REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

February 19-20, 2018, in St. Louis, MO / Hosted by Dynegy

INNOVATIVE ENERGY SOLUTIONS

RJM INTERNATIONAL

Larry Berg – Vice President of Engineering

Overview of Presentation

- Introduction to RJM
- Common Operational Issues
- Our Methodology: Overview
- Component: Detailed Analysis
- Component: CFD Modelling
- Component: Bespoke Hardware Design
- Conclusion

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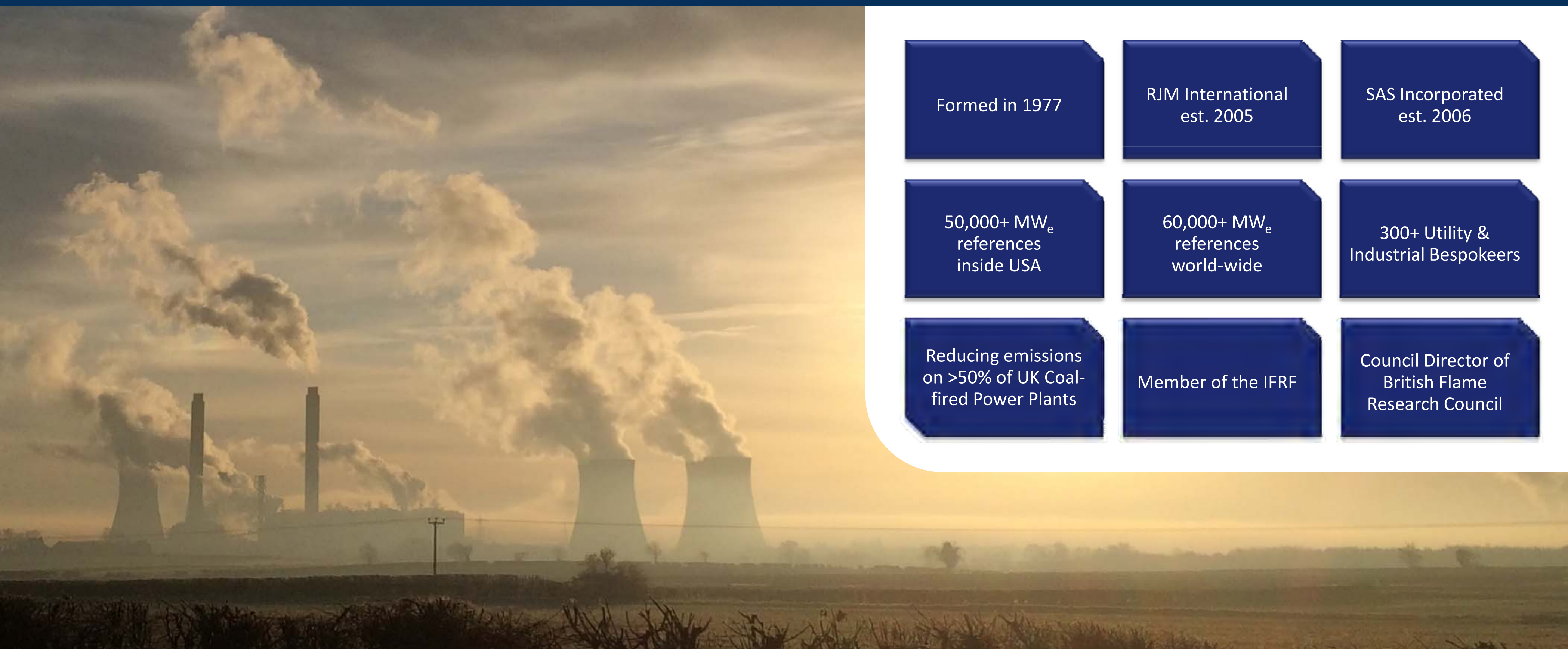
RJM International

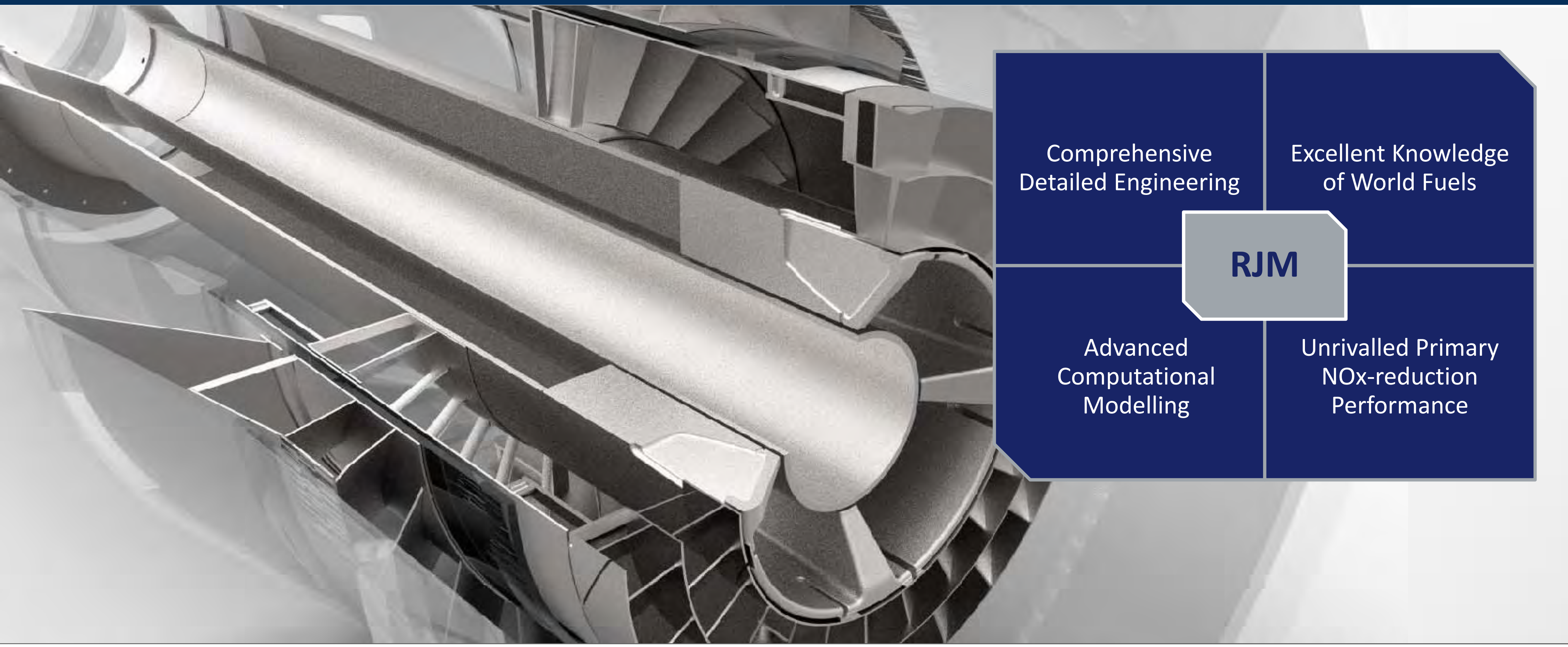
Resolving complex emissions challenges for coal, oil, gas and biomass-fired plant through the application of innovative, cost-effective solutions.

RJM International

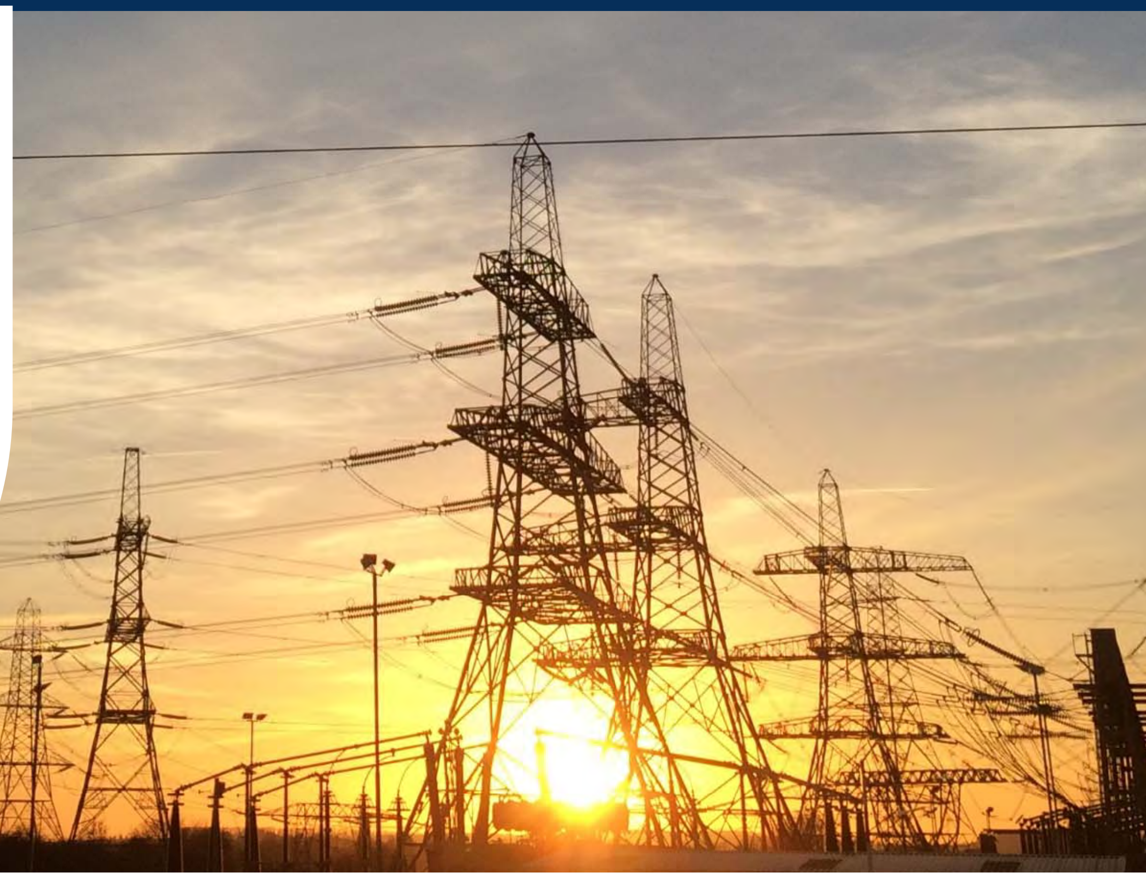


- Formed in 1977
- RJM International est. 2005
- SAS Incorporated est. 2006
- 50,000+ MW_e references inside USA
- 60,000+ MW_e references world-wide
- 300+ Utility & Industrial Bespokeers
- Reducing emissions on >50% of UK Coal-fired Power Plants
- Member of the IFRF
- Council Director of British Flame Research Council

RJM - Engineering Excellence



The RJM Approach



Products and Services

Hardware	Coal Firing Systems	Gas Firing Systems	Oil Firing systems	Biomass Firing Systems	Multi-fuel Burners	Biomass Conversion
	Fuel Conversion	Combustion Upgrades	Secondary Measures	Furnace Protection Systems (Flame Scanners)	Ignition systems	CFD Modelling
Services	Owner's Engineer Services	Technical Services Agreement	Combustion Audit	Investment Assessment	Boiler Optimisation	Boiler Control Systems Tuning
	Fuel Assessment	Benchmarking	Boiler Performance Study	Feasibility/FEED Study	Remote Performance Monitoring	Physical Modelling
Safety	Materials Handling Review	Outage Optimisation	Operator Training	Incident Investigation	Safety System Review	Explosion Protection Assessment (GT)
	Safety Training and Awareness	Fuel Safety (PF Code of Practice)	ATEX Assessment	HAZOP/HAZID	LOPA/SIL Assessment	Baseline / Performance Testing

Successful Projects - Examples

Sub 10 ppm NOx (@ 3% O2, 50 ppm CO)

30% NOx reduction below OEM on brown coal

New T-fired technology (Pat Pend)

New plant performance on 40 year old boilers

50% increase in operational range for 1950's boiler

Elimination of 1 psig fire-side pressure excursions

Inputs and pressures to these include:

- Strong economic incentive to solve emission requirements with combustion modification only. These techniques are known as 'Primary Measures'
- Problems are created created by pushing combustion system performance which must be dealt with in project progression

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Common Operational Issues

These issues can be exacerbated:

- Strong economic incentive to solve emission requirements with combustion modification only. These techniques are known as ‘Primary Measures’
- Problems are created created by pushing combustion system performance which must be dealt with in project progression

Unusual fuels

Past modifications

Combustion system design

Plant “Uniqueness”

Local Conditions, Maintenance, Operator training and knowledge

Local emission mandates

Common Operational Issues (Combustion)

- Over-heating Super Heater
- High CO levels
- Tube Ruptures
- Smoke emitted from Stack
- Loss of Capacity
- High Excess Oxygen Levels
- NOx Emissions above permit
- Burner Instability

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Our Methodology

“Biggest risk of any project is what you don’t know.”

Detailed Analysis – Comprehensive review of Existing Operations

CFD Modelling – Thorough investigation of process modifications

Bespoke Hardware Design – Provide hardware Bespoke engineered for the plant

The RJM Method optimizes information and minimizes risk

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Detailed Analysis

The Combustion Audit

A team of 2 to 3 engineers spend 2 to 3 days at site

Historical and current data is amassed, including collection of boiler drawings

Data collection

Burner information is collected

(type, zone arrangement and dimensions)

Operating conditions

•Flame pattern is observed, as are boiler conditions and operation

Plant operators are interviewed

Detailed report outlining performance limitations and pathways to mitigation, including high level cost-benefit analysis.

Detailed Analysis
Low Windbox Pressure

ASME Power 2013 - 98219

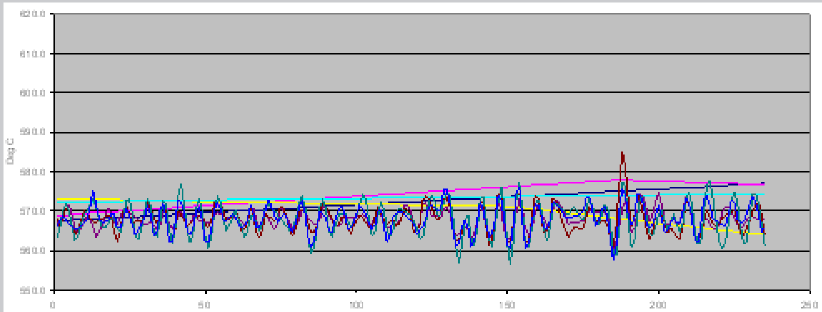
500MWe coal fired boiler had regular SH tube failure and high SH temps

Sequential modifications for Nox performance had lowered Windbox pressure to 0.25”

Detailed Analysis
Low Windbox Pressure

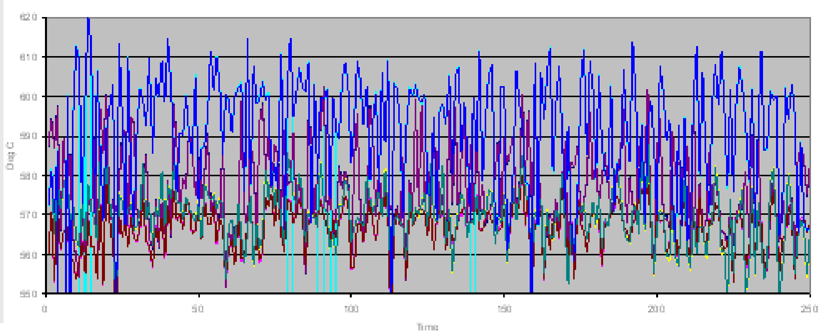
Average Superheater Temperature

Pre OFA



568°C

Post OFA



585°C

ASME Power 2013 - 98219

500MWe coal fired boiler had regular SH tube failure and high SH temps

Sequential modifications for Nox performance had lowered Windbox pressure to 0.25”

Conclusion: Incorrect momentum ratios and long flames

Detailed Analysis

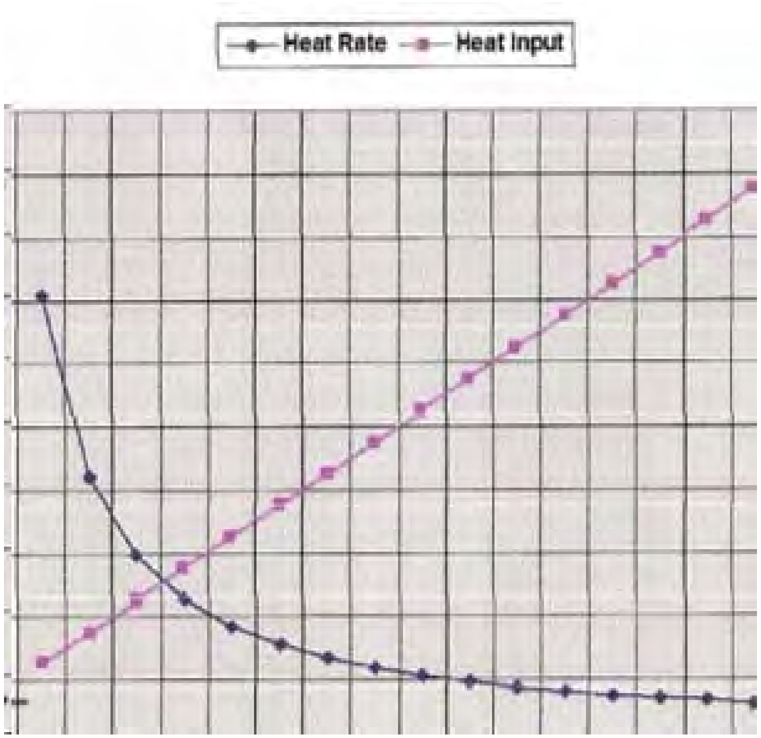
Heat Rate Variation

Client has manual Natural Gas burners

Economic benefits available with increased flexibility

- Increased range with same burner configuration
- Better use of available pressure range
- Need accurate gas flow vs. MW net
- Information determined from details obtained during Combustion Audit

- **Accommodated successful design of hardware**



Detailed Analysis
Localized High CO

Black tubes

Black pipe in windbox

Smaller Nat Gas boiler of late 1970s vintage

Unit either had CO or NOx excursions

- Plant had NOx retrofit late 1990's
- Aromatic odor noticed near one burner
- Econ testing showed very high CO in one location
- Operators had pics from recent outage

Pre-APH CO

Extrapolted to Boiler Front

4	1	1	110
12	4	14	138
203	3	13	928

Detailed Analysis
Improve Stack Opacity

Combustion Audit Findings

During a previous NOx reduction:

- Burners were changed
- Burners were put Out of Service (BOOS)
- At the time, base load at SS
- Problem became acute with new operations
- Rapid load changes, assisted by wind generation

It was strongly suggested that:

- Burners were not adjusted properly
- BOOS were not mixing well

Recommended Action

Inspected burners during outage

- One burner which was supposed 100% open was in fact only 40% open
- The same burner had high CO and aromatics
- All burners registers were adjusted to read properly

Result

- **At start-up**
  - CO and opacity were eliminated
  - NOx was brought down to compliance

Detailed Analysis
Correct Burner Settings

The combustion audit in this case showed visual differences

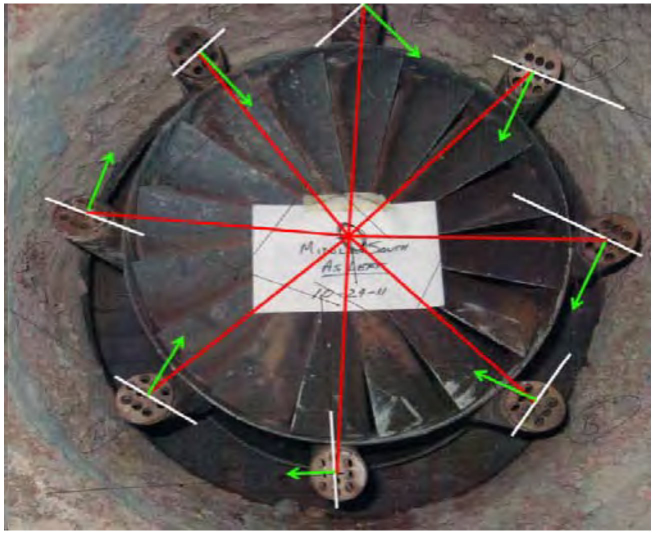
Stable flame

Unstable flame

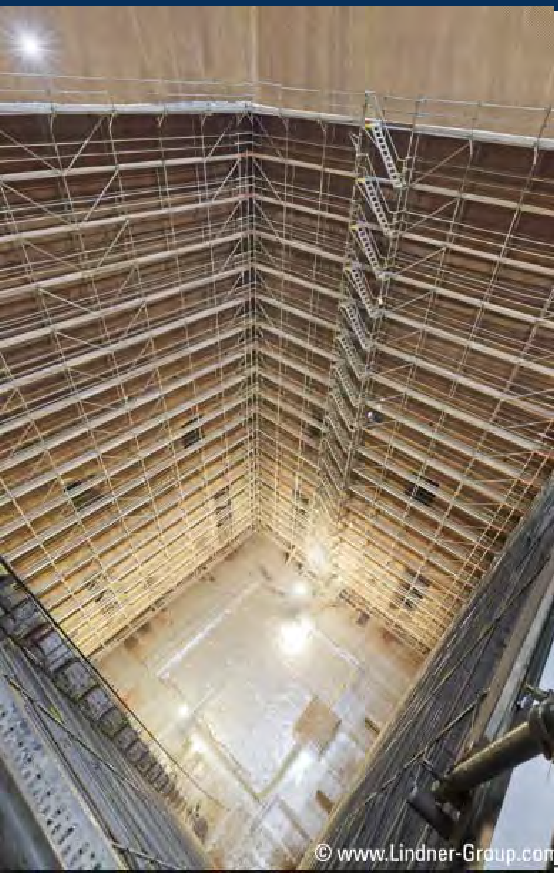
Combustion Audit identified incorrect poker alignment, affecting burner stability.

Recommended Action to realign pokers at earliest available opportunity.

Result on start-up, stability established.



Detailed Analysis
Stalled Furnace



T-Fired "Slagging" Boiler
178 Meter High

Conclusion:
Furnace rotation was compromised, or "Stalled"

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CFD Modeling

Component: CFD Modelling

- Superheater Life Expectancy
- NOx Lower than Expected
- Pressure Excursion
- Stalled Furnace Rotation

CFD Modeling

Senior staff have over 50 years combustion CFD experience with unique combustion models developed over 30 year periods

Achievements include accurate **NOx measurements** in a range of settings:

500 MW, Front wall fired with Columbian coal	1970s gas furnace	New burner installation	New burner installation
• 184 mg predicted, 209 mg achieved • IED compliant	• 100 mg predicted, 98.4 mg achieved	• 15.1 ppm with 1.7% O2, • 25% FGR predicted	• 15.0 ppm with 1.0% O2, • 20-25% FGR achieved

CFD Modeling

Senior staff have over 50 years combustion CFD experience with unique combustion models developed over 30 year periods

Achievements include accurate **CiA measurements** in a range of settings:

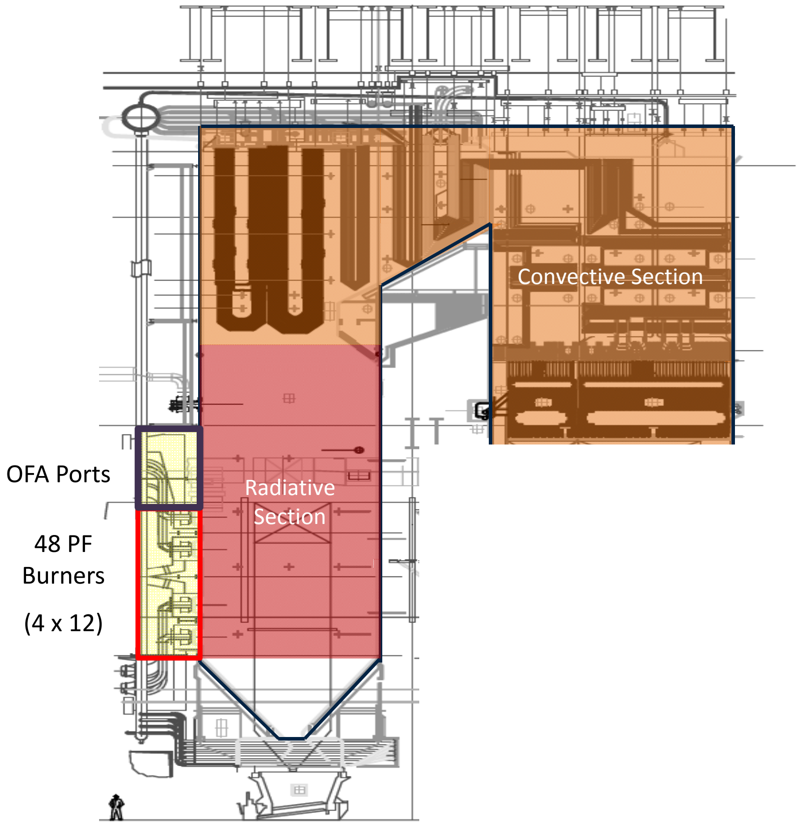
220 MW T-fired boiler, South African coal	500 MW front wall Unit, Columbian coal	620 MW "W – Downshot", Anthracite coal	500 MW Front wall fired, South African coal
• 5.65% CIA, 4.5% O2 predicted • 5.9% CIA, 4.2% O2 achieved	• 5.5% CIA predicted • 6.0% achieved	• 2.4% CIA predicted • 2.7% Measured	• 5.8% CIA predicted • 6.5% measured

CFD Modeling
Published Papers

Unburned Carbon	Using CFD to reduce Unburned Carbon; *Berg, Goldring, Woodward, Smith, 32nd International Technical Conference on Coal, Clearwater FL, 2007*
	Computational modeling and empirical measurement of the devolatization and combustion of a high volatile Colombian coal; *Kryjak, Lester, Perkins, ECCRIA, 2017 (http://www.eccria-conferences.org/)*
NOx reduction	NOx reduction using advanced techniques in a 175 MW multi-fuel corner fired boiler;*Kryjak, Dennis, Ridler, INFUB 2017*
	NOx Emissions Reduction on a Corner Fired Boiler; *Steve Cornwell, John Goldring and James Dennis, "Kotel a Enegeticka Zarizeni, Brno, Czech Republic, 14-16 March 2016*
	Innovative RJM retrofit achieves new Plant NOx Standards on 1970's Gas Units; *Berg, Shields, Goldring, Nesbitt, PGI – 2017, Los Vegas, NV.*
	The cost-effective way to NOx compliance in India; *Goldring, Riley, Cohen, Kryjak, Power-Gen India, 2017*
Operations	Performance Improvements on a Lignite Fired Boiler; *Goldring, Cornwell and Billett; Kotel a Enegeticka Zarizeni, Brno, Czech Republic, 14-16 March 2016*
	Utilization of CFD to Reduce NOx, Improve Efficiency and Reliability of a PC Boiler; *Berg, Goldring, Sharp, ASME Power Gen, paper Power2013-98219*

CFD Modeling

Superheater Life Expectancy



Problem

- Compromised Super Heater Life

Combustion Audit Findings

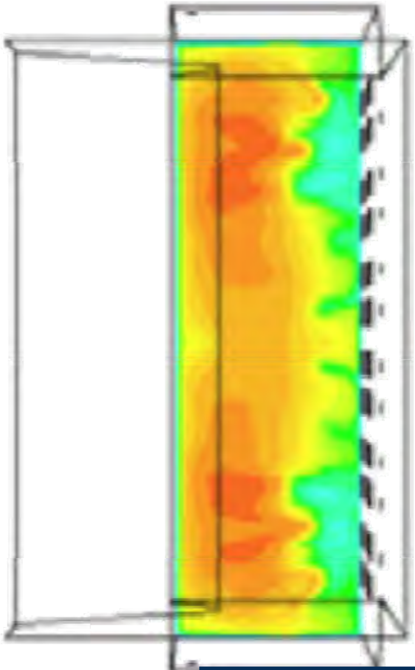
- Low Windbox Pressures (~ 0.25" wg)
- Ruptures started ~ 5 Years after burner modifications
- High Temperatures on Super heater Tubes
- Field Data: the burners are likely oversized
- Resulting in long flame lengths
- (ASME Paper Power2013-98219)

CFD Modeling
Superheater Life Expectancy

- **Combustion Audit** identified low WB pressures
- Client experienced repeated Superheater Tube Failures
- *ASME Paper Power 2013-98219*

- Direct CFD study to investigate **flame lengths**

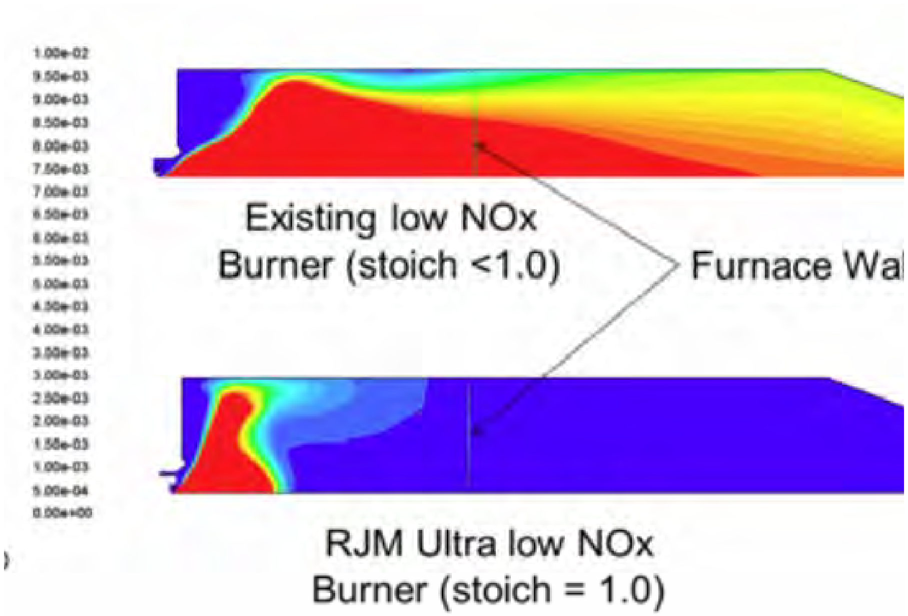
- **Baseline CFD** model shows fire on rear wall
  - Low Secondary Air Velocity
  - High Fuel Momentum



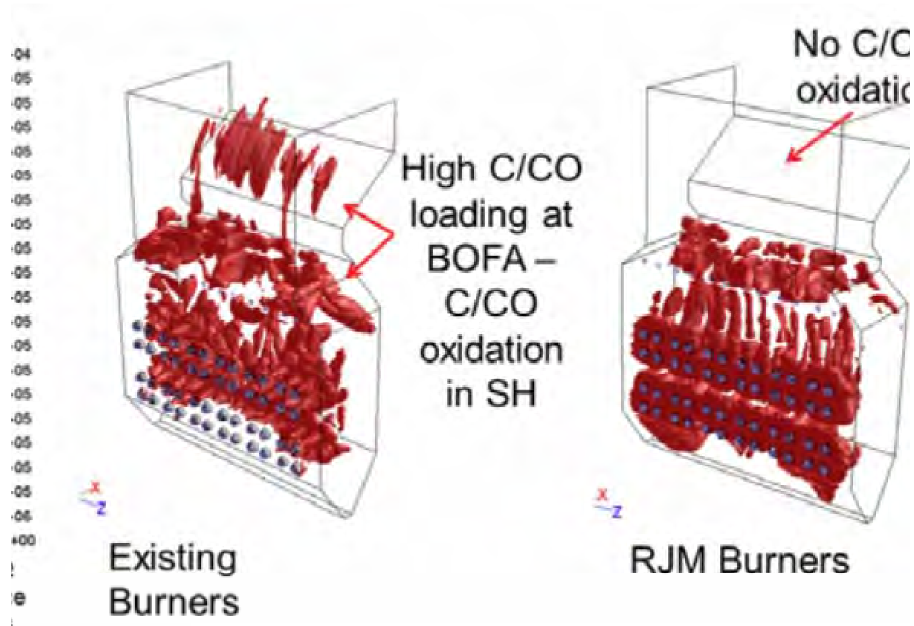
Contours of Temperature taken at burner level

CFD Modeling

Poor SH Tube Life

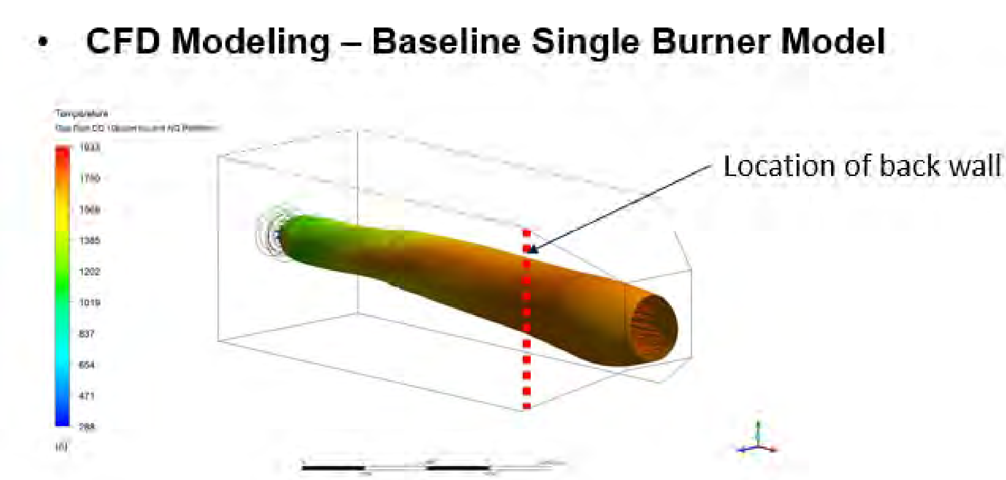


Single burner model
Existing operation has long flame
Proposed has very short flame



Furnace Model
Existing has combustion in SH's
New eliminated SH combustion

CFD Modeling
Lower NOx than Anticipated



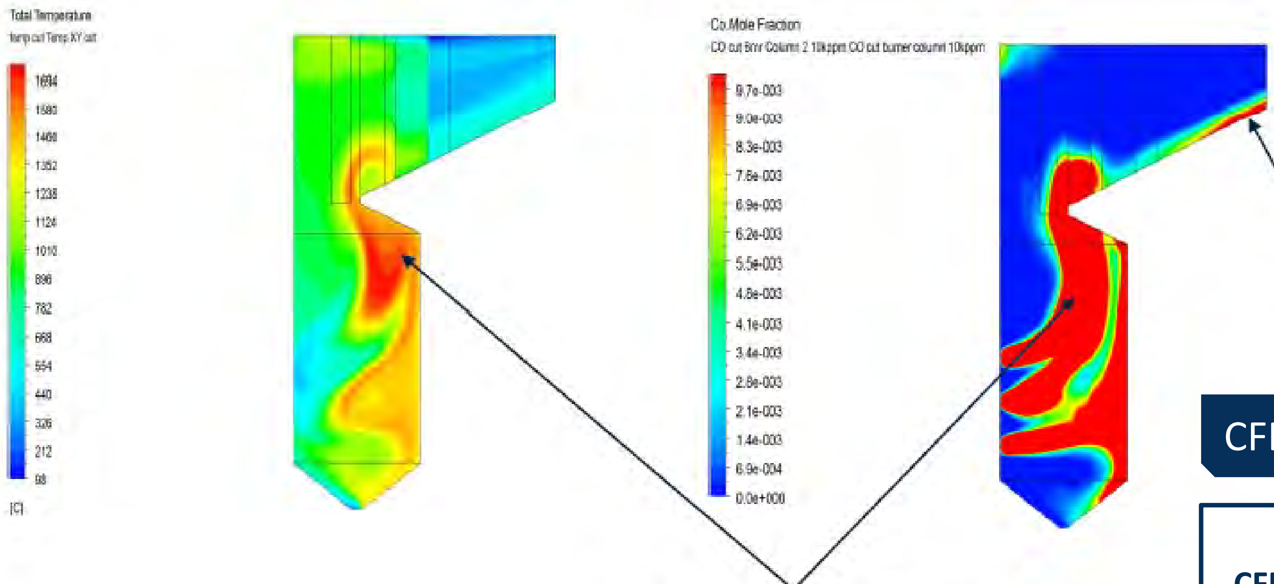
Power Gen Paper PGI 2017
Innovative RJM Retrofit

Combustion Audit showed NOx of 218 mg/Nm^3 (0.13 lbm/MMBtu when closer to 0.3 lbm/MMBtu was anticipated

CFD was used to look for extra cooling on gas flames.

CFD Modeling

Lower NOx Caused by Wall Interaction



CO "escapes from furnace

Temp and CO concentrated on back wall

CFD Modeling – Baseline full furnace

CFD Model did not answer:
Why was furnace set up in this manner?

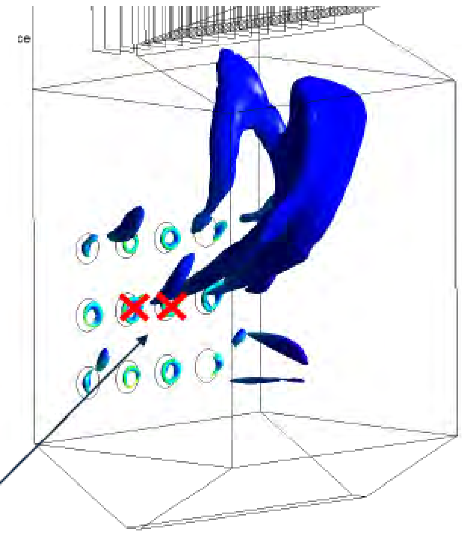
CFD Modeling

CFD Demonstrated Burner Interactions

NOx Reduction

1. CFD Modeling centered on optimal firing pattern
   1. Verified guarantees could be accomplished
   2. Financial incentive for keeping as much generation as possible

2. RJM CleanAir Burner™
   1. Need to optimize arrangement => minimize FGR requirements
   2. Determined that removal of middle burners significantly lowered NOx and FGR requirements



Elimination of burners
Eliminated middle furnace NO Production

CFD Modeling
Pressure Excursion

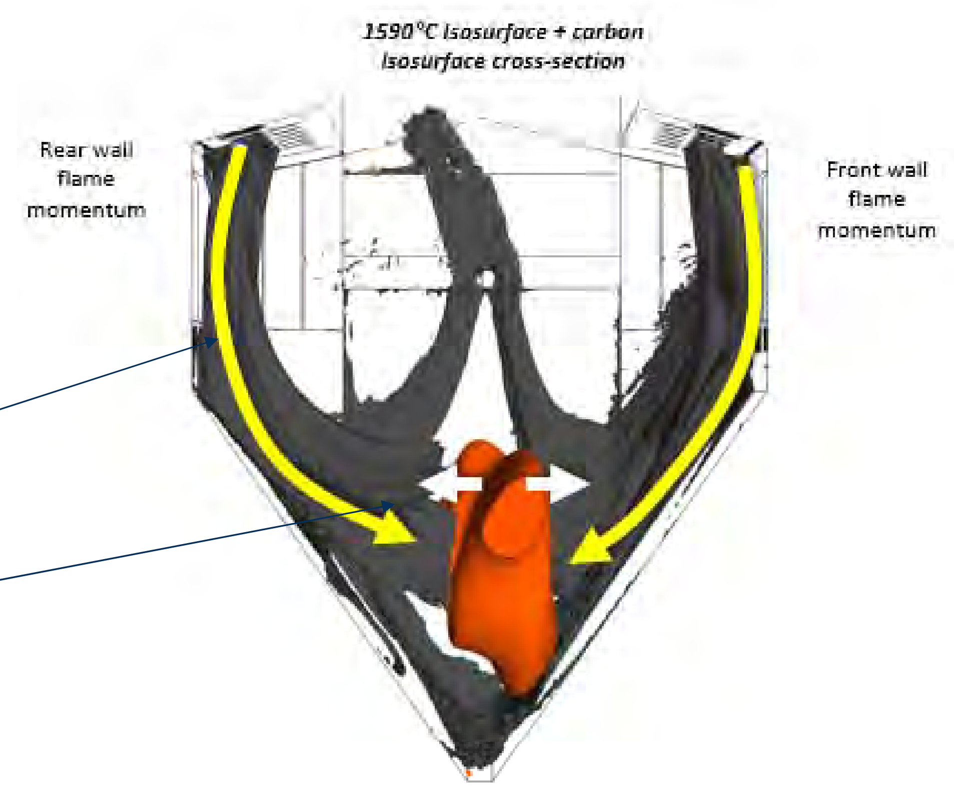
Combustion Audit outcomes:

- 0.5 psig Pressure excursion
- Sudden ignition event of 1.0 lbm coal

CFD to focus on cooling of flame

Coal "sweeps" along furnace wall
Both sides

Small fire in center of boiler



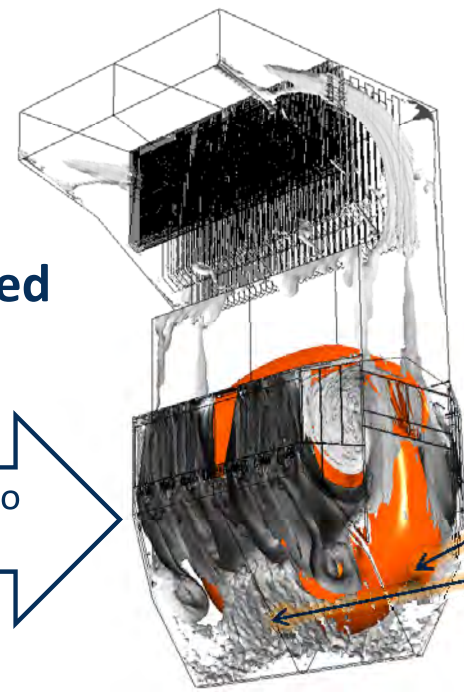
CFD Modeling
Pressure Excursion

PRE-MOD

Combustion Improved

Pressure excursions effectively eliminated

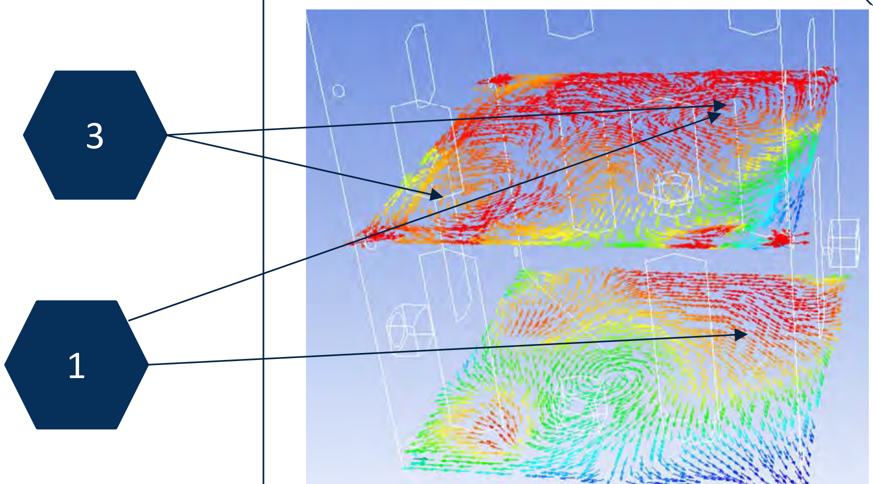
Significant Improvement to Flame



POST-MOD

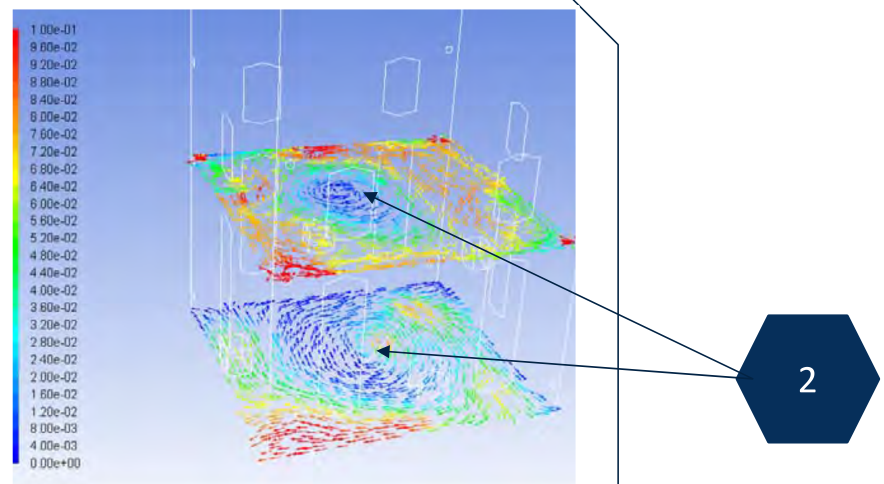
CFD Modeling

Stalled furnace



Combustion audit showed reverse rotations (1)

CFD showed same problem



Post-modification assessment showed better circulation (2) and better segregation of fuel and air

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Bespoke Hardware Design

Separated Under Fire Air (SUFA)

Mixing Devices

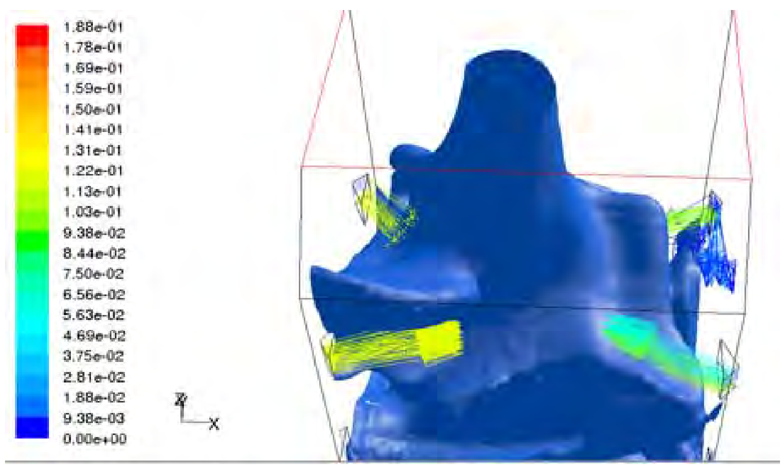
Gas Injectors

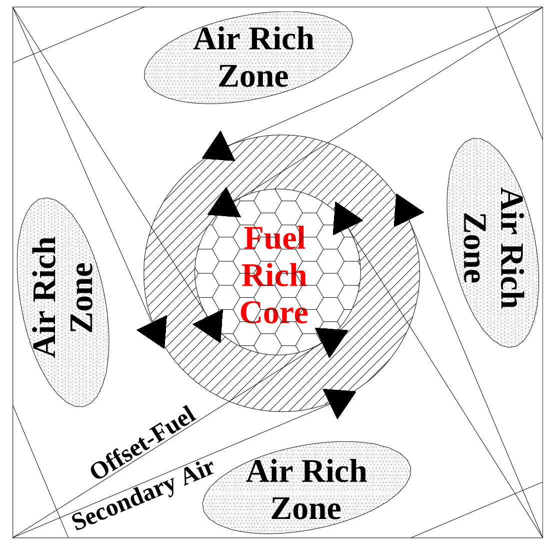
Angled over fire air (OFA) Ports

Bespoke Hardware Design

LNCF Systems

- Patented in late 1990's
- Limited by SOFA performance





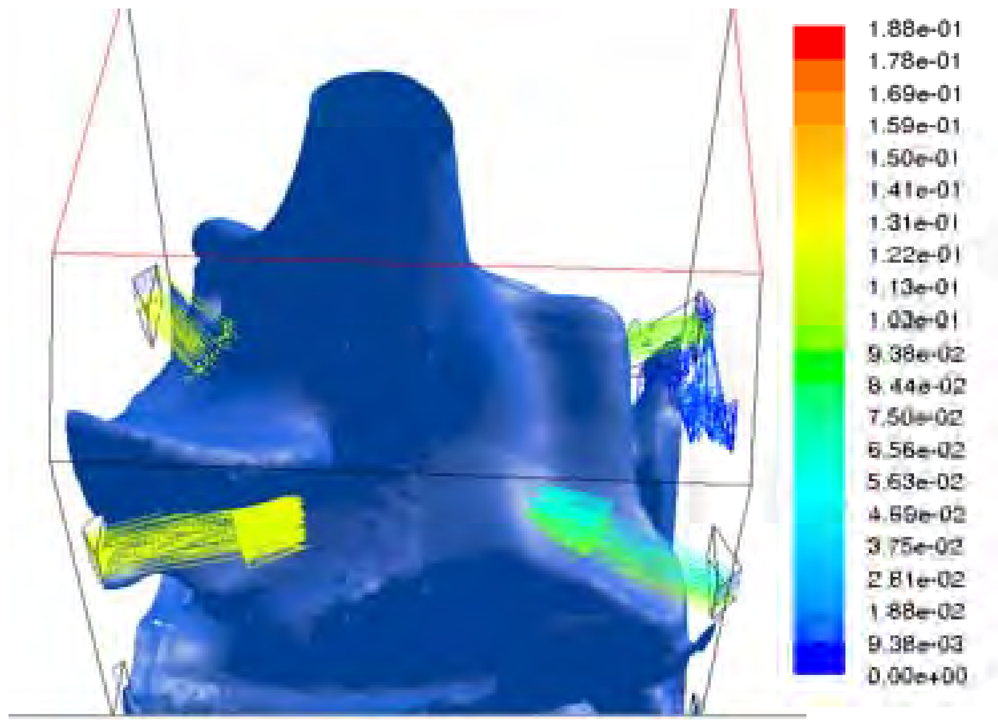
Interaction of SOFA and CO

Bespoke Hardware Design

LNCF Systems

NOx reduction limited by penetration of SOFA to the center of the furnace

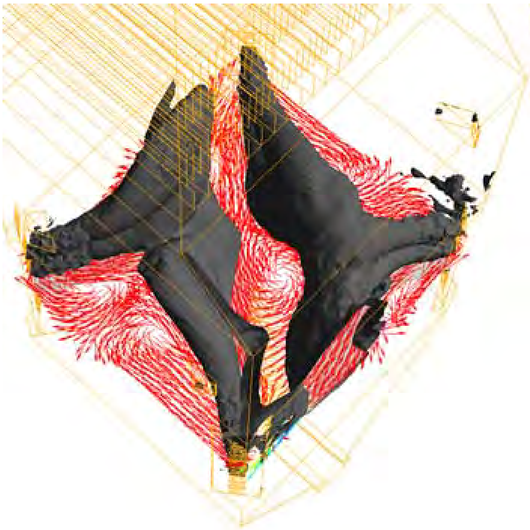
- 10,000 ppm CO Iso-surface
- SOFA Ports have limited ability to penetrate to center of furnace



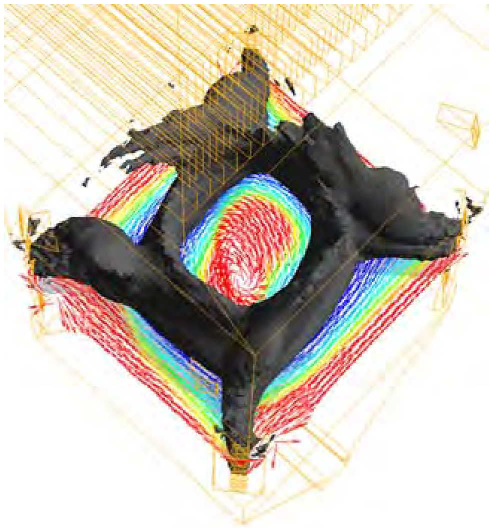
Bespoke Hardware Design
LNCF Systems

SUFA eliminates limitation

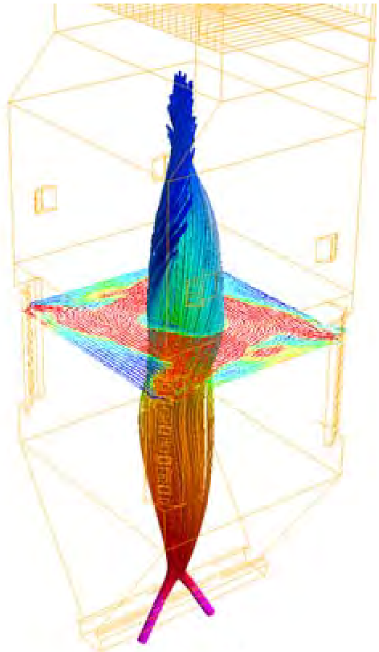
Separated
Under
Fire
Air



Base



Upgrade



Upgrade

Bespoke Hardware Design

LNCF Systems

SUFA eliminates limitation

Separated
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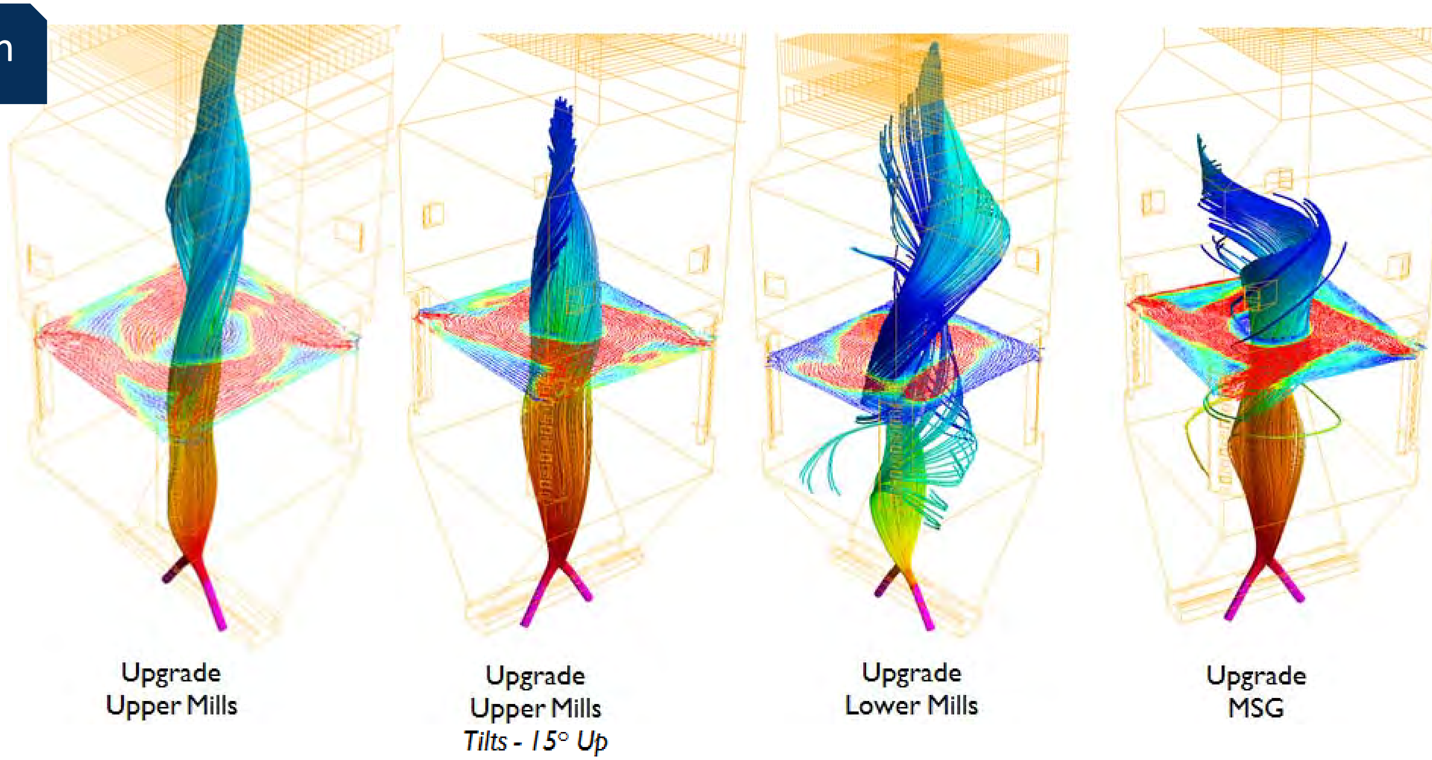


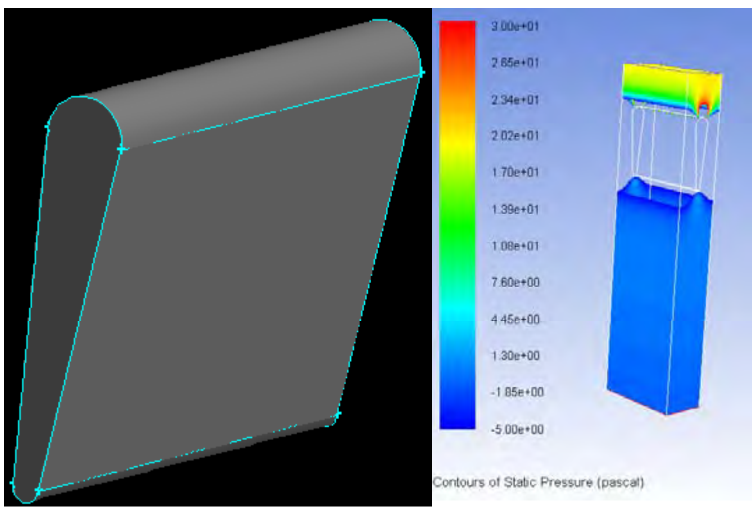
Bespoke Hardware Design

Mixing Devices: Low Pressure

Combustion audit outcome

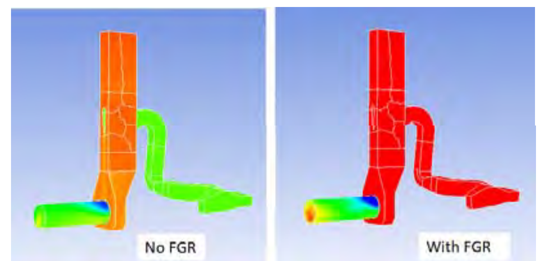
A <u>low pressure drop</u> mixing of two streams was in one case required

The basic design had a loss of 35 Pa



Final design:

1. Used pressure recovery from XFR fan
2. Provided excellent mixing
3. Mixing downstream of choke point

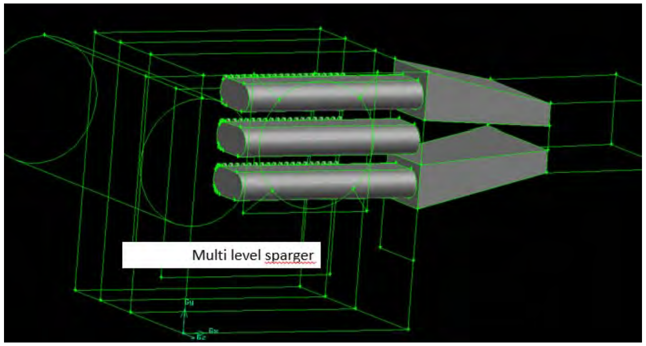


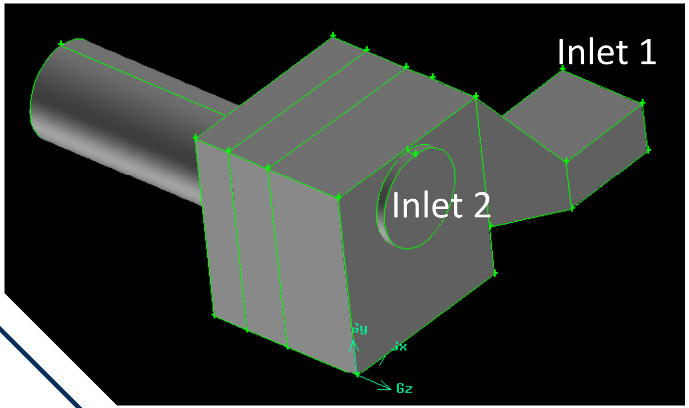
This allowed for greater pressure delivery at the FD fan inlet

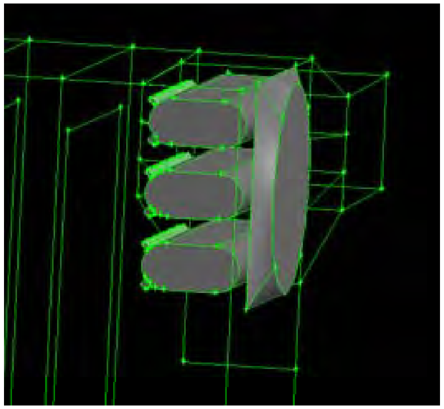
Bespoke Hardware Design
Mixing Devices: Rapid Mix

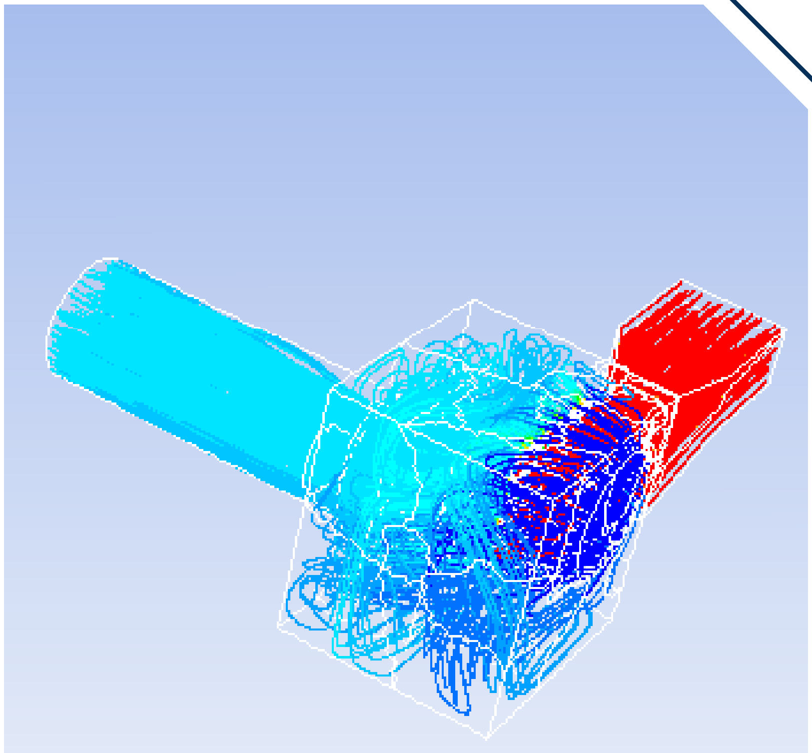
Combustion audit outcome

- Rapid mixing of two streams was required in another case
- Compete mixing was required by the outlet









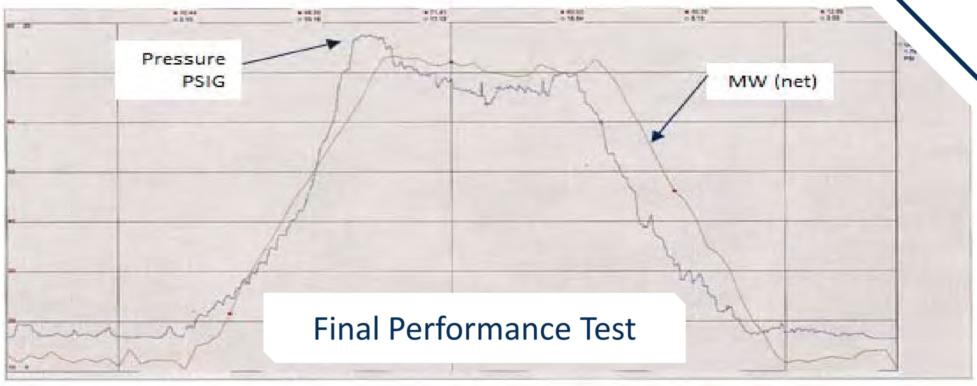
Bespoke Hardware Design
Close pressure control – Gas Injections

Original Performance

- 13 – **55** Mwe net
- 2.5 psig – 14.4 psig

New Performance

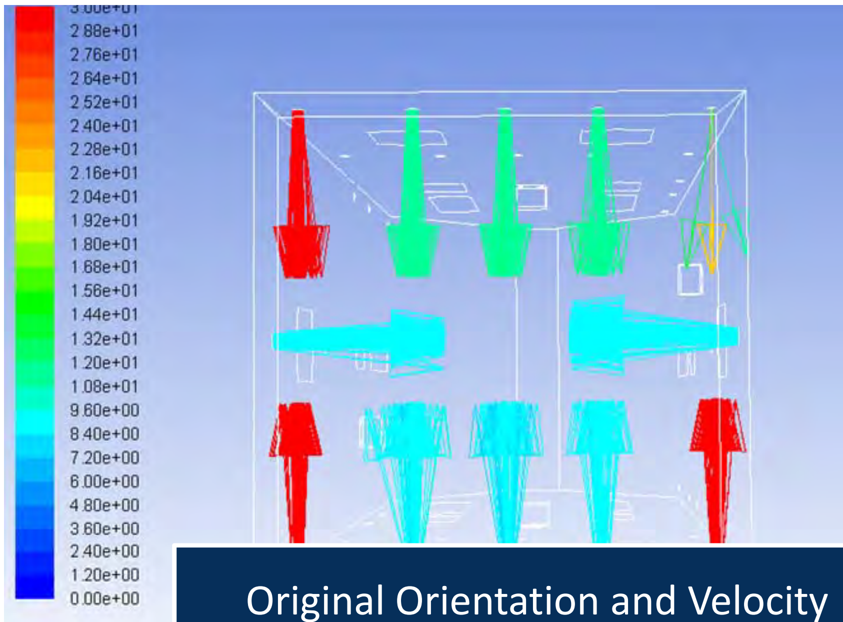
- 13 – **75** Mwe net
- 2.0 psig – 16.6 psig



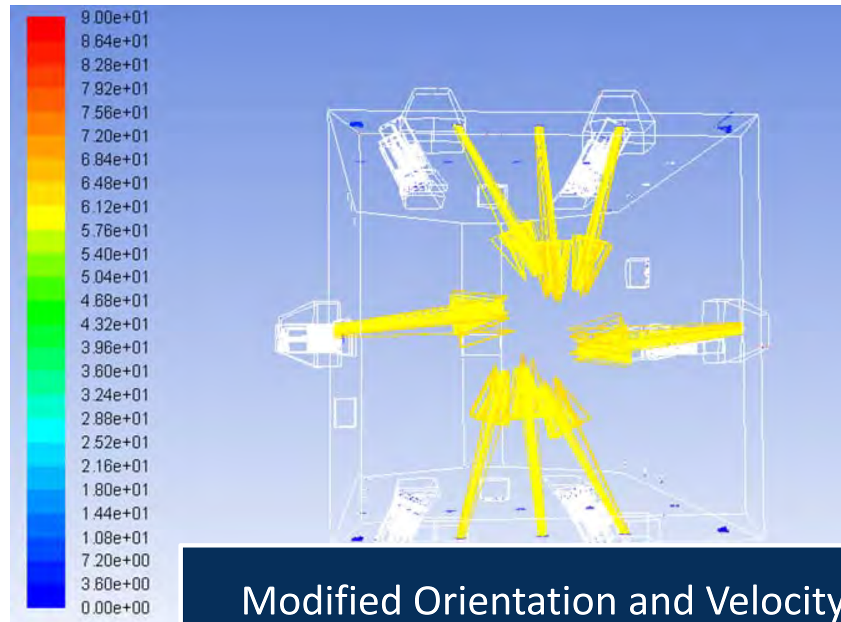
Result

- Minor hardware modifications
- **48% increase in spinning reserve**

Bespoke Hardware Design
Angled OFA Ports



Original Orientation and Velocity



Modified Orientation and Velocity

OFA makes significant contribution to re-establish rotation.

Thank You

RJM International