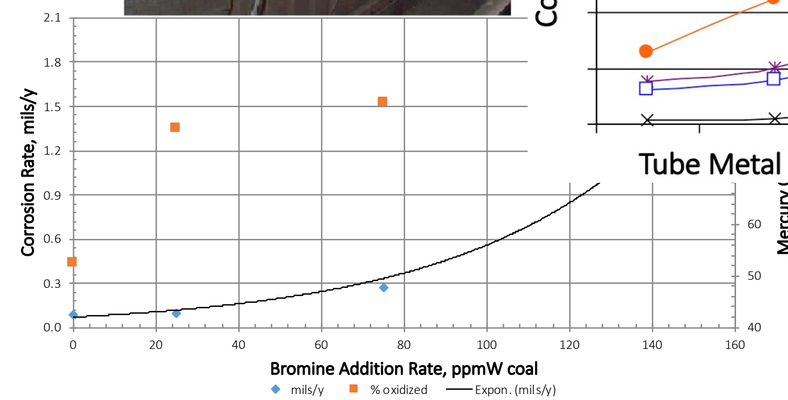
Technical Approach

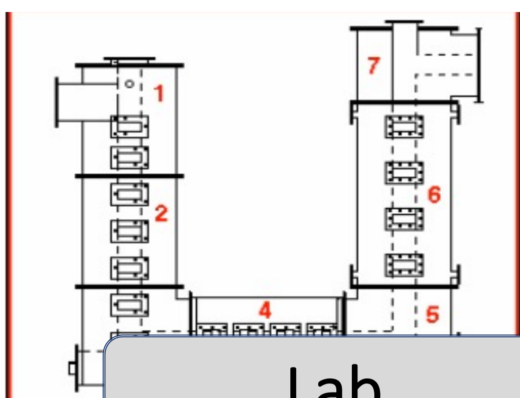


Leveraging REI's Previous Works

- Electrochemical metal wastage sensing system has been applied to
  - low and high temperature zones of the boiler
  - fuel switching and waste-to-energy system
  - material testing for ultra-supercritical steam condition and oxy-firing combustion
- EN-based system provides high sensitivity, real-time, on-line monitoring technology







Lab

Pilot

Full

Project Team

Prime Recipient

REACTION ENGINEERING INTERNATIONAL

- *Project Management*
- *mMPMS Development*
- *Mechanism Derivation*
- *Computational Modeling*
- *Boiler Control Logic Development*
- *Signal Conditioning and Data Communication Module Development*

Sub-Awardees

THE UNIVERSITY OF UTAH	*Pilot-scale Testing*
PACIFICORP	*Full-scale Demonstration*

Project Schedule

Year 1
Oct 2018 – Sep 2019

- Design and construction of prototype sensor body
- Design and fabrication of data processing unit
- CFD analysis of full-scale bituminous coal-fired boiler

Year 2
Oct 2019 – Sep 2020

- Construction of power and cooling unit
- Development of data processing software for bituminous fired unit
- Test and validation of multi-process sensor in a bituminous coal firing pilot-scale combustor
- CFD analysis of demonstration site's full-scale bituminous-fired boiler
- Demonstration of multi-process sensor in a commercial scale bituminous coal-fired boiler

Year 3
Oct 2020 – Sep 2021

- Develop control logic for automated control of bituminous coal-fired boiler

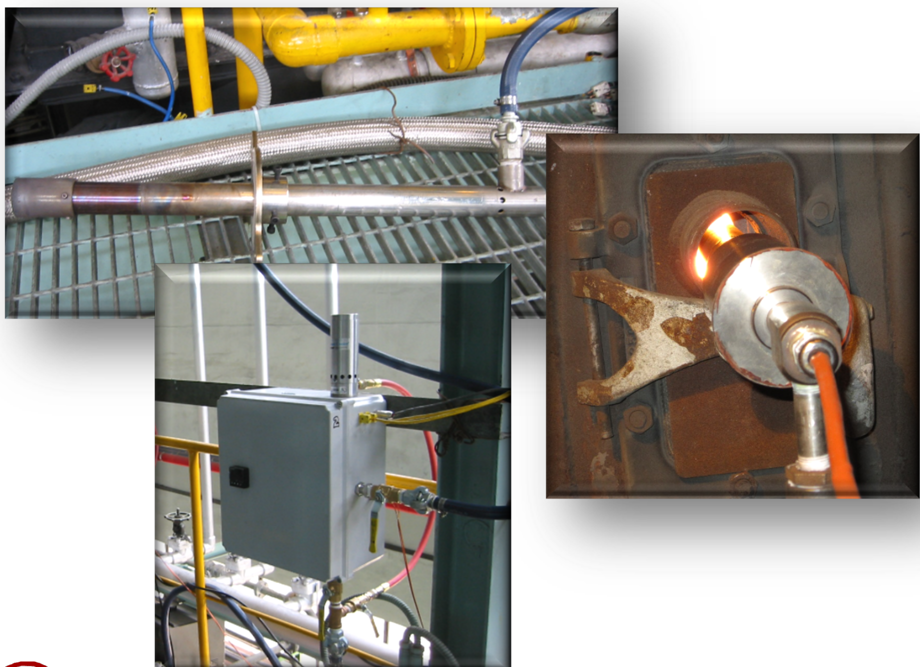
- *Pilot-scale testing delayed due to the COVID-19 pandemic and the following facility shutdown has been completed in July 2020*
- *The full-scale demonstration has started in December 2020*

*m*MPMS Design Concept

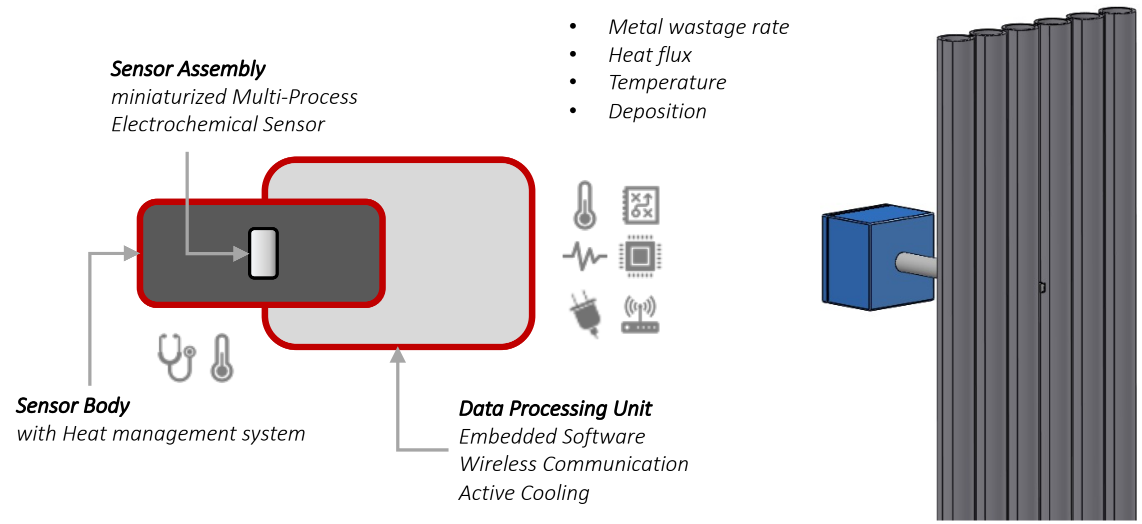
miniaturized **M**ulti-**P**rocess **M**onitoring **S**ystem

Legacy Sensor System

- Existing sensor placed in air-cooled probe
- Requires access port where tubes have been bent to allow access
- Need cooling air arrangement including cooling valve



mMPMS



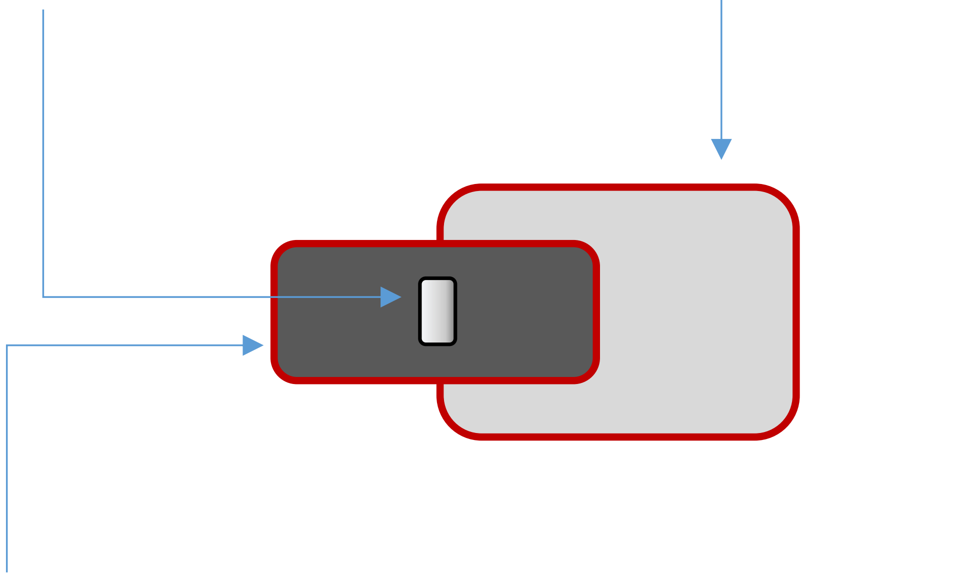
- Use the gap in the membrane for sensor insertion
- Sensor embedded in body with heat management module “without” cooling air
- Multi-process measurements to help condition-based monitoring
- Reduce power requirements

Key *m*MPMS Components

miniaturized **M**ulti-**P**rocess **M**onitoring **S**ystem

Sensor Assembly

- *New ceramics assembled with metal elements*
- *Designed and machined to fit the membrane hole*
- *Designed to reach within ¼” of tube crowns*



Sensor Body

- *Designed for specific waterwall at Hunter plant*
- *Designed to fit the sensor assembly*
- *Based on heat transfer modeling to optimize heat management*

Data Processing Unit

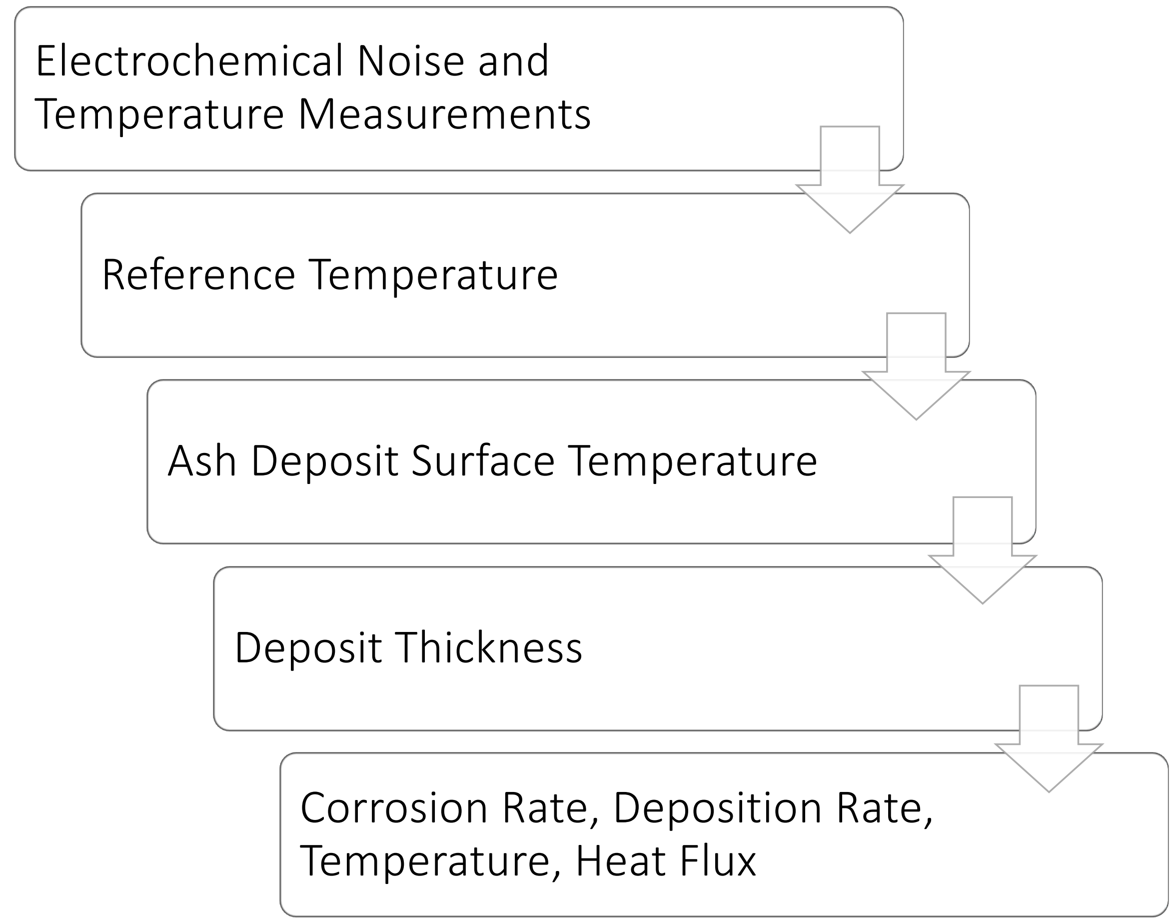
- *Signal conditioning module*
- *Hardened electronics with cloud-capable software*
- *Designed using industrial Internet of Things (IIoT) paradigm*
- *Scalable system to support unlimited sensors*
- *Processing power to enable future support for machine learning/artificial intelligence*
- *Active Cooling*

Signal conditioning module

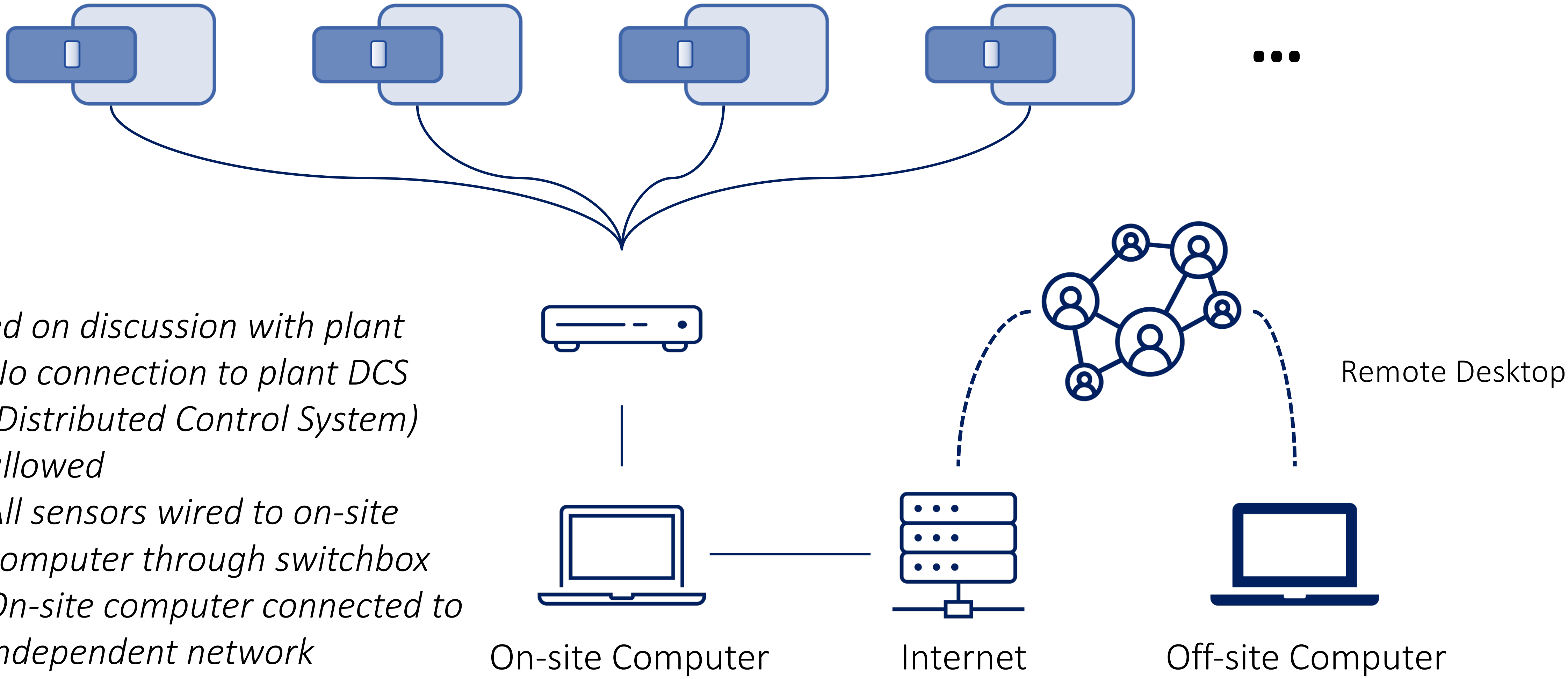
- *Updated and improved the existing signal conditioning module*
- *Simplified electronic design and increased resolution to allow detection of localized attack*
- *Implemented full digital signal conditioning*
- *Implemented full digital data communications*
- *Embedded “smart” electronics at board level (embedded controller)*

Multi-Process Monitoring

- Leveraged the legacy metal wastage monitoring capability
- Developed quantitative heat flux and deposition correlation based on sensor signal
- Tested and validated during pilot-scale testing



Remote Access & Data Communication



Based on discussion with plant

- *No connection to plant DCS (Distributed Control System) allowed*
- *All sensors wired to on-site computer through switchbox*
- *On-site computer connected to independent network*
- *Remote desktop software to connect to on-site computer*

Hunter Plant: Demonstration Host

PacifiCorp

- Located near Castle Dale, Utah
- Three units with total generating capacity 1,320 MW
- Plant is interested in combustion optimization and NOx reduction while avoiding tube failure

Demonstration Plan

Mounting hardware installation during Outage

- Support pipe
- Cutting the hole in the webbing

Pre-demonstration site visit

- After mounting hardware installation
- Site preparation check list (Equipment, Desired operating conditions…)

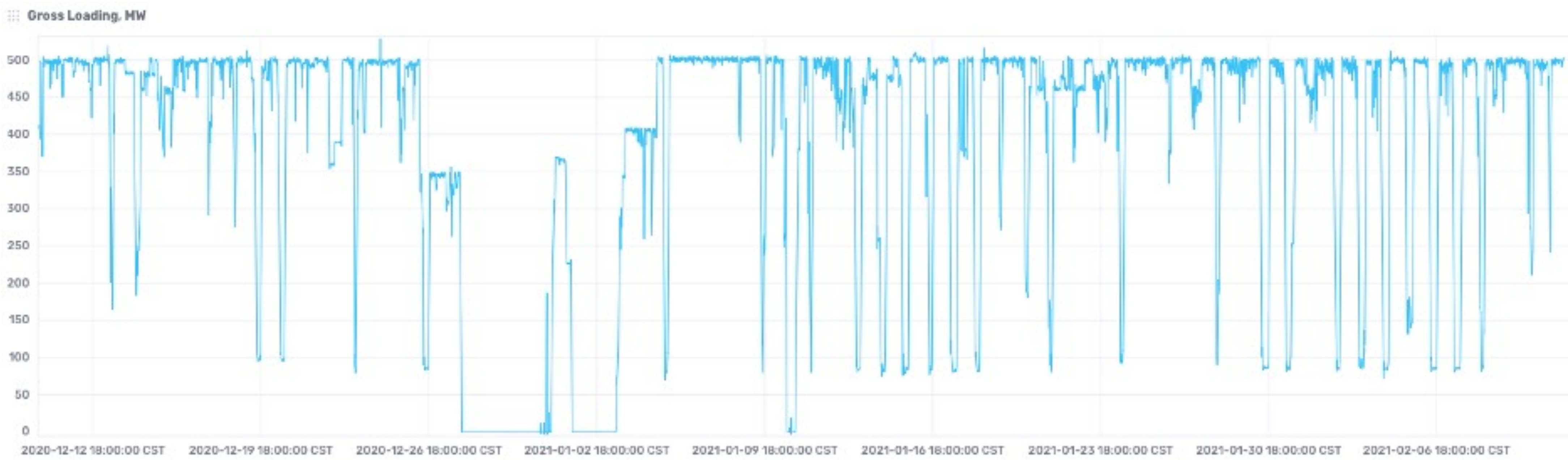
5-week Demonstration

- 5-week monitoring
- Targets Dec 2020 – Jan 2021
- *Monitoring continued*

Data Analysis & Control Logic Development

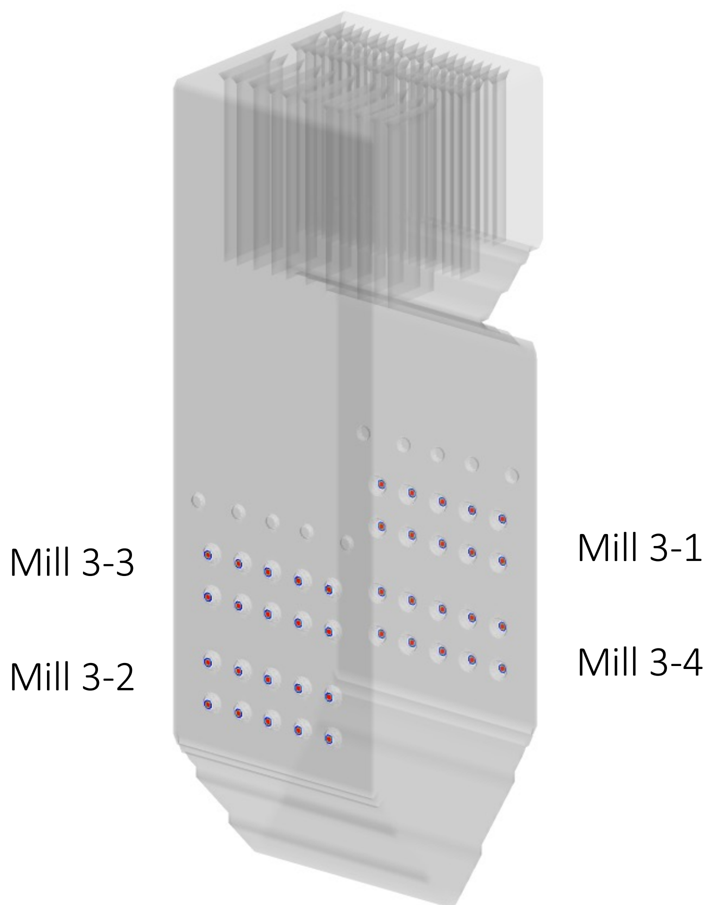
- Focus of Year 3
- Plant and sensor data review
- Boiler operation logic including soot blower operation

Load Swing at Hunter Plant

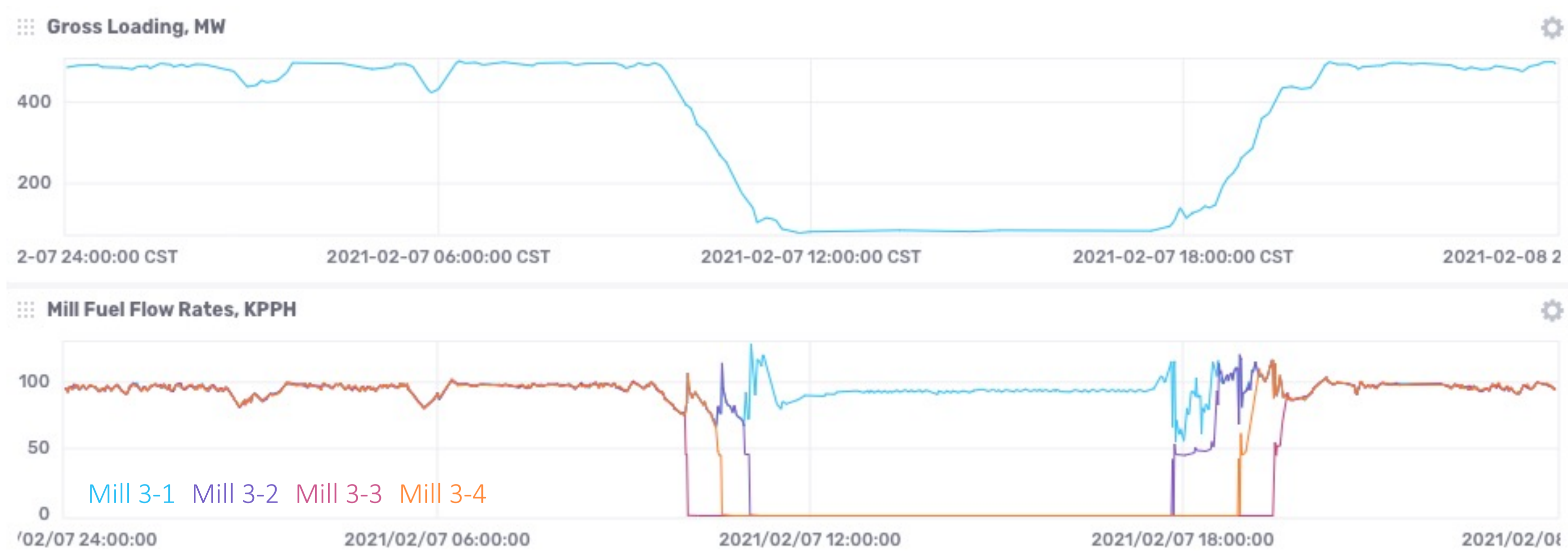


- As California solar power ramps up, the unit has cycled more aggressively down to less than 20% of full loading
- The loading changed daily during monitoring
- Load swing related waterwall wastage is a concern

Mill Operations



Equipped with 40 B&W DRB-4Z LNBs and 10 dual-register OFA ports

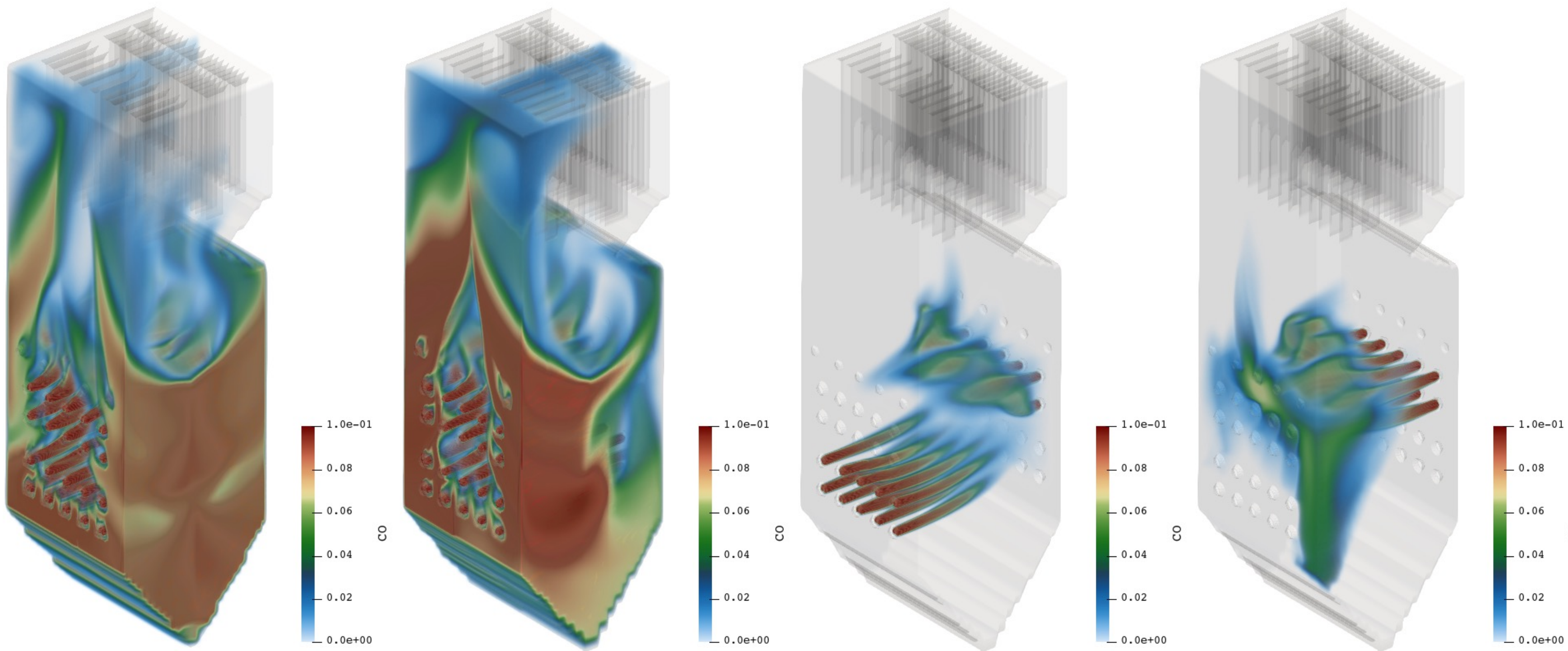


500 MW		~ 350 MW		~ 230 MW		~ 100 MW	
Mill 3-1	O	Mill 3-1	O	Mill 3-1	O	Mill 3-1	O
Mill 3-2	O	Mill 3-2	O	Mill 3-2	O	Mill 3-2	X
Mill 3-3	O	Mill 3-3	X	Mill 3-3	X	Mill 3-3	X
Mill 3-4	O	Mill 3-4	O	Mill 3-4	X	Mill 3-4	X

Changes in mill operations can result in significant change in the near wall environment

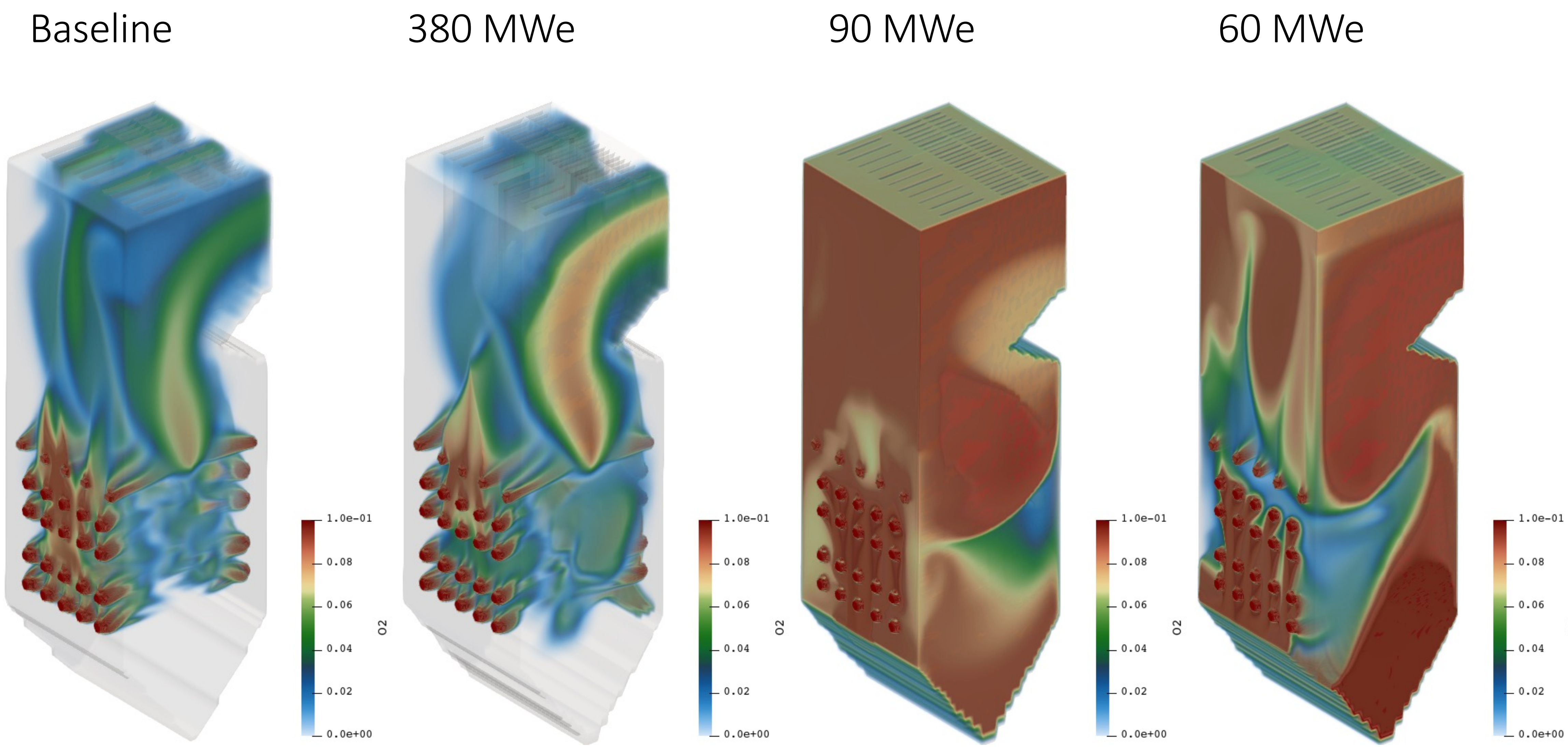
CO: Front and Right Side View

Baseline 380 MWe 90 MWe 60 MWe



Volumetric rendering showing 3D distribution of CO in the furnace

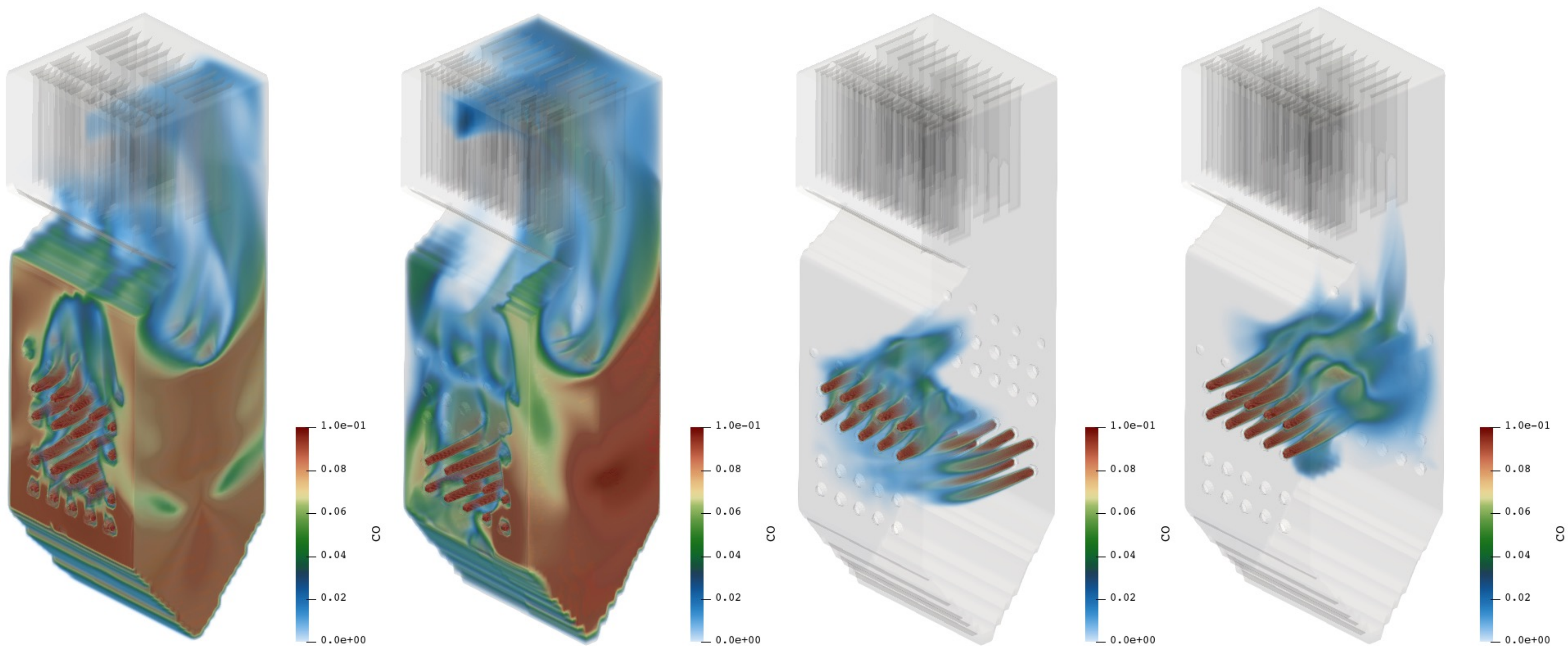
O_2: Front and Right Side View



Volumetric rendering showing 3D distribution of O_2 in the furnace

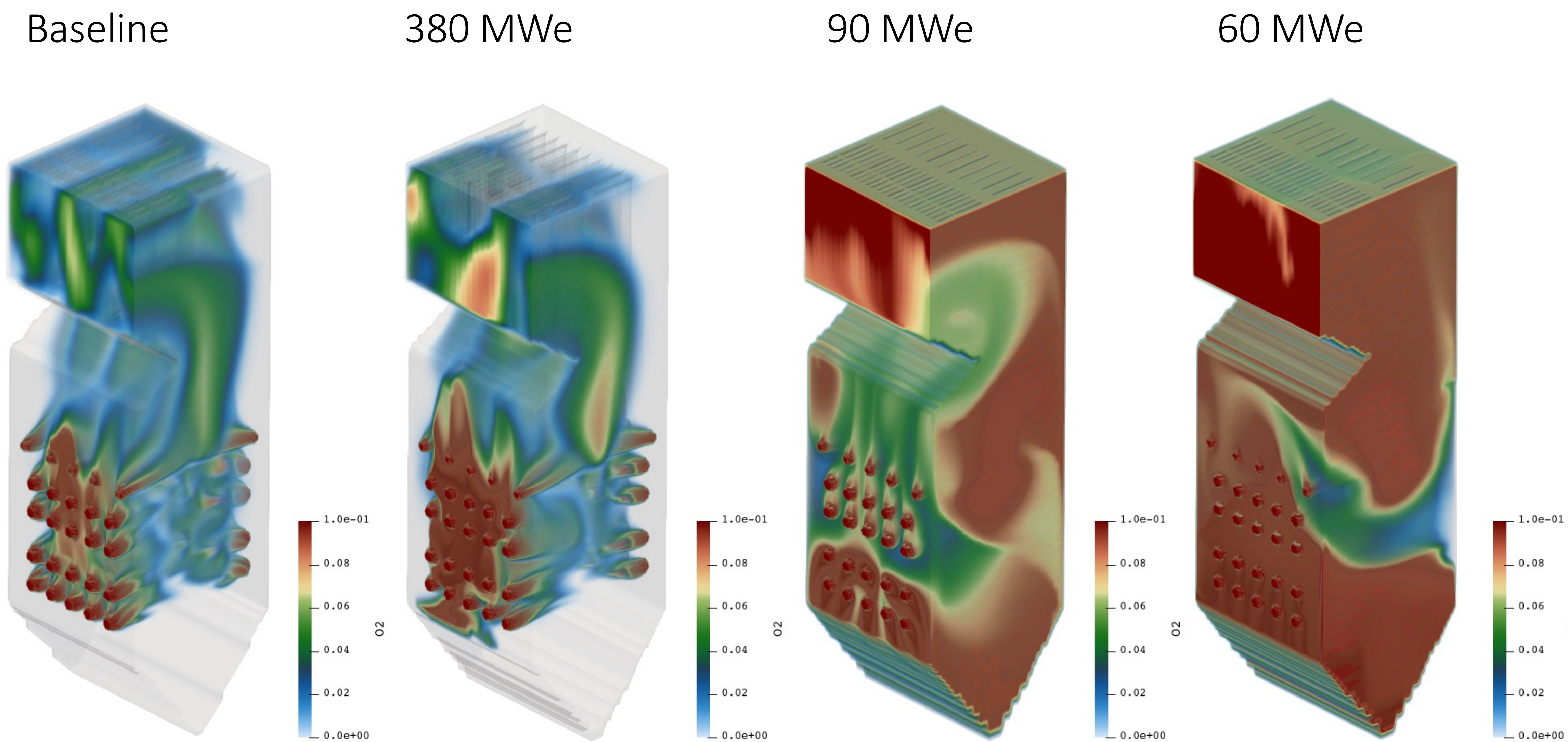
CO: Rear and Left Side View

Baseline | 380 MWe | 90 MWe | 60 MWe



Volumetric rendering showing 3D distribution of CO in the furnace

O_2: Rear and Left Side View

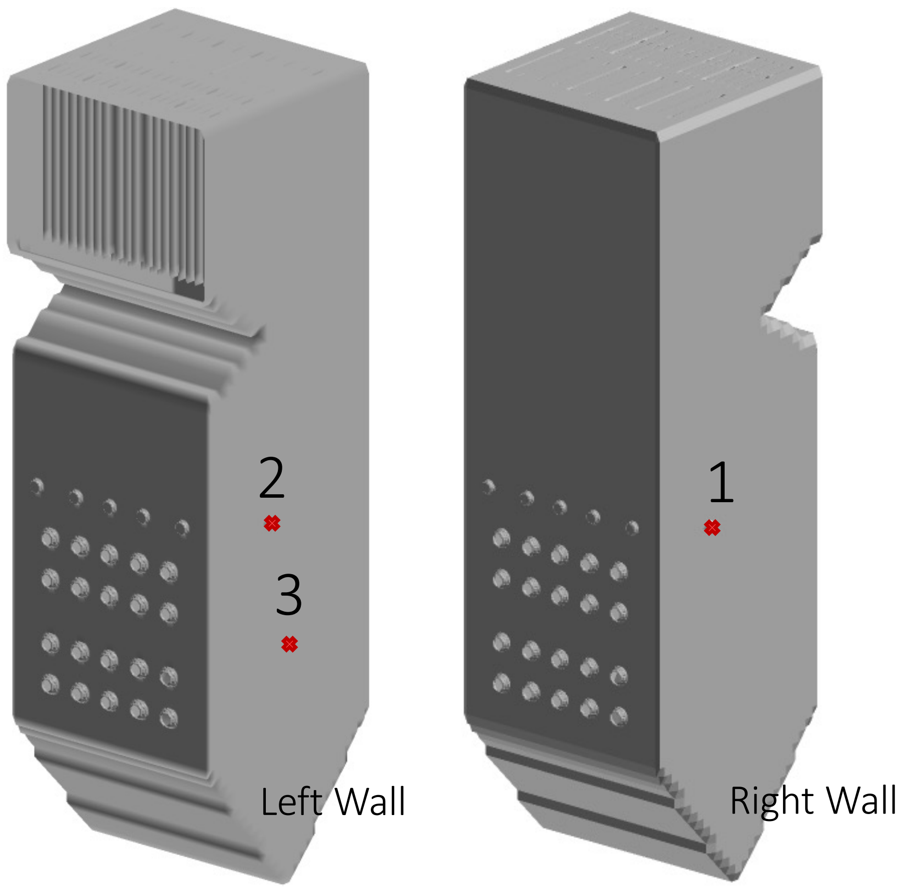


Volumetric rendering showing 3D distribution of O_2 in the furnace

Implication of Heavy Cycling

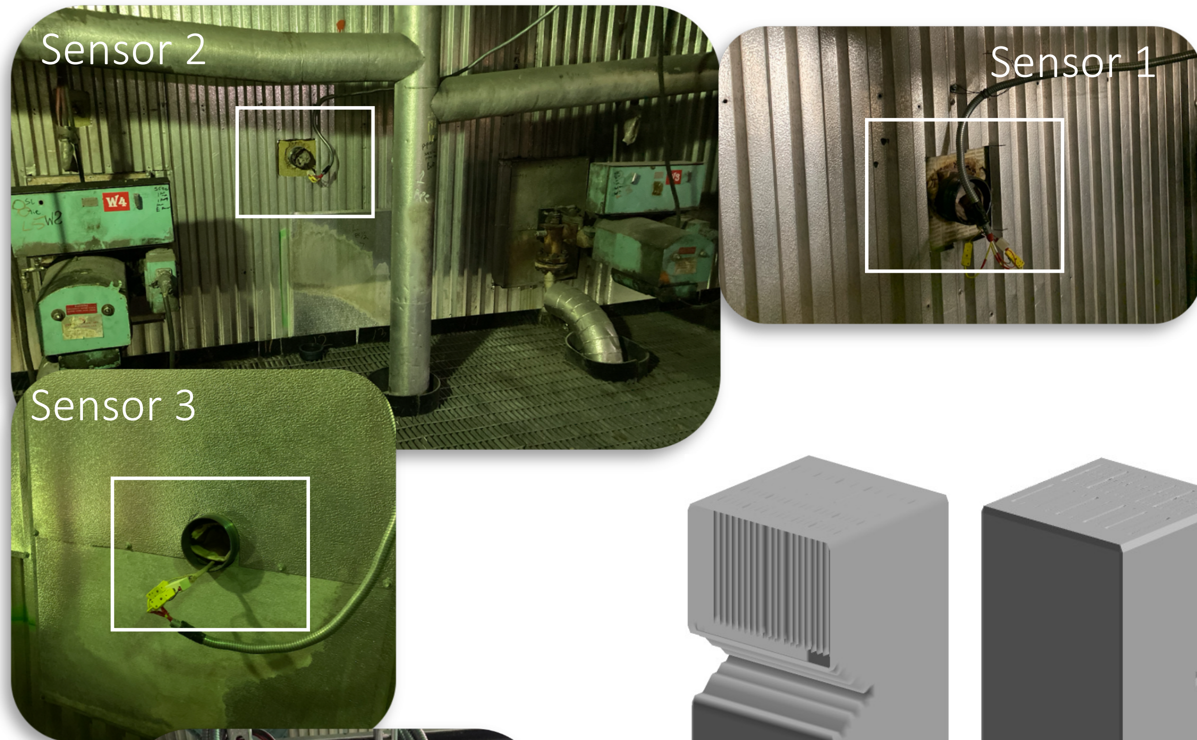
- Heavy cycling at Hunter can change the near wall environments from oxidizing to reducing or vice versa in relatively short time
- Alternating conditions between oxidizing and reducing can
  - limit the formation of the protective oxide scale on the metal
  - repeat formation and shedding of the oxide scales
  - expose bare tube metal surface to corrosive species in the furnace
  - deposit with unburned carbon can form locally reducing conditions for sulfidation
  - This alternating conditions, as a result, can accelerate fire-side tube metal wastage

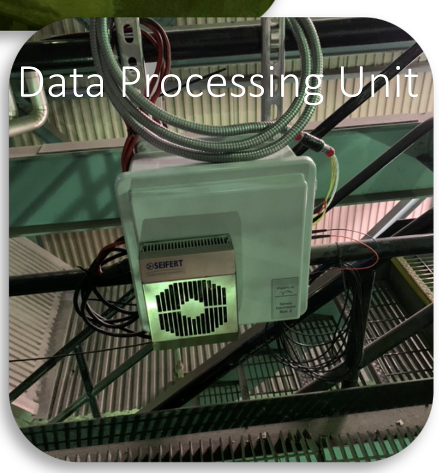
Sensor Locations

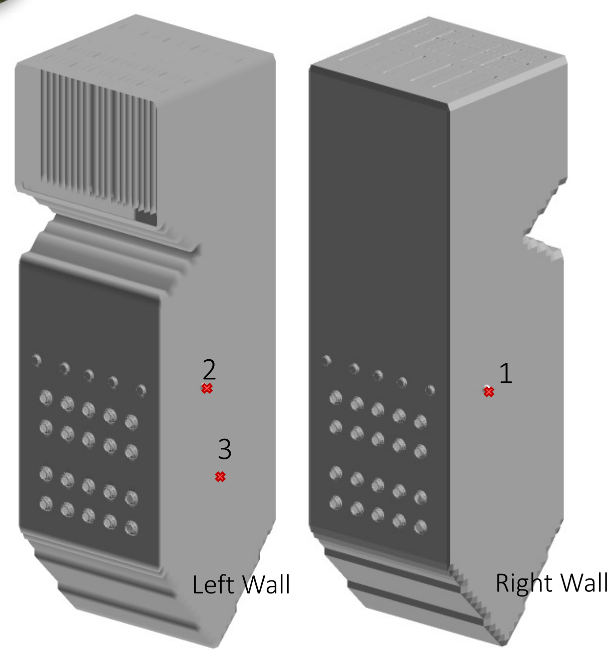


- Sensor locations are based on plant observations and CFD modeling
- 2 sensors placed just below OFA on either side wall
  - High metal wastage
  - Alternating between oxidizing/reducing while cycling
- 1 sensor placed in center of burner region on left wall
  - Location of highest metal wastage

System Installation



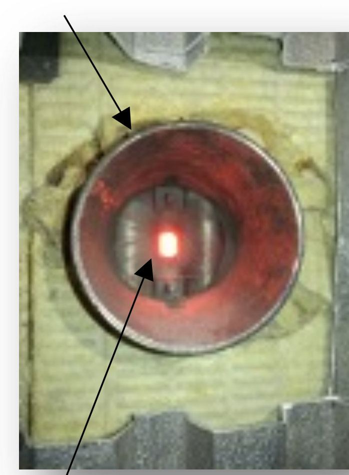




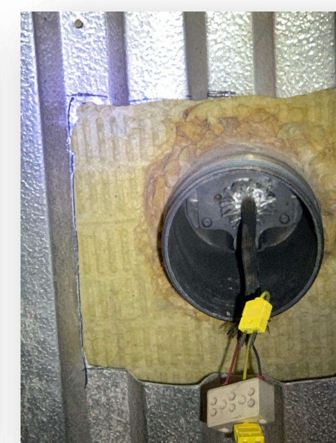
DPU is installed nearby rail

Pipe welded to boiler tubes and capped off to seal membrane hole when not in use

Support pipe



Membrane hole



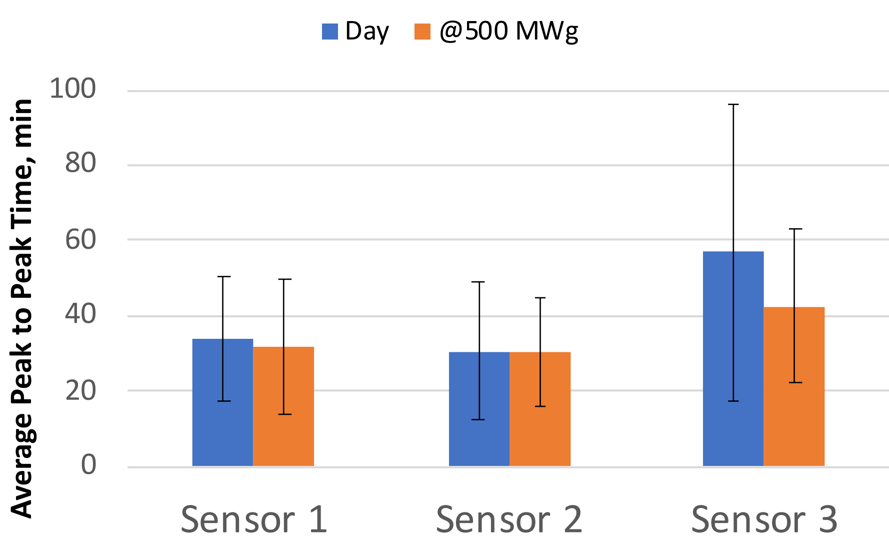
Installed Sensor

Data from Installation Week

December 9 – 16, 2020

- Boiler cycles between 100 to 500 MWg during this time frame
  - -150 MW/hr- +230 MW/hr
- Mill fuel flow rates change accordingly

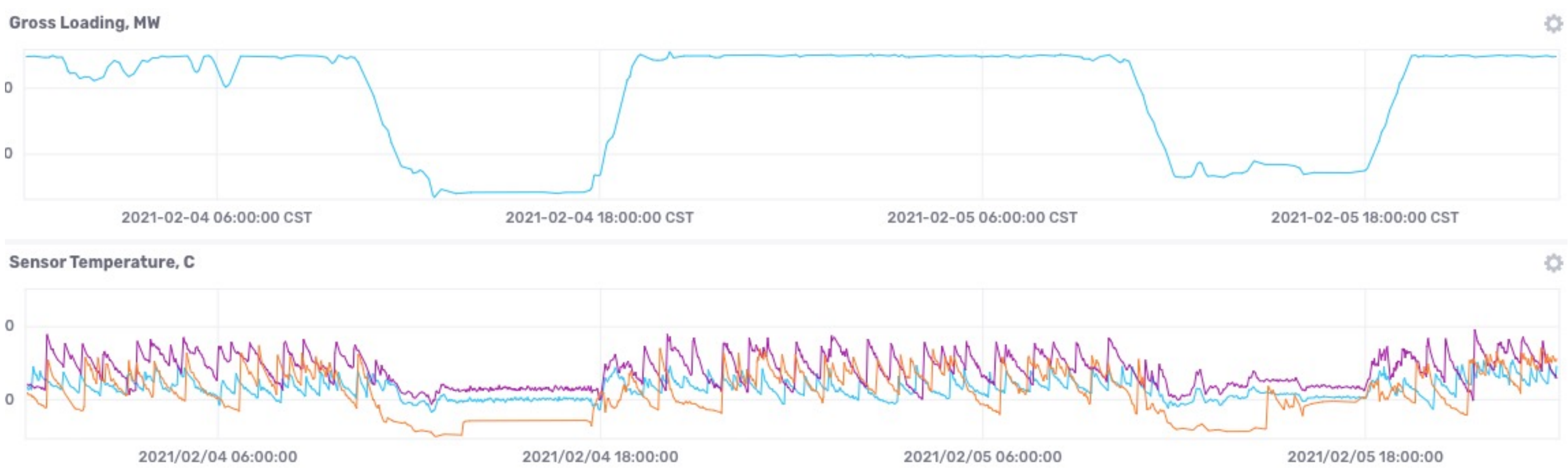
Sensor Temperature Changes

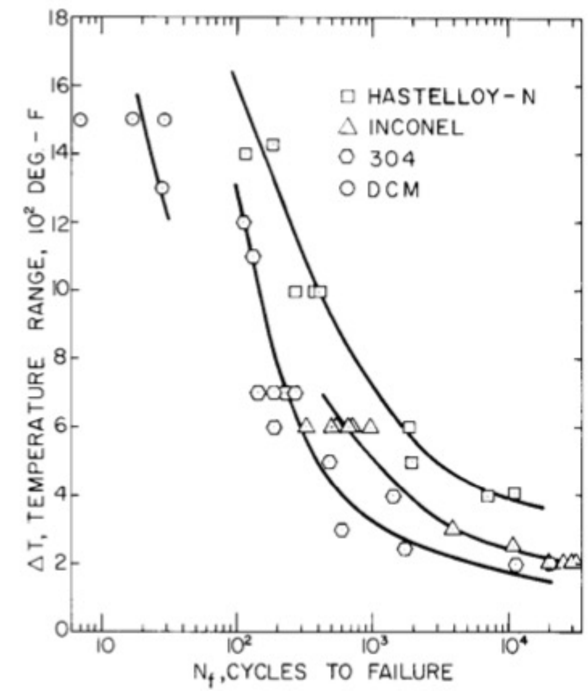


- Periodic changes in sensor temperature are observed
- This can be related to deposit formation and removal
  - wall blower operations
  - Inherent fluctuations of the flow and/or heat release pattern in the furnace from the wall burners
  - natural shedding of the deposits
- Similar temperature fluctuation found and high correlation with soot blower operation was observed in the Leland Old Station demonstration
- Burner zone sensor is more sensitive to loading changes:
  - Sensor 3 shows the higher average peak to peak time than the sensors 1 & 2
  - When only 500MWg conditions are considered, Sensor 1 and 2 do not show much change, but Sensor 3 decreases

Thermal Fatigue of Metal

February 4 & 5, 2021





[Carden, A. E. "Thermal-Fatigue Resistance: Material, Geometric, and Temperature Field Considerations," ASME 65-GTP-5, 1965]

- The metal surface temperature periodically fluctuates in all three sensors: Sensor 1 and 2 every 30 minutes less than 100C, Sensor 3 every 40-60 minutes over 100 C difference
- Reduced loading decrease the metal temperature and reduce the degree of the fluctuation or remove the fluctuations
- Temperature cycling can cause thermal fatigue of the metal and the data can be used for tube health monitoring

January 17 & 18, 2021

Date Change

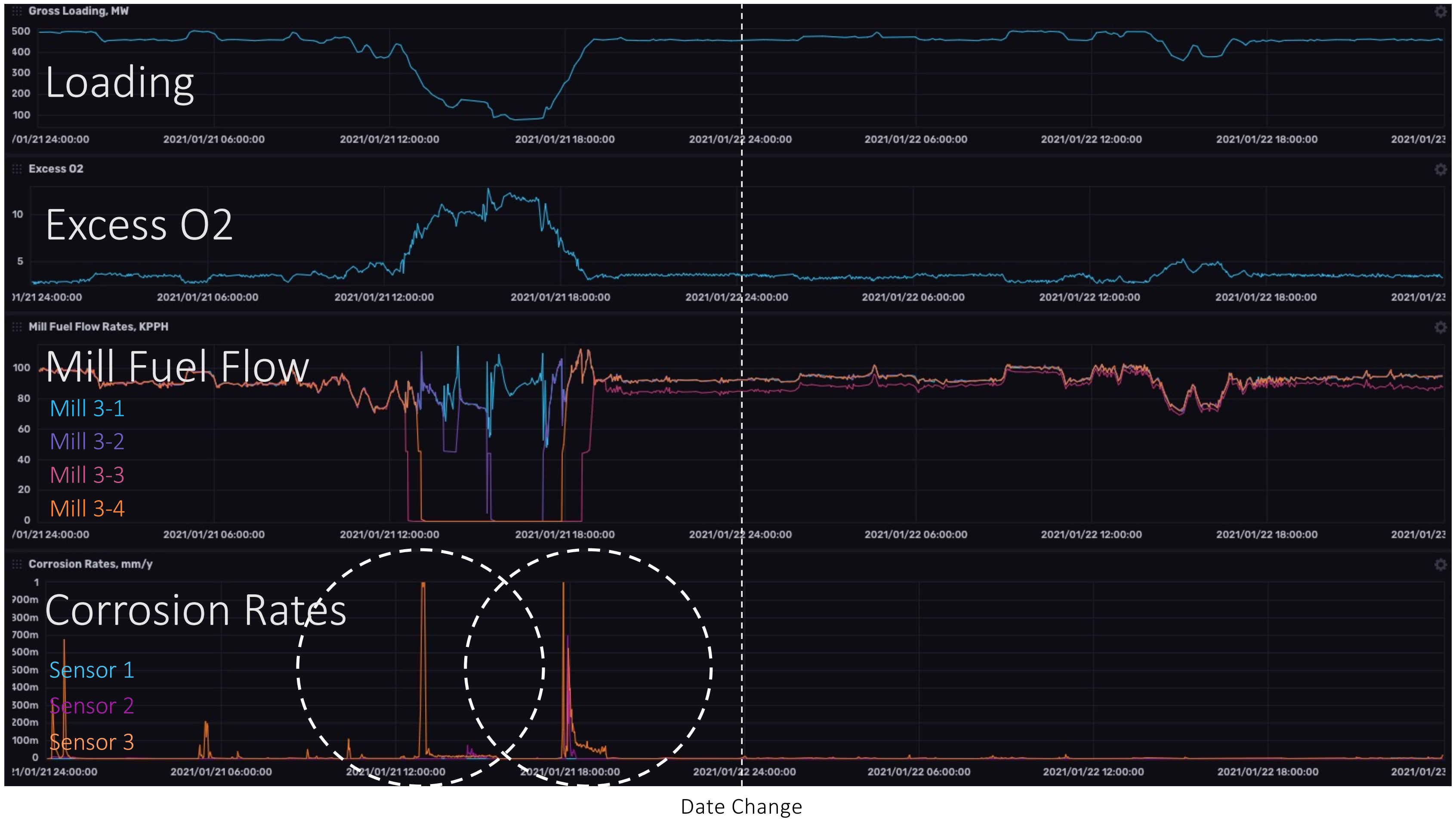
January 17, 2021

- Loading changes from 500MW to 80MW to 500 MW in one day (ramping down starts in the morning and reaches 80MW at noon and stays there about 5 hrs before ramping up to 500 MW)
- When load reduces, the mill operation changes in the order: #3-#4-#2 (reverse order when ramping up)
- Low corrosion rates during ramping down and at low loading, but moderate to high corrosion rates during ramping up (high rates from Sensor 3)

January 18, 2021

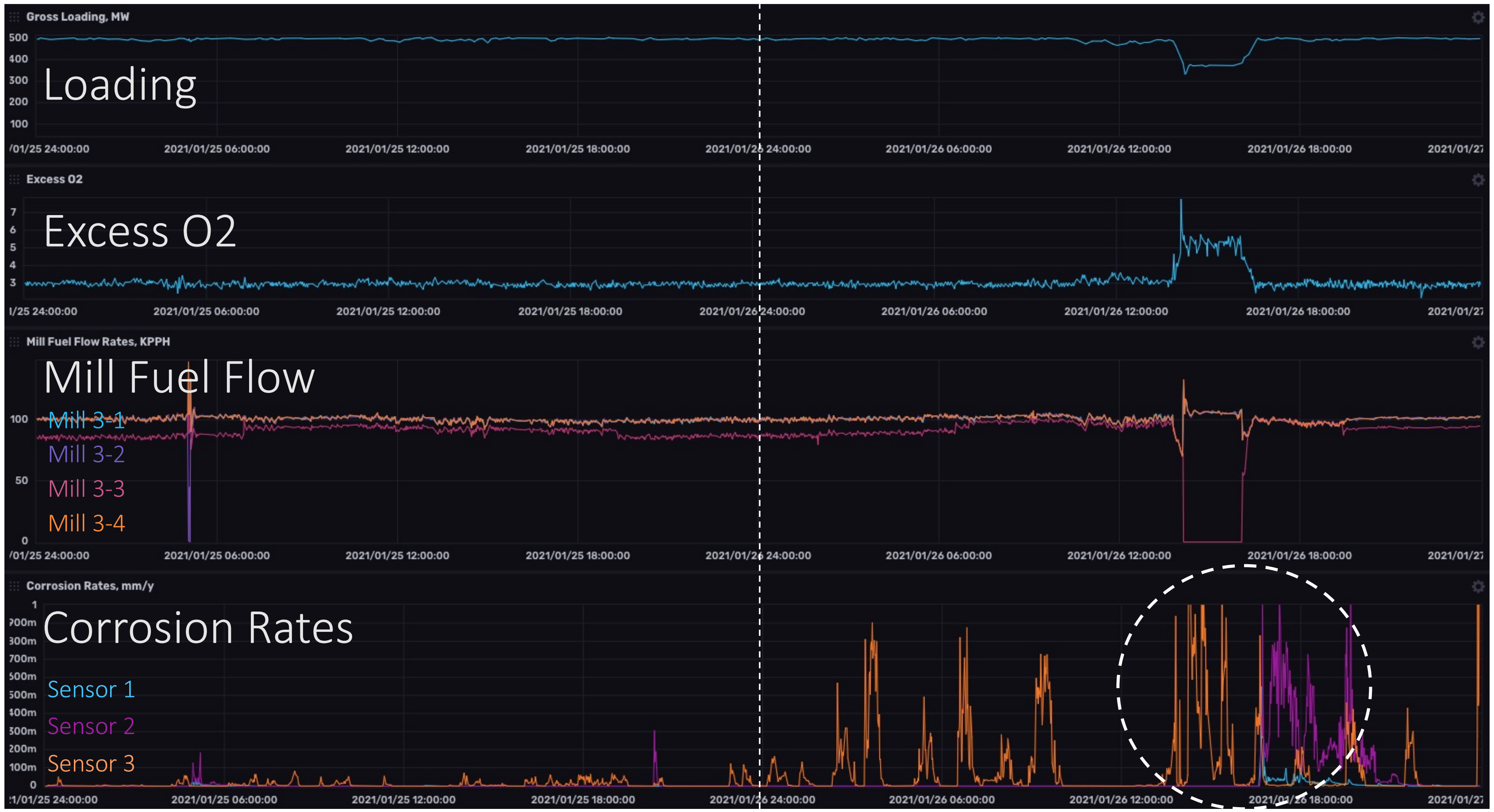
- Similar loading changes
- Low corrosion rates during ramping down and moderate rates during ramping up (more activities from Sensor 3)

January 21 & 22, 2021



1/21/21
• 500MW to 100MW then back to 500MW • Mill #3 - #4 - #2 off • When #4 off, sensor 3 show moderate corrosion rates • Ramping up again shows some corrosion activities on sensor 3: especially when mill#3 on
1/22/21
• Slight load decrease and no significant corrosion activities are shown

January 25 & 26, 2021



Date Change

1/25/21
• The loading maintained • Mill#3 has lower flow rates than the other mills • Low corrosion rates
1/26/21
• Early morning, moderate corrosion rates (Sensor 3) • Loading changes to 375MW by shutting off mill#3 • Then sensor 3 shows moderate-to-high corrosion rates initially followed by moderate rates at sensor 2

January 29 & 30, 2021

Date Change

1/29/21
• Low corrosion rates • Slight loading change but not significant • Mill#3 has lower flow rates than the other mills
1/30/21
• Loading reduced to 90MW • Mill off order: #3-#4-#2 • Sensor 3 shows high corrosion rates during cycling while the other sensors show low corrosion rates • During ramping up and down show high corrosion rates • During the same time frame, relatively high deposition measured at Sensor 3

January 31 & February 1

Date Change

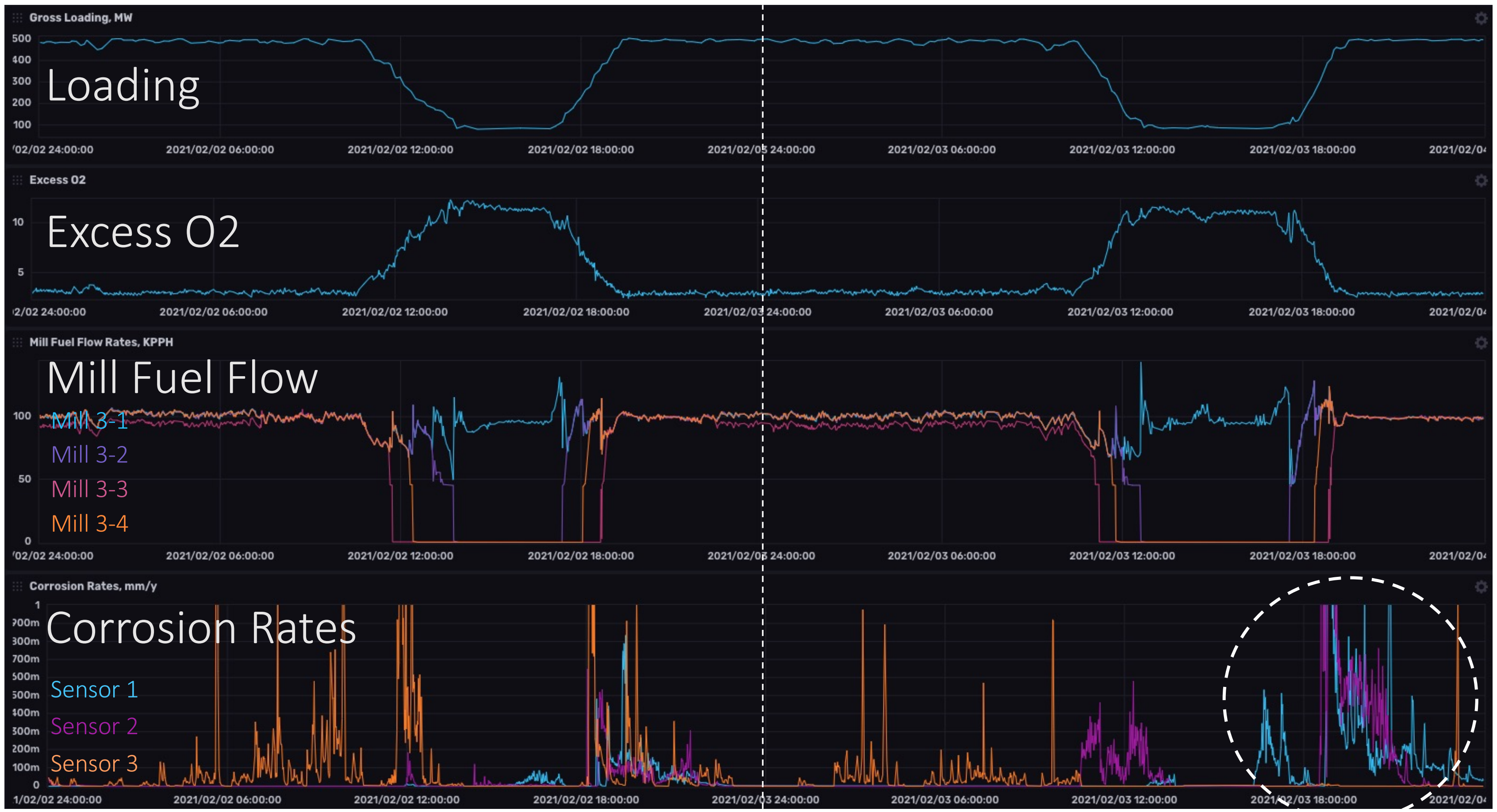
1/31/21

- Loading reduced to 100MW
- Mill off #3-#4-#2 order
- Loading back up to 500MW before operating at 250MW
- During transition moderate to high corrosion rates especially when ramping up
- At lower loading, the corrosion rates were low
- Deposition at the same time was low too

2/1/21

- Loading didn’t change much, but #3 has lower coal flow
- Some low to moderate corrosion activities
- Sensor 3 shows more corrosion activities than the other sensors (maybe it’s located at the burner zone and more sensitive to the mill operation)

February 2 & 3, 2021



Date Change

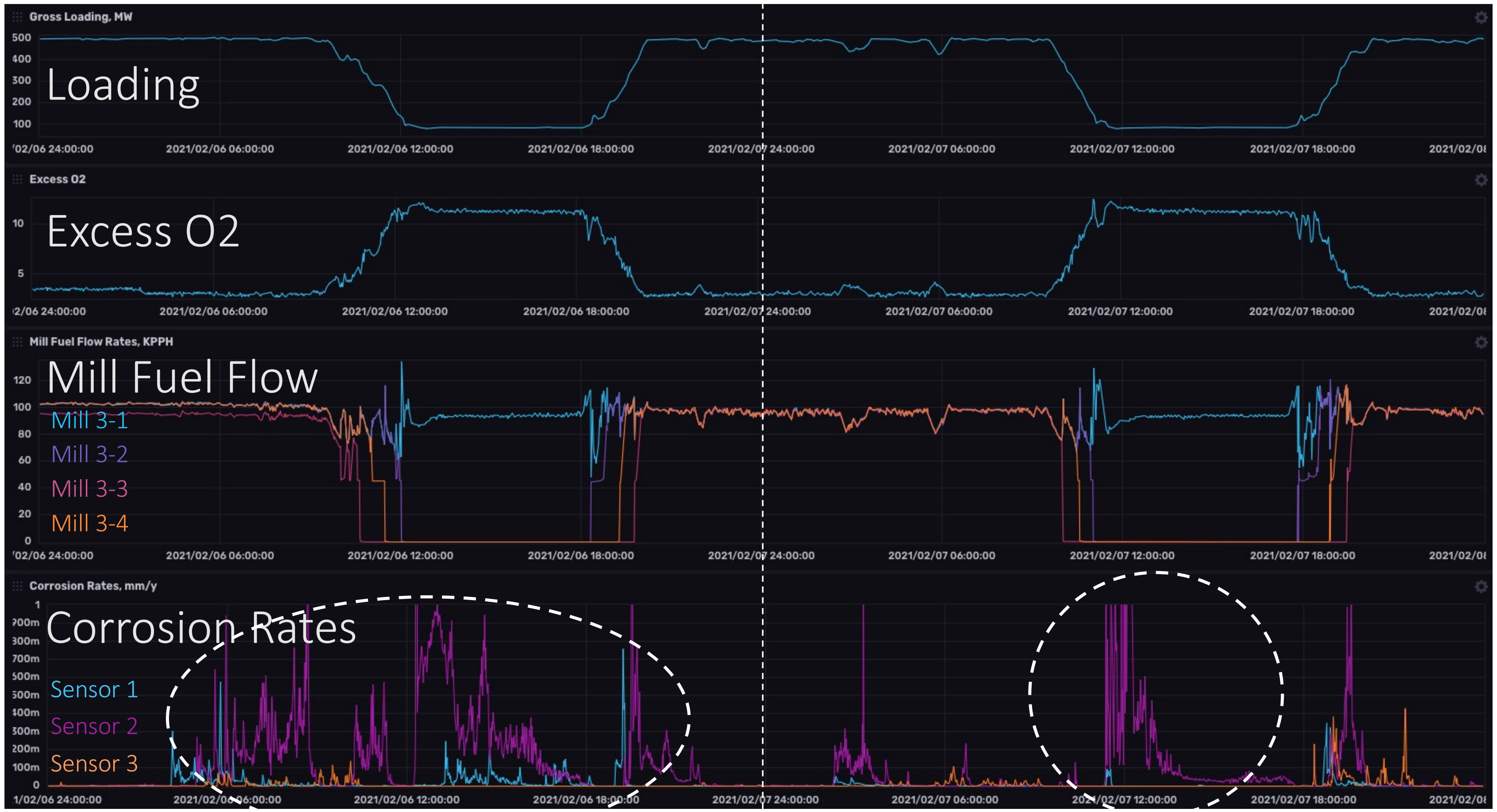
2/2/21

- Loading reduced to 100MW
- Mill off #3-#4-#2 order
- During transition moderate to high corrosion rates and sensor 3 seems more sensitive
- Ramping down: sensor 3 shows moderate to high corrosion rates
- Ramping up: In addition to sensor 3, sensors 1 and 2 also show low-to-moderate corrosion rates

2/3/21

- Similarly loading reduced to 100 MW
- Sensor 2 shows some activities but low rates during ramping down
- During ramping up, sensors 1 and 2 show moderate-to-high corrosion rates, not much corrosion activities from sensor 3
- During this, deposition was high for sensor 3 (maybe inert deposit)

February 6 & 7, 2021



Date Change

2/6/21

- Loading reduced to 100MW
- Mill off #3#4#2 order
- Moderate-to-high corrosion rates from sensor 2, but low from sensors 1&3
- This corrosion behavior is different from the previous experience, which illustrate dynamic nature of corrosion in the furnace (this can include some coal changes as well)
- During ramping up, moderate rates from sensor 1 and 2

2/7/21

- Loading reduced to 100 MW,
- Ramping down: Sensor 2 show moderate to high corrosion rates
- Ramping up: all sensor some corrosion activities, but low except sensor 2

Summary

- Successful development of mMPMS:
  - Miniaturization and modification of the sensors accommodating membrane installation and passive cooling
  - New signal conditioning module with improved data communication and resolution
  - Replacement of legacy data acquisition hardware with easily maintainable and scalable electronics
  - More than 50% of size reduction with updated electronics and smaller form factor
  - Development of new big data platform for collection and analysis
- Three mMPMS sensors and associated data processing units were successfully installed through the membrane walls in Hunter Unit 3
- mMPMS was demonstrated successfully
  - Sensitive to the near wall environment
  - Corrosion activities increase during transition: especially when the unit is ramping up, moderate to high corrosion rates are experienced
  - Burner belt sensor is more sensitive to the mill operation than the other sensors: this may be due to its proximity to the burners
- Deposition and heat flux data will also be analyzed
- Achieved 3200+ hrs continuous operation

Next Step: Data Analytics & AI

Artificial Intelligence

- Correlation analyses can provide some information about the direct relationship between parameters, but the true relationships are often too complex to be identified directly
- AI and Machine Learning provide many advanced, sophisticated model building methods to "map" or relate process inputs to desired process output(s)

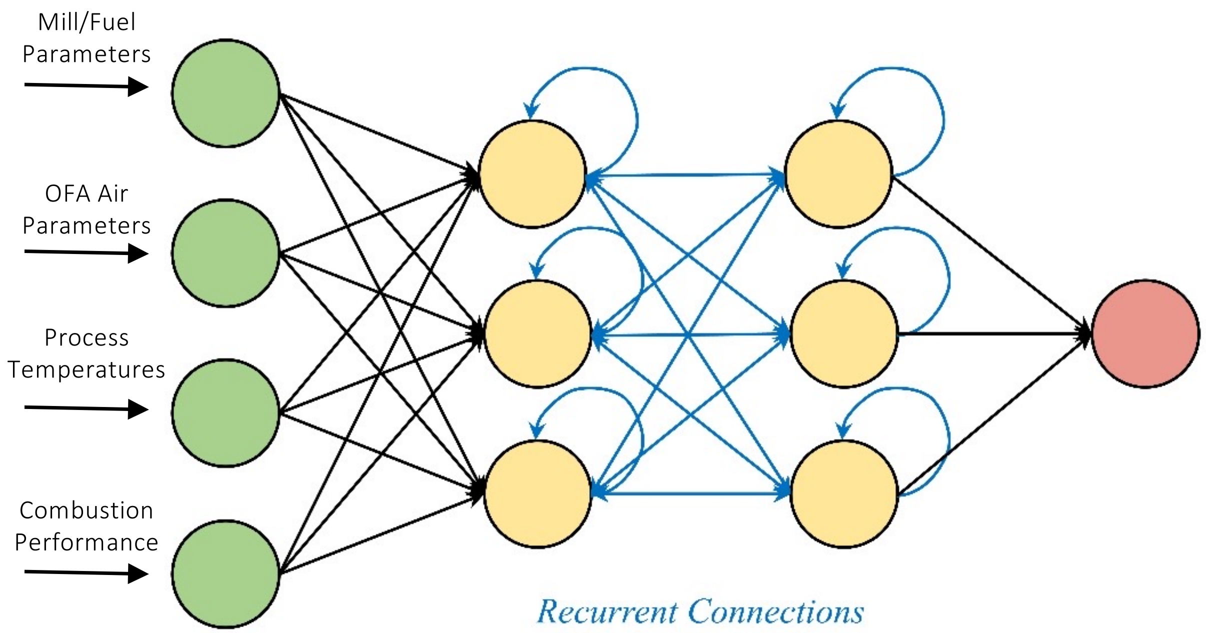
	probe1_ENCR (mm/year)	probe2_ENCR (mm/year)	probe3_ENCR (mm/year)
Excess O2 AVG	-0.047901457	-0.01548266	0.011076714
Coal Totalizer	0.053143478	0.015142987	-0.008097179
Total Fuel Flow	0.052006586	0.015152316	-0.008353875
Total Air (kPPH)	0.053597459	0.009199032	0.001801199
Total OFA Flow	0.042631326	0.013532556	-0.002117334
Mill 3-1 PA Flow KLBH	0.007607481	0.021972937	0.006985214
Mill 3-2 PA Flow KLBH	0.051114912	-0.005216228	0.027717287
Mill 3-3 PA Flow KLBH	0.038575819	0.015741014	-0.032441699
Mill 3-4 PA Flow KLBH	0.050857814	0.006198516	-0.008861001
Mill 3-1 PA Temp (In)	0.001619432	0.009858778	0.049902927
Mill 3-2 PA Temp (In)	0.054516454	-0.008966451	0.034331821
Mill 3-3 PA Temp (In)	0.037512267	0.01691799	-0.033500339
Mill 3-4 PA Temp (In)	0.055163999	0.003674841	-0.022658022
Mill 3-1 Coal Air Out Temp	-0.006460352	-0.003656918	0.011400496
Mill 3-2 Coal Air Out Temp	0.04136282	-0.028645716	0.021876816
Mill 3-3 Coal Air Out Temp	0.025478254	-0.001266893	-0.058430245
Mill 3-4 Coal Air Out Temp	0.043255335	-0.011292167	-0.041451968
Mill 3-1 Fuel Flow KPPH	0.017767251	0.028801402	0.012136985
Mill 3-2 Fuel Flow KPPH	0.053980259	0.000345505	0.027730943
Mill 3-3 Fuel Flow KPPH	0.037206097	0.022163041	-0.029951162
Mill 3-4 Fuel Flow KPPH	0.052120216	0.011176565	-0.019177461
AH 3-1 AIR IN AVG TEMP	-0.040283343	-0.003203362	0.014000965
AH 3-1 AIR OUT AVG TEMP	0.051406146	0.005719515	-0.013734743
AH 3-1 GAS IN TEMP	0.054505408	0.006199996	-0.008773677
AH 3-1 GAS OUT AVG TEMP	0.053118543	0.007583274	-0.014883644
AH 3-2 AIR IN AVG TEMP	-0.060358393	-0.00382564	0.023657919
AH 3-2 AIR OUT AVG TEMP	0.052871588	0.003482941	-0.018229712
AH 3-2 GAS IN TEMP	0.053452835	0.006936904	-0.008534969
AH 3-2 GAS OUT AVG TEMP	0.044374346	-0.069600158	0.056341899

Preliminary Correlation analysis, weak correlations among all parameters

Process Optimization using AI/ML

Artificial Intelligence
Machine Learning

The resulting AI models can then be used to optimize the process and realize minimum corrosion rates while also respecting other process limitations (e.g., low emission rates, acceptable efficiency and process temperatures, etc.)



Possible Control Structures with Constraints	Minimum Corrosion	Emission Rates < Limits	High Combustion Efficiency
Structure 1	Model Objective	Constrained Input	Constrained Input
Structure 2	Model Objective	Model Objective	Constrained Input
Structure 3	Model Objective	Constrained Input	Model Objective

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