REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

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

Improvement of Coal-Fired Power Plant Operation and Lifetime through Integration of New Data Streams

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Reinhold Conference
2018 NOx-Combustion-CCR Round Table
February 20, 2018

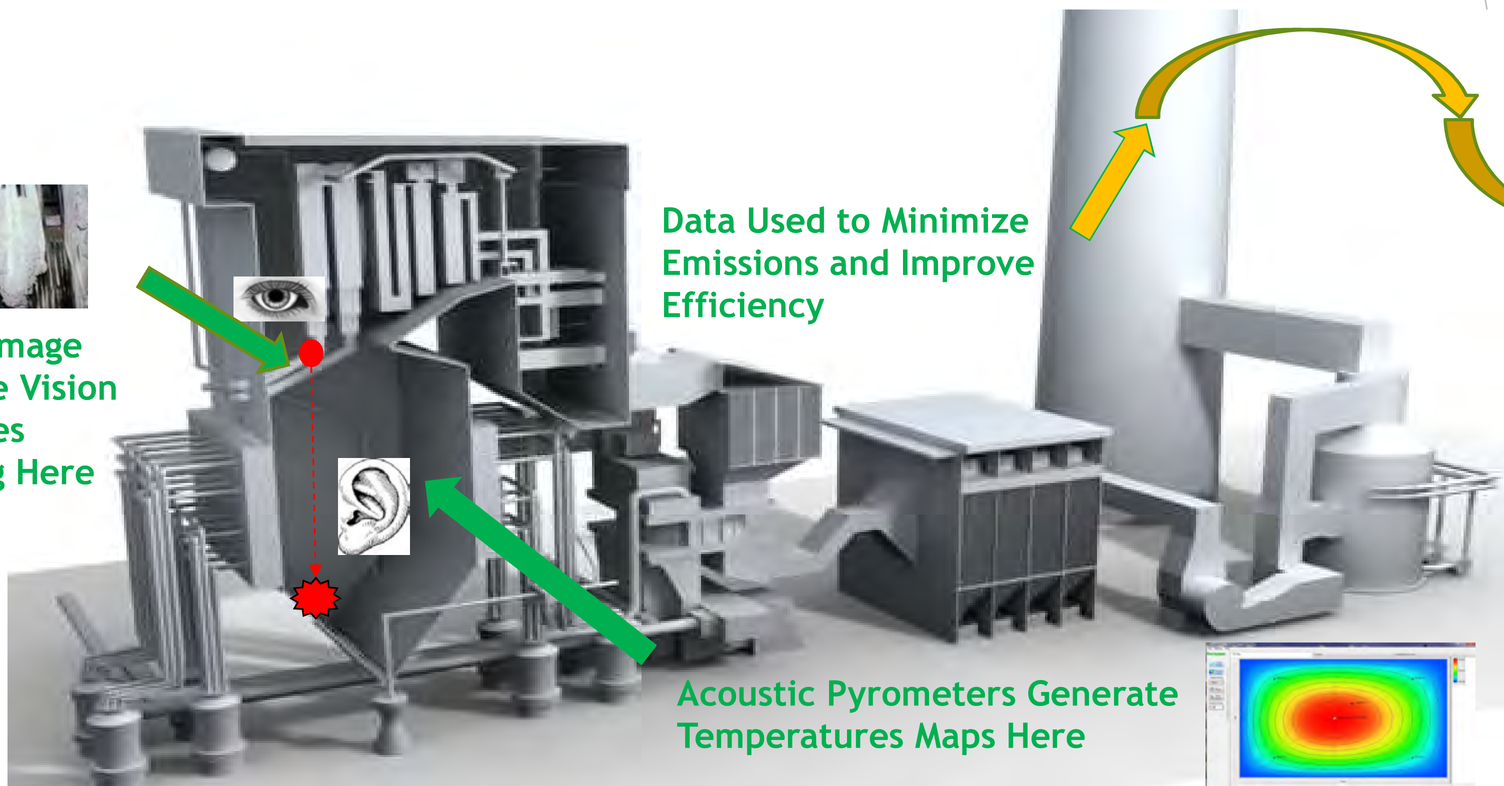
Outline

- Boiler Interiors: Slagging and Pollutant Formation
- Mid-IR Imaging and Slag Index
- Slag Index at Duke Energy
- Temperature and Acoustic Pyrometry
- Flow of Data and Information

Reduce Slagging/Pollutant Formation

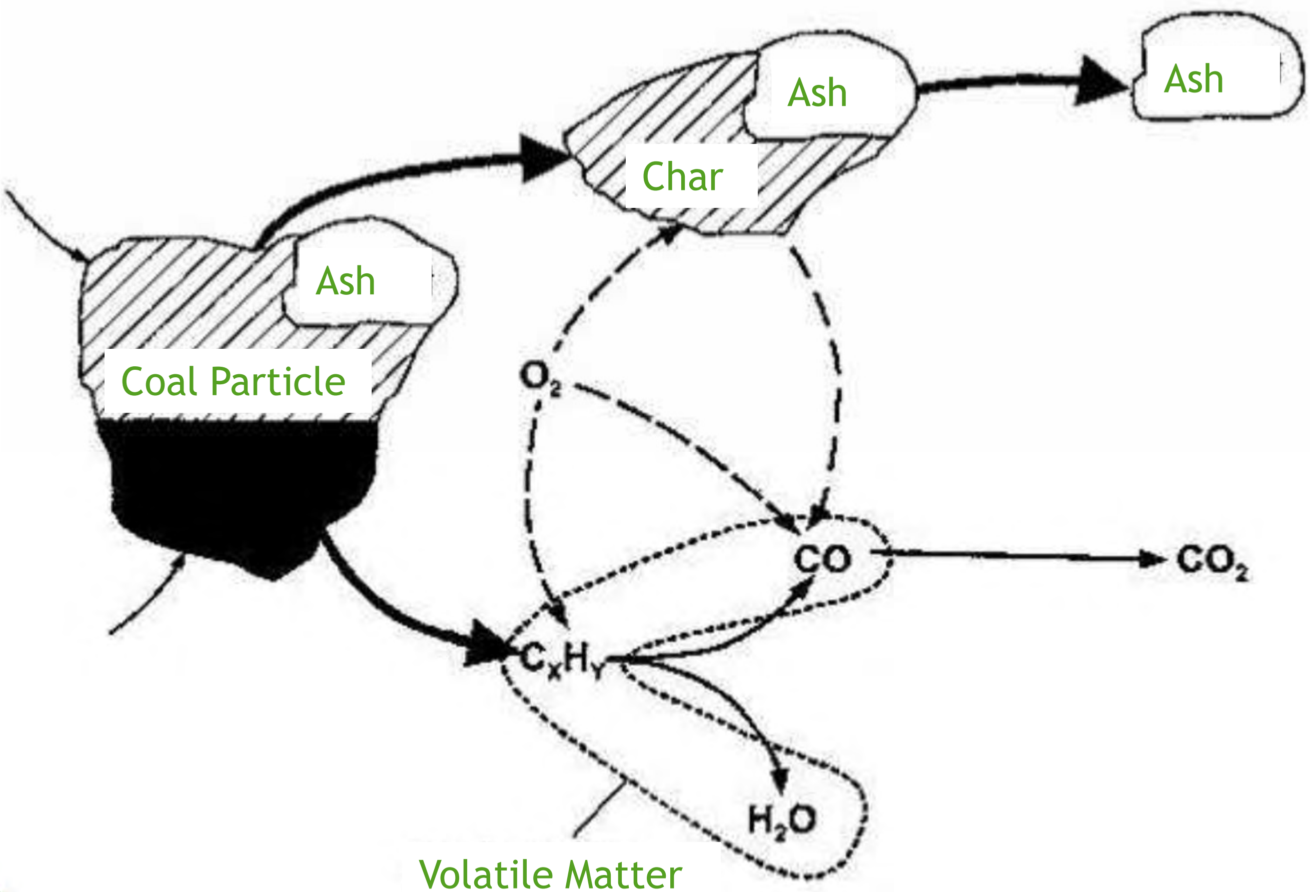
⇒ Load Cycling/Fuel Switching is a Key Driver

Mid-IR Image Machine Vision Measures Slagging Here

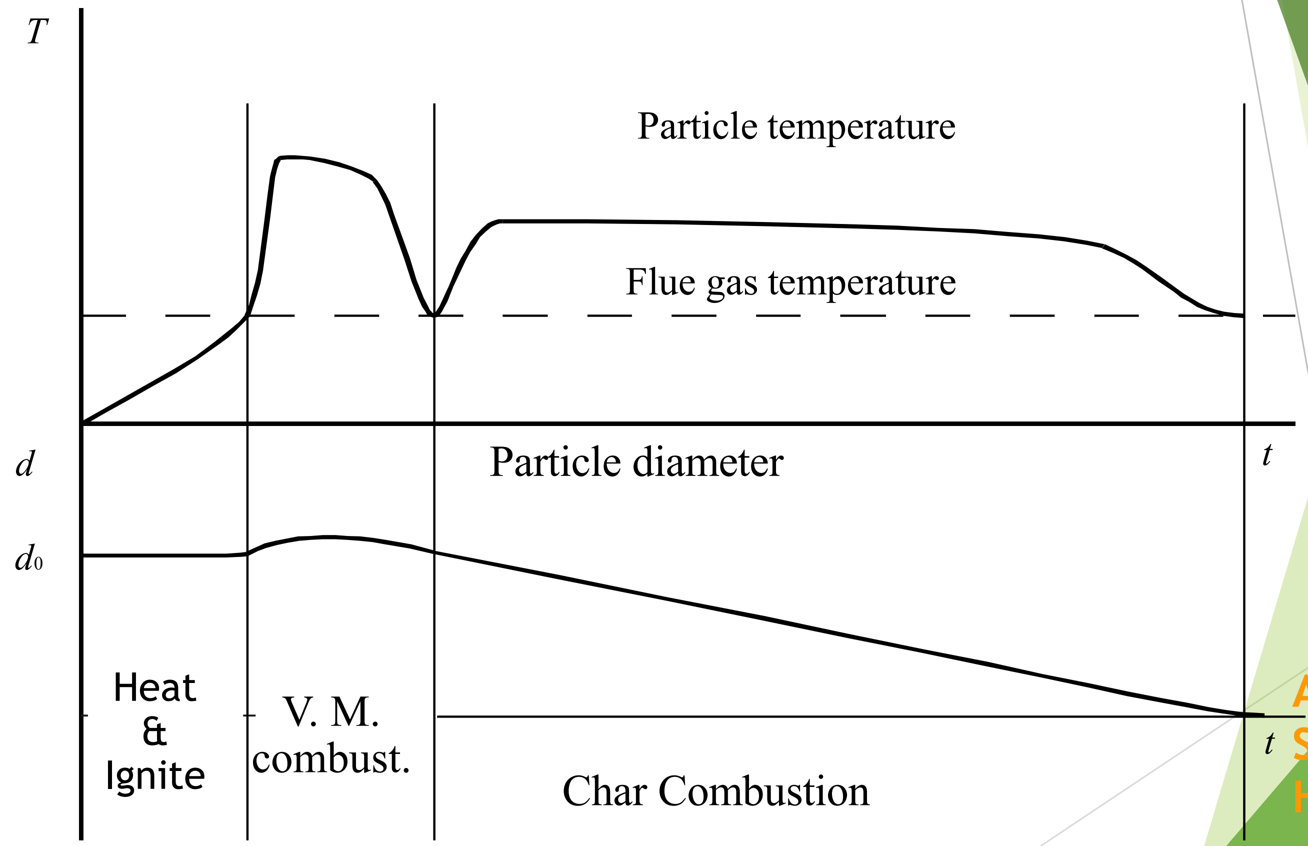


Temperature Map

Origin of Ash/Slagging



Particle Temperature and Diameter



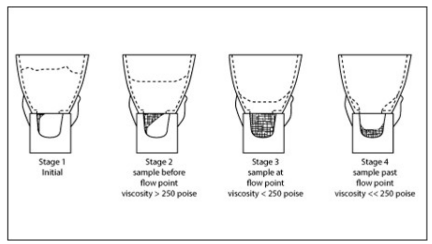
Ash Deposition is a Key Problem

- Issues
  - Heat Transfer Degradation: Lower Efficiencies
  - Costs of Removal
  - Shutdowns and Maintenance Problems
- Molten Particles are Retained whereas Much of the Dry Ash Rebounds and is Re-entrained in the Flue Gas

Ash Fusion Temperatures

- **Ash Fusibility Test (Ash Fusion Temperature)**
  - Stages of Softening and Flow

- **Ash Viscosity Test**



- **Ash Chemistry** (Duzy, 1965)
  - $(Fe_2O_3+CaO+MgO+K_2O+Na_2O) \times S / (SiO_2+Al_2O_3+TiO_2)$

Index Limitations

- Ash Fusion Test Temperatures
  - Weak Reproducibility, Variability up to 360 F
  - Ash Samples Reacted at Temps < Initial Deformation Temperature
- Viscosity Measurements
  - Ashes Sticky at Temperatures below Temperatures at Which Viscosity Can Be Measured
  - Uncertainties Up to +/- 50%
- Ash Chemistry
  - Fails if Most of Iron is in Form of Siderite vs Pyrite

Thermal NOx

- Extended Zeldovich Mechanism
  - $N_2 + O \rightarrow NO + N$
  - $N + O_2 \rightarrow NO + O$
  - $N + OH \rightarrow NO + H$
- Exponentially Fast at High Temp (T> 2900F) when Oxygen Present

Sulfur in Coal

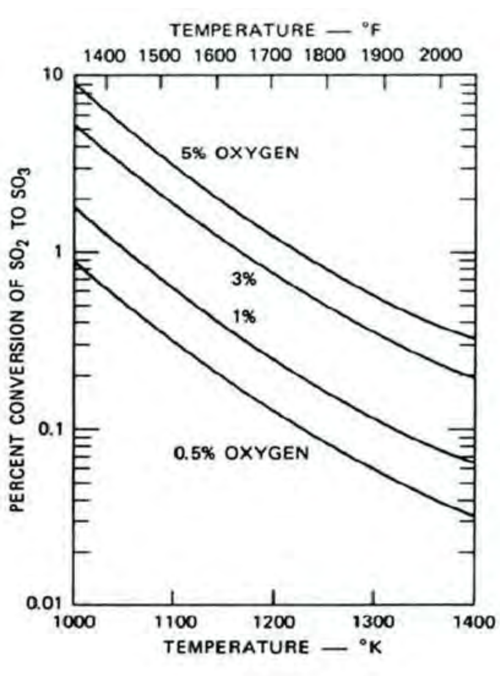
- Sulfur Generally Occurs in Four Forms
  - Pyritic Sulfur (Included and Excluded)
  - Sulfate Sulfur
  - Organic Sulfur
  - Free Sulfur

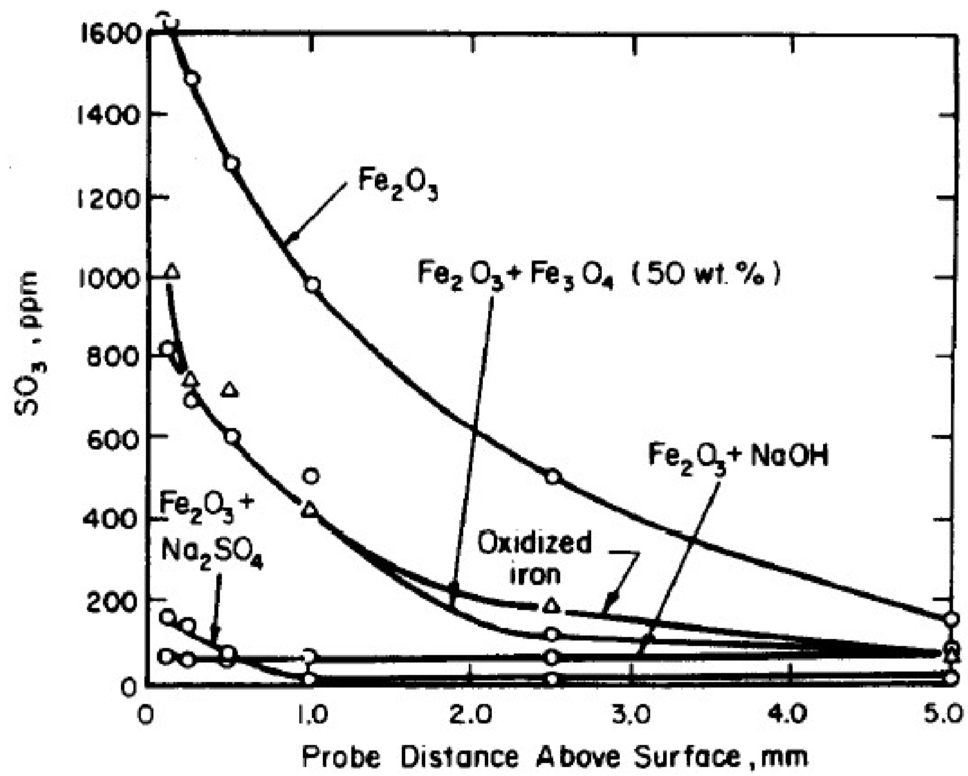
- Pyritic Sulfur (FeS_2) is Often the Most Important:
  - Influences Slagging
    - E.g., *Multiplicative* in Duzy Ash Chemistry Index
  - Influences Acid Gas Formation

Pyrite Oxidation

- $FeS_2 \rightarrow (1\text{-}x)\ Fe_{(1\text{-}x)}S + (1\text{-}x)\ S$
- $Fe_{(1\text{-}x)}S + (1+x/2)\ O_2 \rightarrow (1\text{-}x)\ FeO + SO$
- $Fe_{(1\text{-}x)}S + (1\text{-}x)\ SO \rightarrow (1\text{-}x)\ FeO + (1\text{-}x/2)S_2$
- $Fe_{(1\text{-}x)}S + (1\text{-}x)\ O \rightarrow (1\text{-}x)\ FeO + S$
- $FeS_2 + O_2 \rightarrow FeS + SO_2$
- $FeS_2 + SO \rightarrow FeS + S_2 + O$
- $FeS + O_2 \rightarrow FeO + SO$
- $FeS + SO \rightarrow FeO + S_2$
- $FeS + O \rightarrow FeO + S$
- $2FeO + O2 \rightarrow Fe_2O_3 + O$
- $FeO + Fe_2O_3 \rightarrow Fe_3O_4$

SO_3 Production Effects





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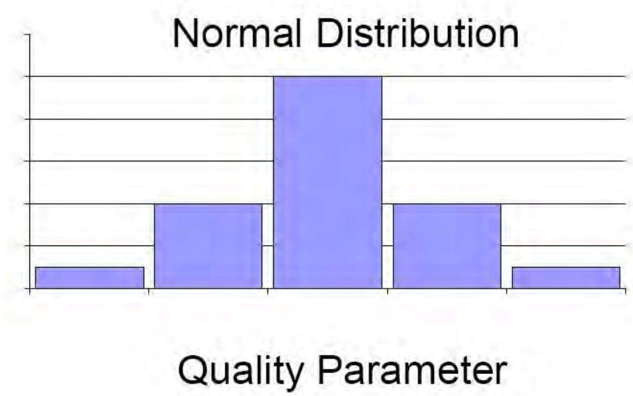
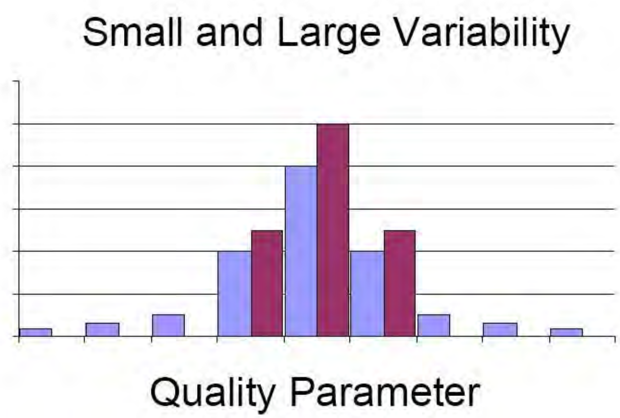
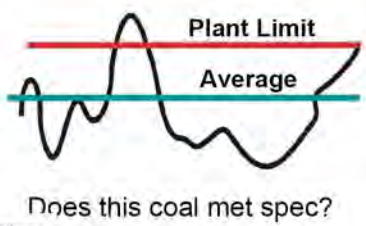
Coal Parameter Variability







Operating Considerations

- Coal Composition
- Coal Particle Size
- Air Distribution
- Burner Operation
- Excess Air Level
- Flame Impingement
- Sootblower Operation
- Boiler Load

Outline

- Boiler Interiors: Slagging and Pollutant Formation
- **Mid-IR Imaging and Slag Index**
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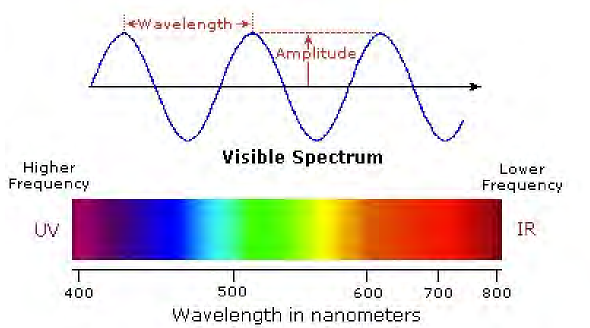
Why Mid-Infrared Imaging?

- **Main Visible Image Obscuration is due to Particle Scattering**
- **Particle Scattering Decreases as Wavelength Increases**
  - ~ $1/\lambda^4$ Rayleigh Scattering

UV is less than 400 nm

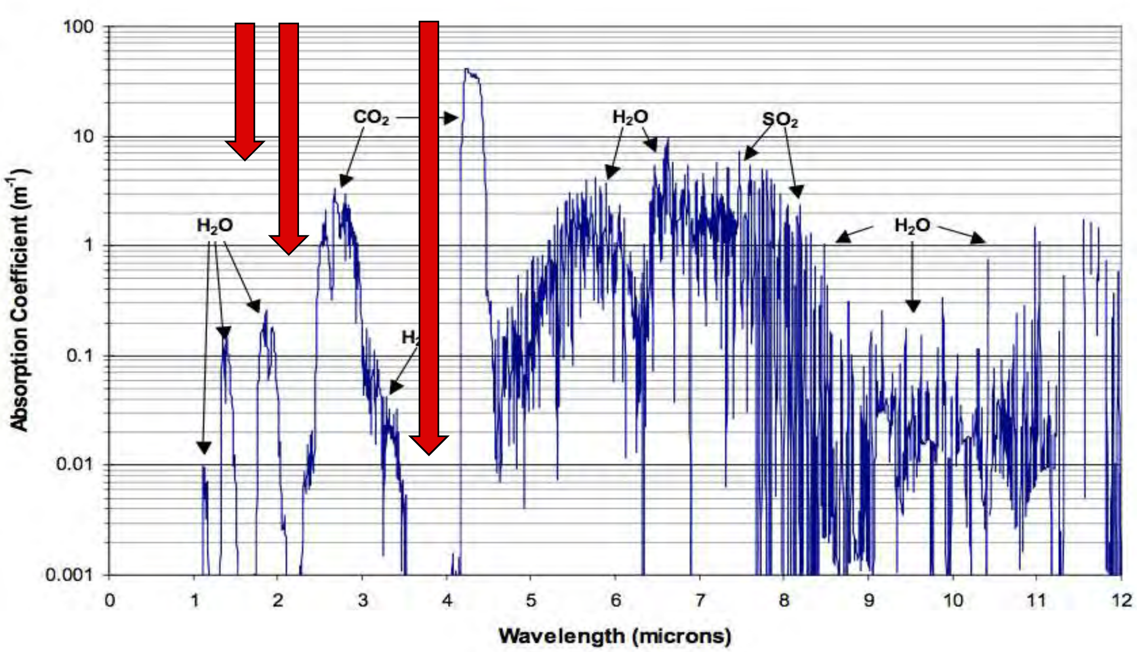


IR is greater than 800 nm

So viewing with longer wavelengths is desirable?

Viewing Windows

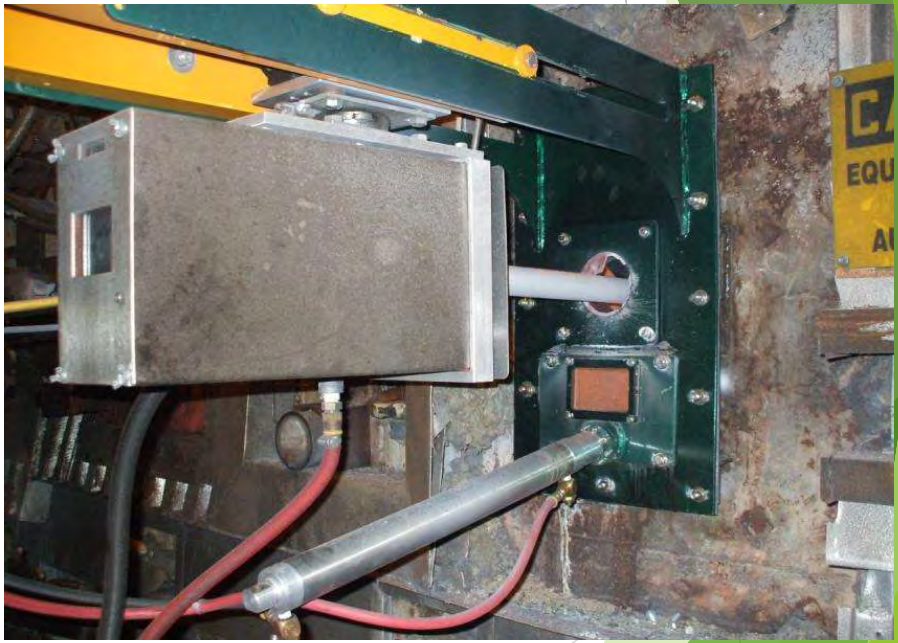
There are only certain windows available though!



Mid-IR Boiler Inspection Cameras

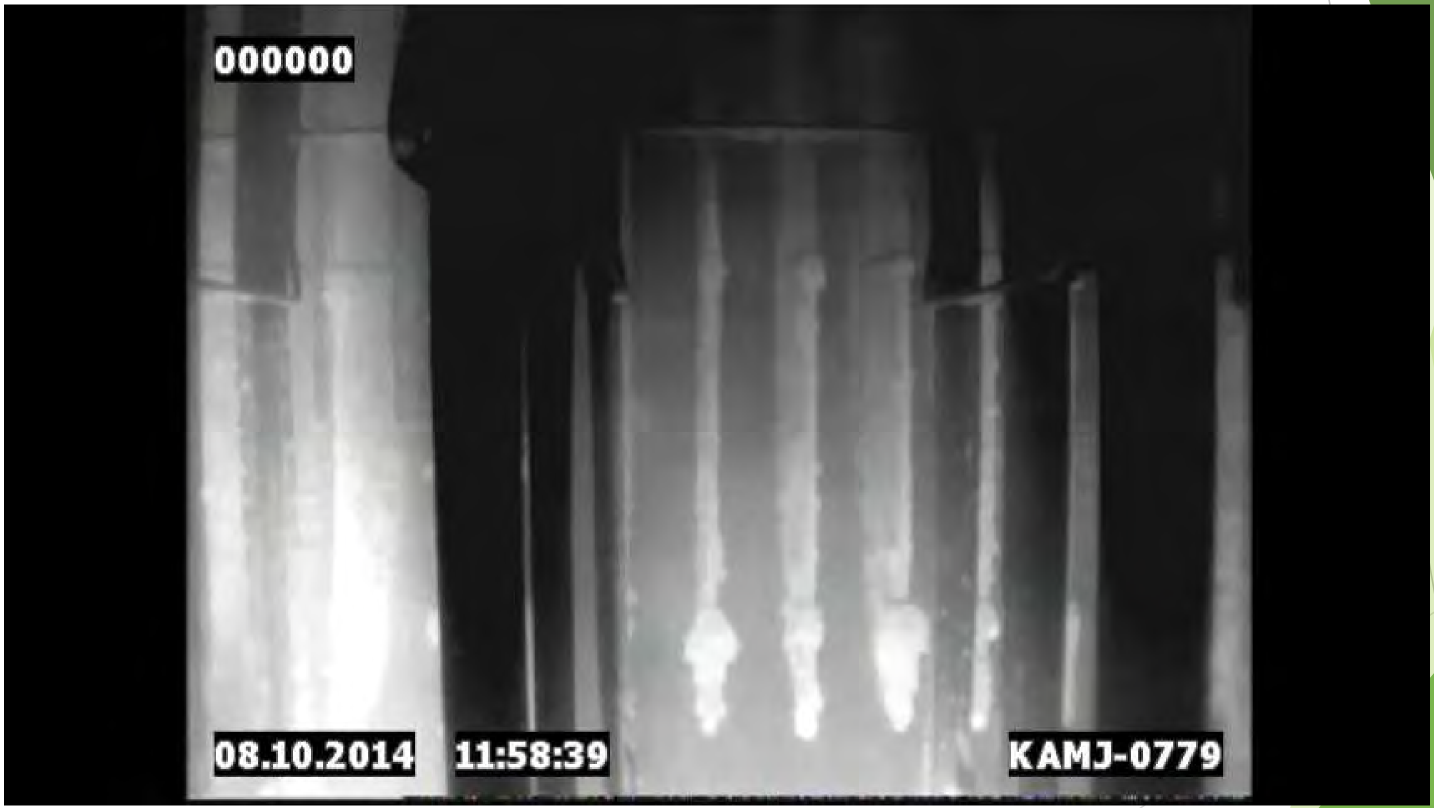
Imaging Core

Mobile

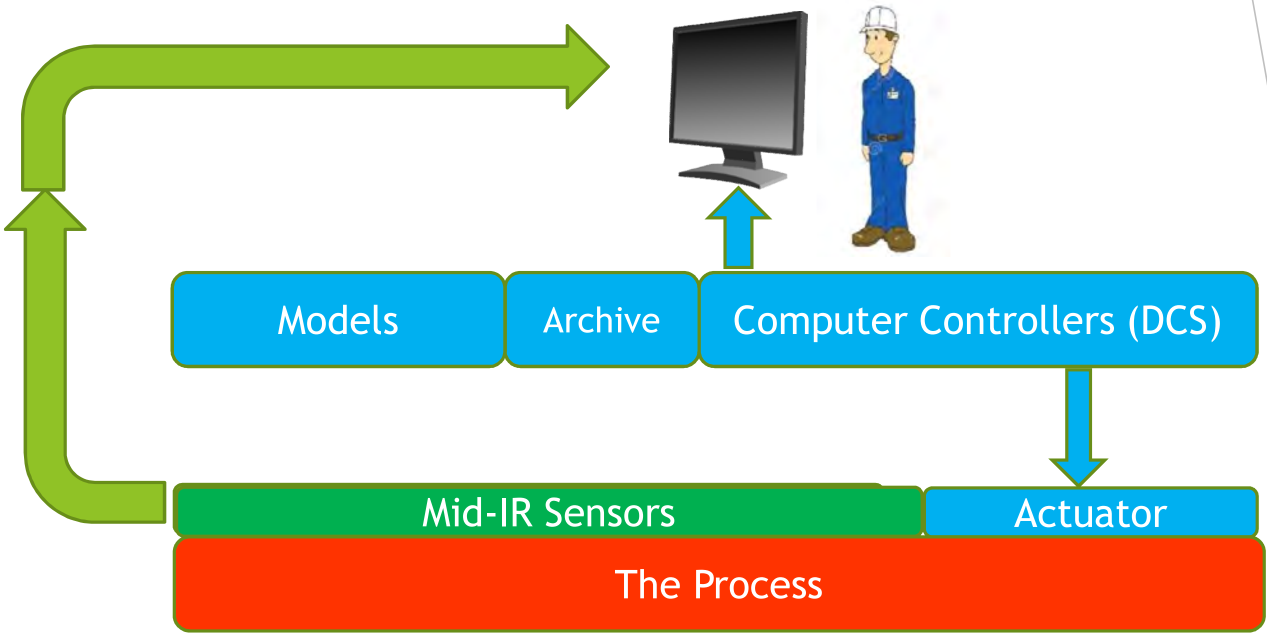


Fixed Mount

Mid-IR View of Upper Furnace



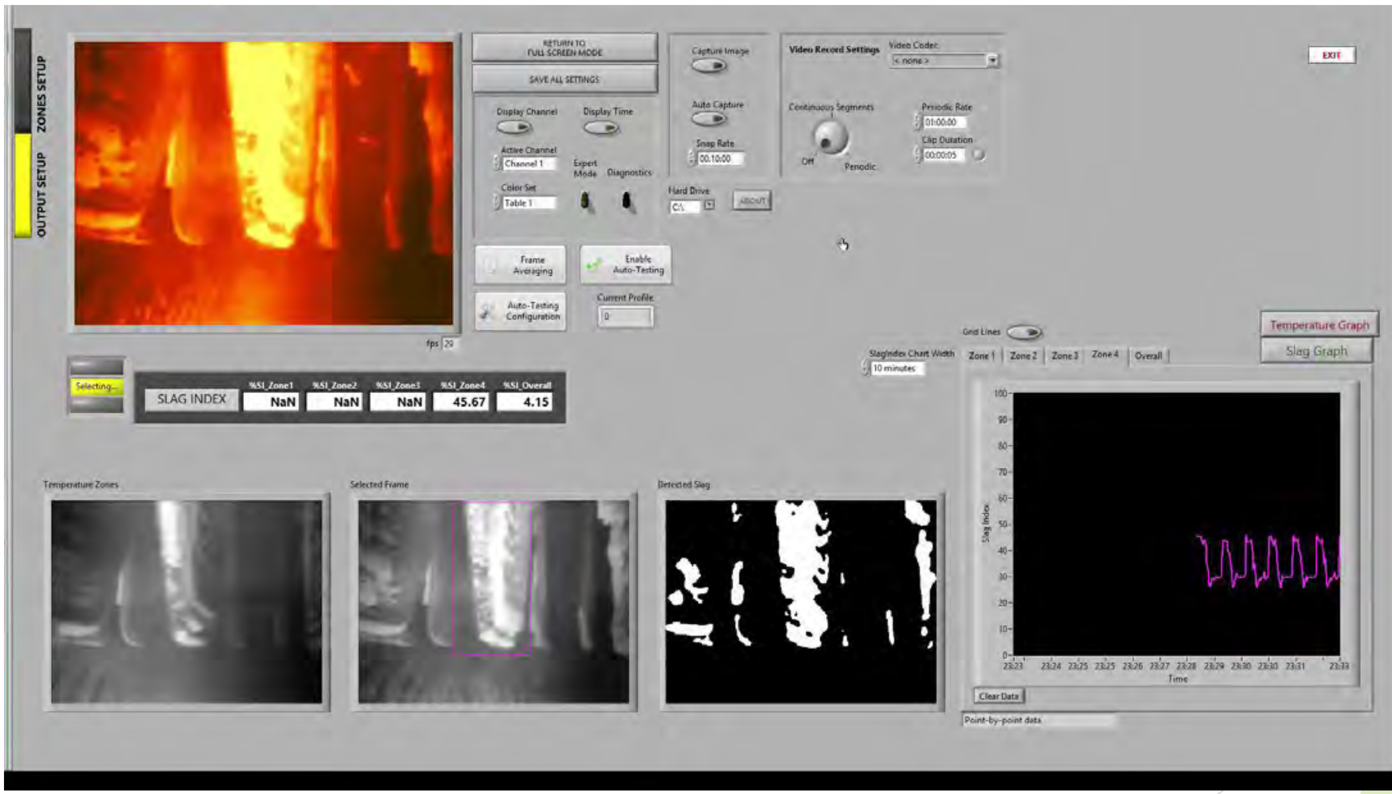
Data Flow 1: Direct Video to Operator



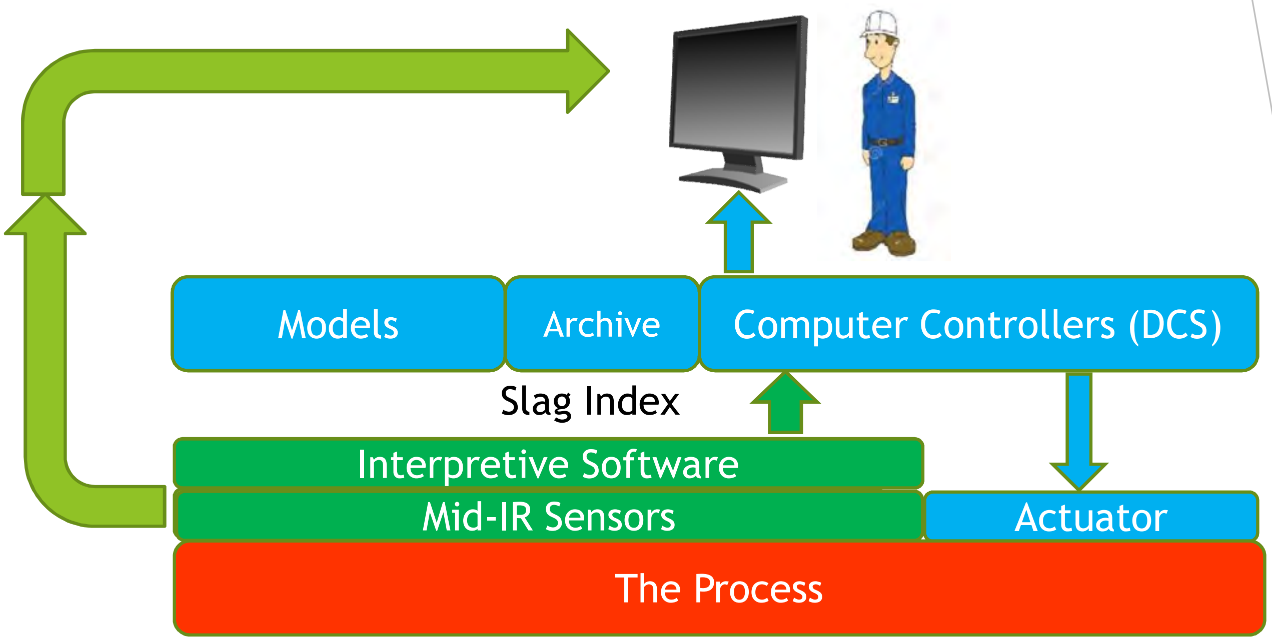
Where Does Slag Index Fit In?

- Provides a **tangible metric** that does not require human interpretation.
- Expands use of IR Imaging technology towards **automated interpretation** and **closed-loop control**

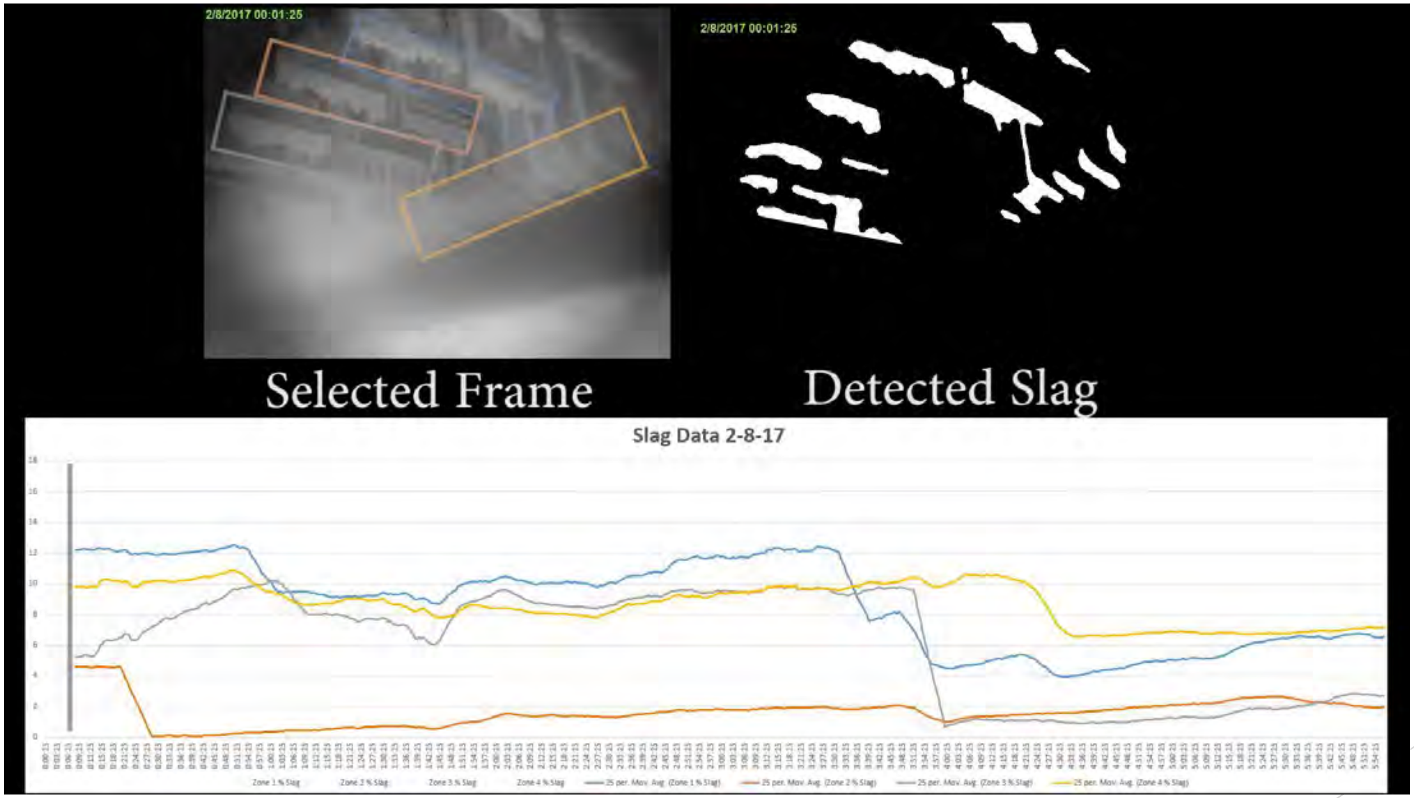
Slag Index Software Dashboard



Data Flow 2: Interpretive Software to DCS



Time-lapse Report Example



Utilization?

So, now that we have this tool, what can we do with it?

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- Boiler Interiors: Slagging and Pollutant Formation
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- **Slag Index at Duke Energy**
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Infra-Red Camera Boiler Applications at Duke Energy

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Duke Energy IR Camera Applications

- Currently have 20 IR cameras (12 permanent installations and 8 portables) across the fleet
- Cameras are used for,
  - Monitoring units for slag/clinker build-up that could result in a clinker fall & slope tube damage
  - Chemical dosing optimization
  - Better understand the operational “triggers” that lead to slagging
  - Sootblowing effectiveness
  - Coal blend slagging propensity
  - An instrument supplying the numerical quantity of ash build-up in the furnace, independent of Operator perception.

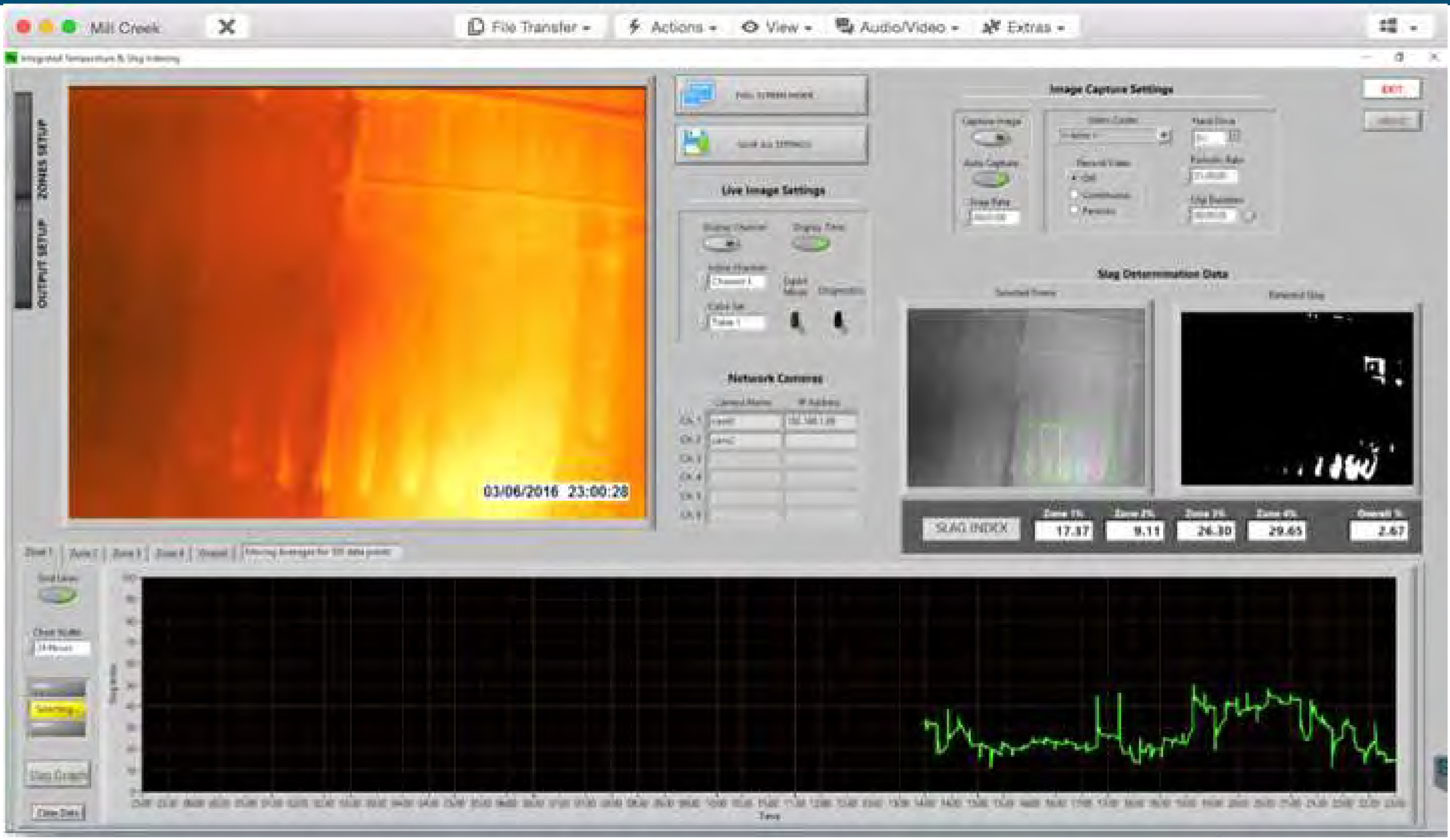
IR Cameras, the Outputs

- IR cameras supply continuous visual and quantitative data.
- Using up to 4 zones for each camera, the known areas in the furnace that slag can be more thoroughly monitored for ash build-up increases.
- The camera software produces reports for the previous days operation. The "Timelapse Report" combines the slag index trend with a 2.5 minute video.
- Like any measurement, yesterdays data is something we should learn from, but we need to use this instrument/data to affect the outcome of todays operations.

RC_Timelapse Report 4-18-2017.avi.mp4

RC_Timelapse Report 5-16-2017.avi.mp4

Slag Index Software Dashboard



IR Camera Outputs – Using this tool to Help Current Op’s

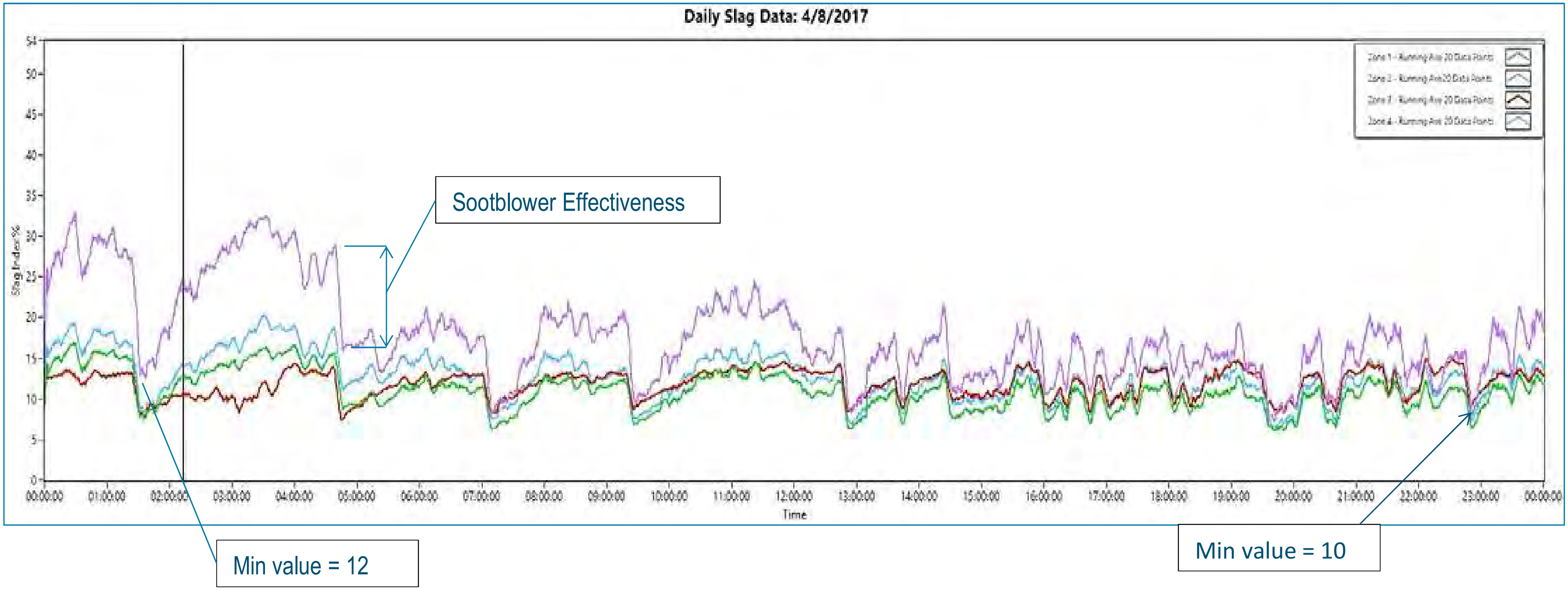
- The best way we have found to use this Slag Index software is to have the operator monitor the SI software dashboard , noting the SI value trends as the shift progresses. If the sootblowers are not effective, the SI values climbing, then other proactive steps need to be taken to insure unit reliability such as,
  - load reduction to shed,
  - Substitution of mills in-service to affect FEGT’s
  - slag mitigation chemical dose rate change,
  - more aggressive sootblowing cycles,
  - investigate sootblower air/steam supply pressures/lance nozzle condition,
  - fuel change to give the unit a chance to recover

Slag Index Data – From Daily Reports – yesterdays NEWS

- Zone Specific Sootblower Effectiveness,
  - If there is no reduction in SI value when the sootblowers are actuated (ie no slag/ash removed), then we are wasting compressed air or steam and wearing out the sootblowers and boiler tubes. This is a quantification of the bond strength between the boiler tubes and the ash, and between ash to ash.
- Zone Specific Average SI values
  - Is there more or less build-up in the yesterday vs the day before? A bulk understanding of this can be determined by taking the average of all the SI values each day
- Zone based trends in SI value
  - Is the SI value higher at the end of the day than the beginning? This can be misleading. Example,
    - At 00:01 the SI value for a particular zone was 10, and the sootblowers in that area had just cycled, compared to 23:59, the SI value was 20 and the sootblowers had not cycled since 21:00. If the increase in SI from 21:00 till 23:59 was significant, this metric could be misleading.

Daily SI Trending

- Is it ash build-up if a sootblowing cycle removes it?



Operational “Triggers” for Slagging

	Predictive Slagging Metrics				Operations Slagging Metrics								
Date	Predicted HH Index	Predicted SH Slagging Potential	Predicted Ash Fusion Temp		Actual Max FEGT	Left Side SB's OOS	Right Side SB's OOS	%age of day > 645 MW's	%age of day < 2.5% Backpass O2	%age of day FEGT > 2150°F	Number of Sootblowing Cycles in the day	Ash Loading in Lbs/MMBtu	Combined Daily Operational Index (Green=0, Yellow=1,Red=2)
4/8/2017	1.24	(1.65)	2205		2157	15	16,28	54%	4.5%	1.39%	8	7.30	4
4/9/2017	1.19	(1.63)	2228		2156	15	16,28	30%	18.8%	1.04%	7	7.33	6
4/10/2017	1.00	(1.71)	2255		2139	15	16,28	11%	3.1%	0.00%	8	7.03	1
4/11/2017	1.05	(1.68)	2242		2157	15	16,28	36%	9.4%	3.13%	8	7.15	2
4/12/2017	1.05	(1.46)	2166		2158	15	16,28	31%	51.7%	2.78%	8	6.90	2
4/13/2017	1.45	(1.74)	2115		2168	15	16,28	21%	25.3%	10.07%	8	7.26	8
4/14/2017	1.25	(1.65)	2203		2169	15	16,28	15%	3.8%	5.56%	8	7.31	3
4/15/2017	1.19	(1.65)	2219		2074	15	16,28	0%	0.0%	0.00%	8	7.28	2
4/16/2017	1.36	(1.68)	2165		2000	15	16,28	0%	0.0%	0.00%	7	7.31	5
4/17/2017	1.25	(1.65)	2201		2145	15,27	16,28	18%	7.3%	0.00%	8	7.30	5
4/18/2017	1.20	(1.65)	2216		2153	15	16,28	50%	52.4%	0.35%	8	7.28	5
4/19/2017	1.12	(1.64)	2240		2168	15	16,28	49%	80.2%	16.67%	7	7.27	7
4/20/2017	1.00	(1.47)	2320		2167	15	16,28	55%	68.4%	15.28%	8	6.83	5
4/21/2017	1.00	(1.33)	2318		2179	15	16,28	61%	7.6%	24.31%	8	6.91	5
4/22/2017	1.25	(1.50)	2172		2144	15	16,28	24%	0.0%	0.00%	8	7.19	3
4/23/2017	1.55	(1.71)	2112		2176	15	16,28	31%	0.7%	27.78%	8	7.40	7
4/24/2017	1.53	(1.71)	2112		2168	15	16,28	57%	19.8%	4.17%	6	7.37	11
4/25/2017	1.27	(1.58)	2230		2201	15	16,26,28	26%	34.4%	54.17%	7	7.49	9
4/26/2017	1.06	(1.42)	2204		2255	15	16,26,28	7%	8.7%	79.86%	7	7.06	9
4/27/2017	1.00	(1.31)	2316		2234	15	16,26,28	60%	2.1%	77.08%	5	NA	8
4/28/2017	1.09	(1.38)	2178		2255	15	16,26,28	60%	0.0%	75.00%	7	7.02	10
5/14/2017	1.24	(1.64)	2187		2098	9,15	16,26,28,34	32%	0.3%	0.0%	9	7.21	2
5/15/2017	1.00	(1.27)	2207		2084	9,15	16,26,28,34	66%	0.3%	0.0%	8	6.63	3
5/16/2017	1.00	(1.39)	2186		2118	9,15	16,26,28,34	93%	33.7%	0.0%	8	6.82	6
5/17/2017	1.00	(1.29)	2215		2080	9,15	16,26,28,34	68%	4.2%	0.0%	10	6.68	3
5/18/2017	1.05	(1.26)	2159		2110	9,15	16,26,28,34	73%	4.2%	0.0%	7	6.98	5
5/19/2017	1.00	(1.40)	2199		2131	9,15	16,26,28,34	63%	3.1%	0.0%	9	6.86	2
5/20/2017	1.00	(1.15)	2206		1993	9,15	16,26,28,34	0%	0.0%	0.0%	6	6.52	5
5/21/2017	1.07	(1.49)	2200		1595	9,15	16,26,28,34	0%	0.0%	0.0%	9	6.99	2
5/22/2017	1.00	(1.05)	2234		1611	9,15,27	16,26,28,34	0%	0.0%	0.0%	8	6.34	4
5/23/2017	1.35	(1.64)	2155		2106	9,15	16,26,28,34	64%	9.0%	0.0%	9	7.25	5
5/24/2017	1.00	(1.28)	2186		2135	9,15	16,26,28,34	66%	4.9%	0.0%	9	6.70	4
5/25/2017	1.41	(1.45)	2129		2189	9	16,26,28,34	56%	0.3%	0.3%	8	7.25	8
5/26/2017	1.23	(1.62)	2189		2158	9	16,26,28,34	60%	3.8%	0.7%	8	7.21	4
5/27/2017	1.49	(1.41)	2081		2144	9	16,26,28,34	19%	1.7%	0.0%	8	7.30	8

SI Data Using Daily Cumulative Results

Combined Daily Operational Index (Green=0, Yellow=1,Red=2)	Date	Slag Index Data: Zone 2 (Left Side)	Zone 3 (Right Side)	Zone 2 Cumulative Slag Build-up	Zone 3 Cumulative Slag Build-up	Chemical Addition: Magnesium Hydroxide Dose rate (Lbs/Ton of Coal)	Calcium Carbonate Dose rate (Lbs/Ton of Coal)
4	4/8/2017	-2	0	-2	0	0	0
6	4/9/2017	-2	3	-4	3	0	0
1	4/10/2017	10	2	6	5	0	0
2	4/11/2017	-4	1	2	6	0	0
2	4/12/2017	4	-2	6	4	0	0
8	4/13/2017	1	5	7	9	0	0
3	4/14/2017	5	6	12	15	0	0
2	4/15/2017	-1	-1	11	14	0	0
5	4/16/2017	-5	2	6	16	0	0
5	4/17/2017	7	5	13	21	0	0
5	4/18/2017	10	0	23	21	0	0
7	4/19/2017	18	0	41	21	0	0
5	4/20/2017	5	3	46	24	0	0
5	4/21/2017	2	6	48	30	0	0
3	4/22/2017	-5	0	43	30	0	0
7	4/23/2017	5	5	48	35	0	0
11	4/24/2017	4	0	52	35	0	0
9	4/25/2017	2	7	54	42	0	0
9	4/26/2017	0	0	54	42	0	0
8	4/27/2017	2	5	56	47	0	0
10	4/28/2017	-5	-4	51	43	0	0
2	5/14/2017	10	-2	10	-2	1.2	1.2
3	5/15/2017	-6	8	4	6	0.9	0.9
6	5/16/2017	18	-10	22	-4	0.9	0.9
3	5/17/2017	-11	16	11	12	1.2	1.2
5	5/18/2017	6	-3	17	9	1.2	1.2
2	5/19/2017	-11	0	6	9	1.5	1.5
5	5/20/2017	-2	0	4	9	2.0	2.0
2	5/21/2017	0	0	4	9	2.0	1.2
4	5/22/2017	0	0	4	9	2.0	1.2
5	5/23/2017	-2	0	2	9	2.0	1.0
4	5/24/2017	2	3	4	12	2.0	1.0
8	5/25/2017	-2	5	2	17	2.0	1.0
4	5/26/2017	10	4	12	21	2.0	1.0
8	5/27/2017	-3	-11	9	10	2.0	1.0

4/8/17

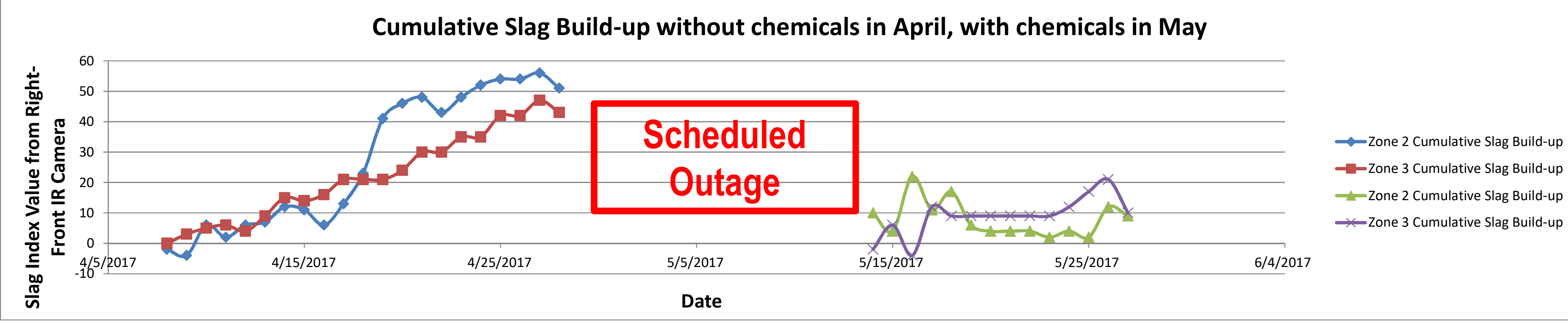
4/21/17

4/28/17

5/14/17

5/27/17

Chemical Trial Results



- The fundamental difference with chemicals was that the ash build-up increased & decreased about the same throughout the 15 days
- During the non-chemical addition trial, the daily cumulative increase/decrease was skewed much more to the increasing slag, resulting in an overall increase.
- The camera SI data is providing operations information that can be used every shift. They provide engineering data that is used to make decisions on operational changes which lead to improved operations and reliability.

Benefits of IR Cameras as an Operations Tool

- This new instrument **quantifies** the,
  - Sootblower effectiveness
  - Daily increase/decrease of ash (using the daily average of 4300+ SI values)
  - The connection between particular coal blend and the slag changes throughout a day
  - Correlation to HVT testing for localized reducing atmosphere’s resulting in localized slagging
  - Effectiveness/Ineffectiveness of slag mitigation chemicals
  - Slag Index values can be connected to DCS with alarm settings for ash increase ramp rate and absolute value

IR Camera Difficulties – Most Recent Experiences

- Severe WW slagging results in interference with camera visual & data collection capability. In-rushing cool ambient air through the viewport tends to freeze the molten slag on the inside of the WW.

U1_LC_10-9-2017.avi.mp4

- One option to minimize the cold air influx would be a closure plate with a spring loaded lens collar to seal the viewport opening with the door opened.

Summary

- The purpose of these cameras is **<u>not</u>** to use them as a "rear view mirror" pretty picture that eliminates the need for an Operator to walk down the boiler.
- As Slag Index values change, it signals the Unit Operator to take action.
- We can't remove the ash that's in coal, so slagging/ash build-up is something that needs to be managed. IR cameras with SI software provide operations another tool for this management.
- We would also like to use the IR camera outputs as feedback to the VISTA software in Fuels evaluations.

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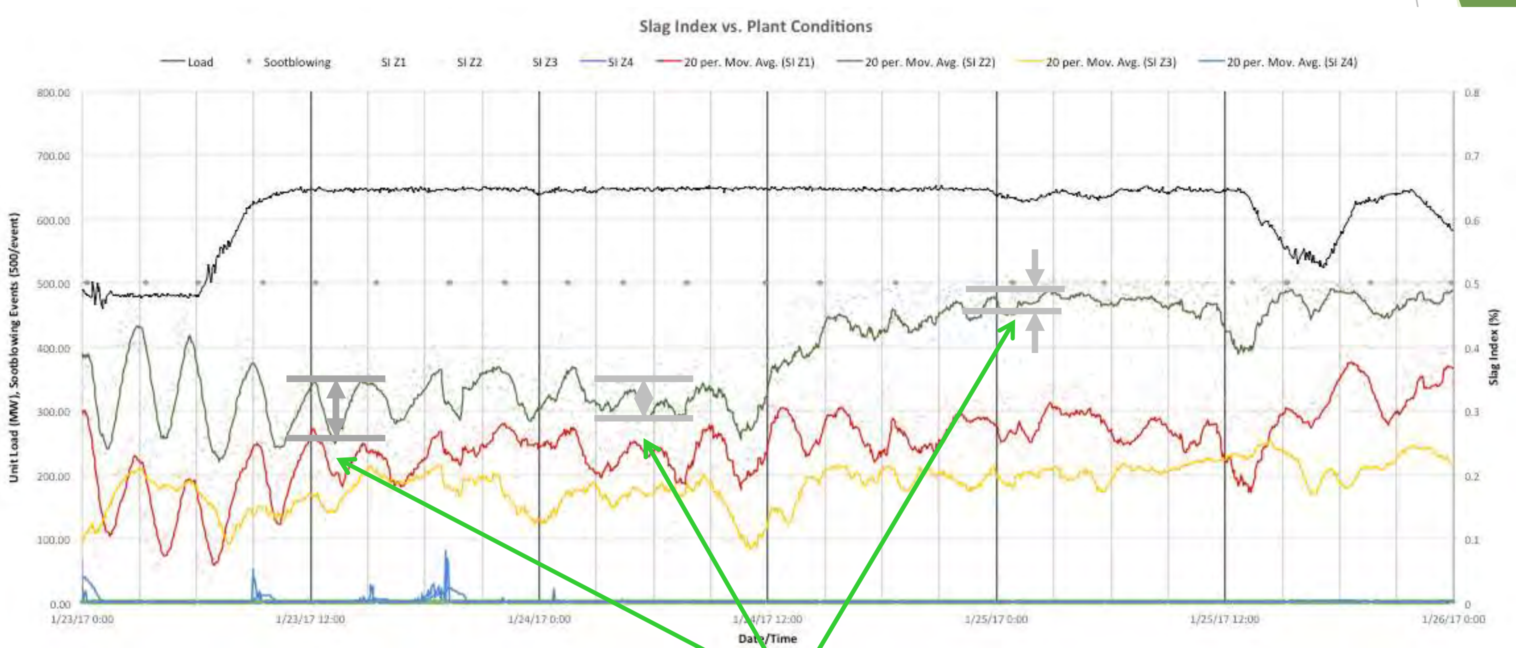
Slag Index: 2 Day Snapshot



Decreasing Peak/Valley Separation shows increasing Tenacity

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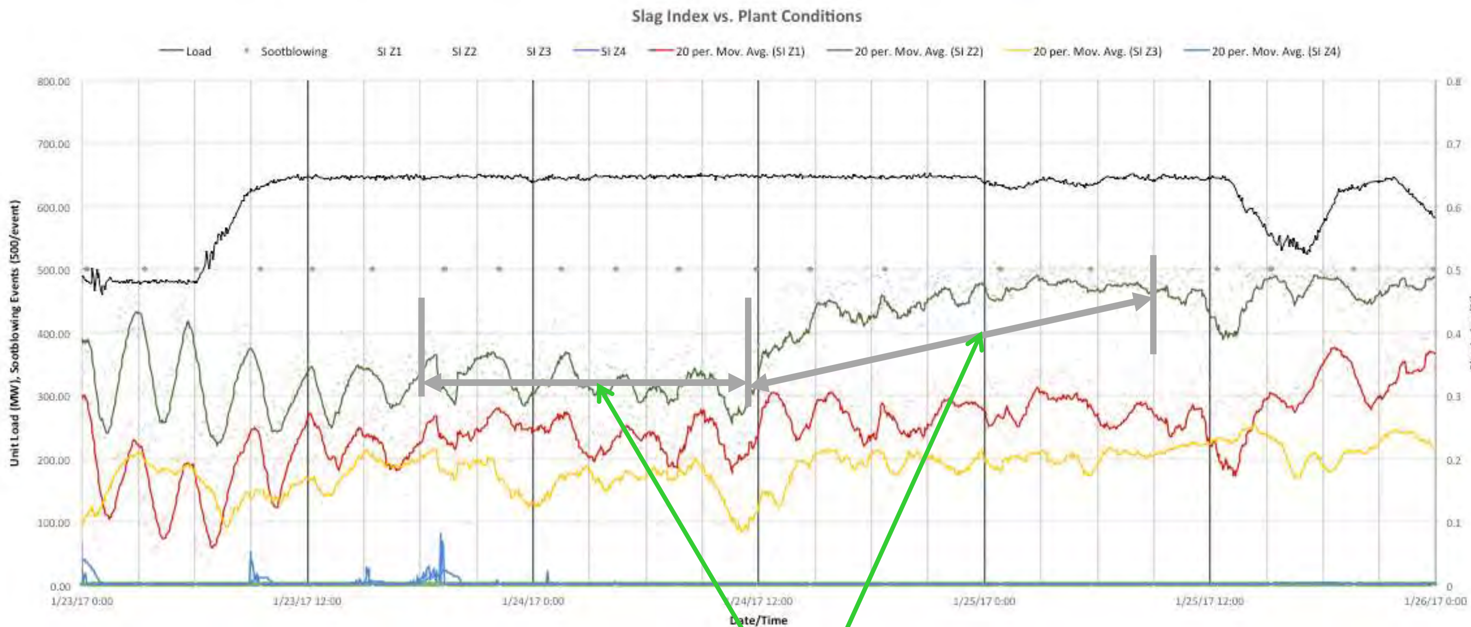
Slag Index: 2 Day Snapshot



Increasing Period to Period SI Level Indicates Deposit Growth

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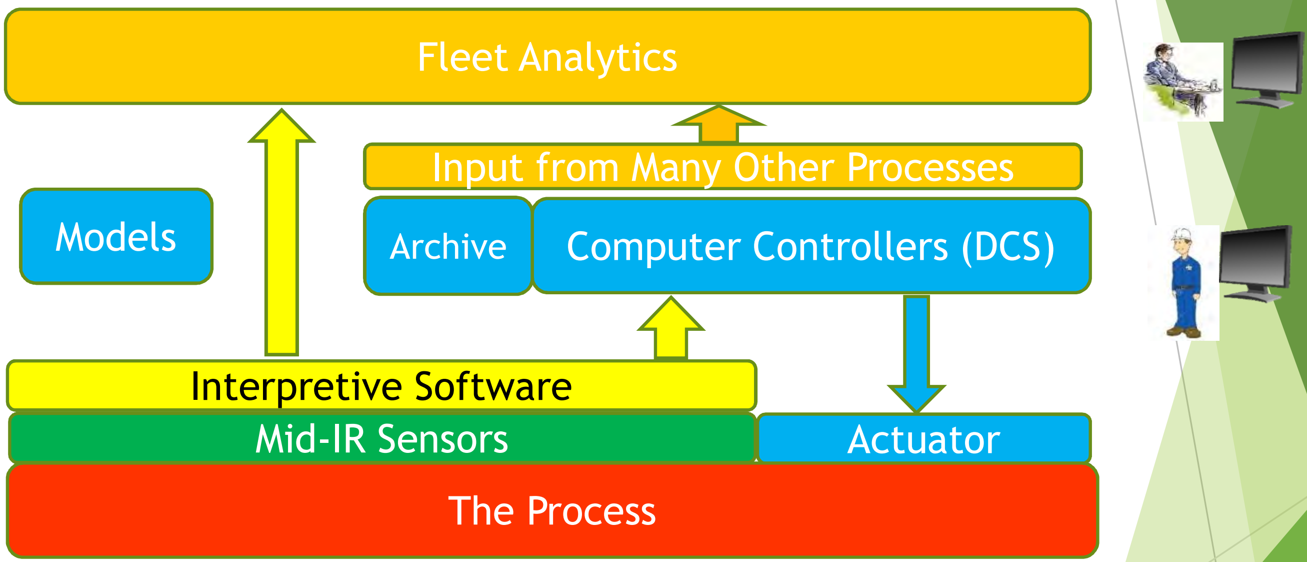
Alerts of Problematic Events

- Problematic Events
  - RGE (Rapid Growth Event)
  - Cycle Growth Strength >> 0
- Decrease of Cleaning Effectiveness Over Multiple Cycles
  - Slag Tenacity
  - Maintenance Prediction
- Impact of Fuel Switching on Slag Cycle
- Impact of Mills on Cycle Types and Strengths

Data Flow 3: Networking



Outline

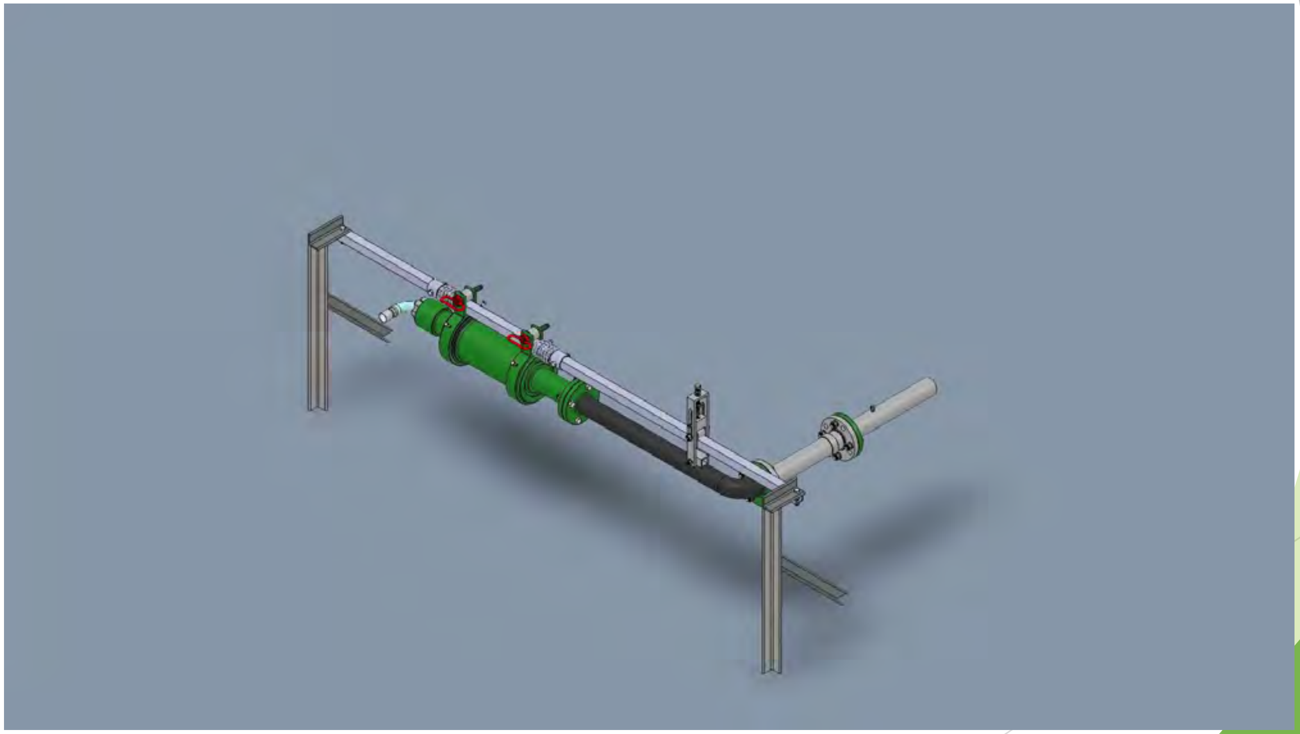
- Boiler Interiors: Slagging and Pollutant Formation
- Mid-IR Imaging and Slag Index
- Slag Index at Duke Energy
- Temperature and Acoustic Pyrometry
- Flow of Data and Information

Gas Temperature Measurements

- Key to Physical and Chemical Processes
  - Heat Transfer
  - Chemical Kinetics
- Key to Slag Formation (Ash Fusion)
- Key to Pollutant Formation (e.g., Thermal NO_x & SO_3)

Acoustic Pyrometry

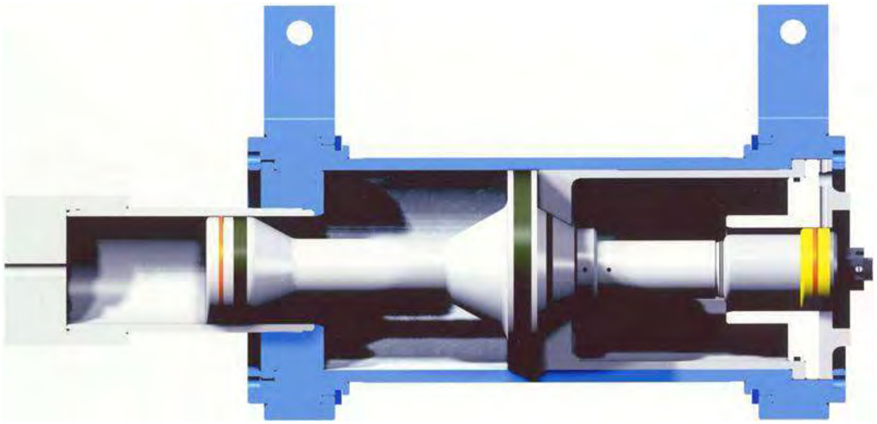
Sound Speed Related to Temperature: $\mathbf{c^2 = \gamma RT}$



Information from Temperature Data

- Flatness of Temperature Distribution
- Hot Spot Location
- Fireball Location
- Surface Impingements

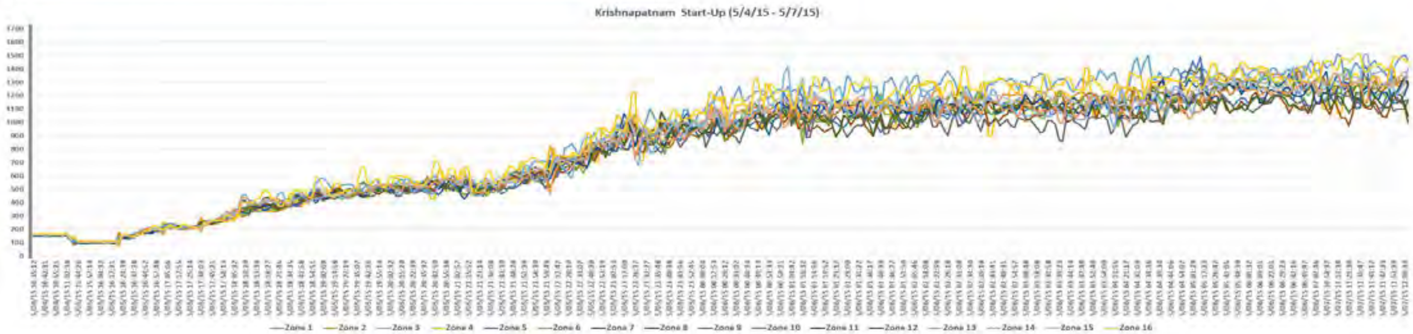
Powerful Sound Generator



- Loud Sharp Sound Sources
  - Using Plant Air Only; Safe and Reliable

AP Start-Up/Operating Data

Boiler is Cold



Installation Example: Ninghai

- Large Boiler Servicing Shanghai (1,000 MW)

50 Systems Installed in China

Enertechnix

Potential Benefits (from Users)

- AP for Startup Assistance
  - Temp Control
  - Header Temperature Differential/Stress
  - Startup Coal Fineness Affects Mill Loadings
- Combustion
  - Fireball Position
  - Flame Impingement
  - Mill Fineness Impact
  - HP/Ton + CO + Pipe Velocity
  - Oxygen Balancing

Potential Benefits (Cont'd)

- Low Load NOx Control
- Gas Cofiring Feedback for Fuel Balancing
- Intelligent Sootblowing
- Lower Furnace Heat Transfer
- Atemperating Spray/Reheat Wall Coordination
- SNCR Control
- Online Deslagging

Outline

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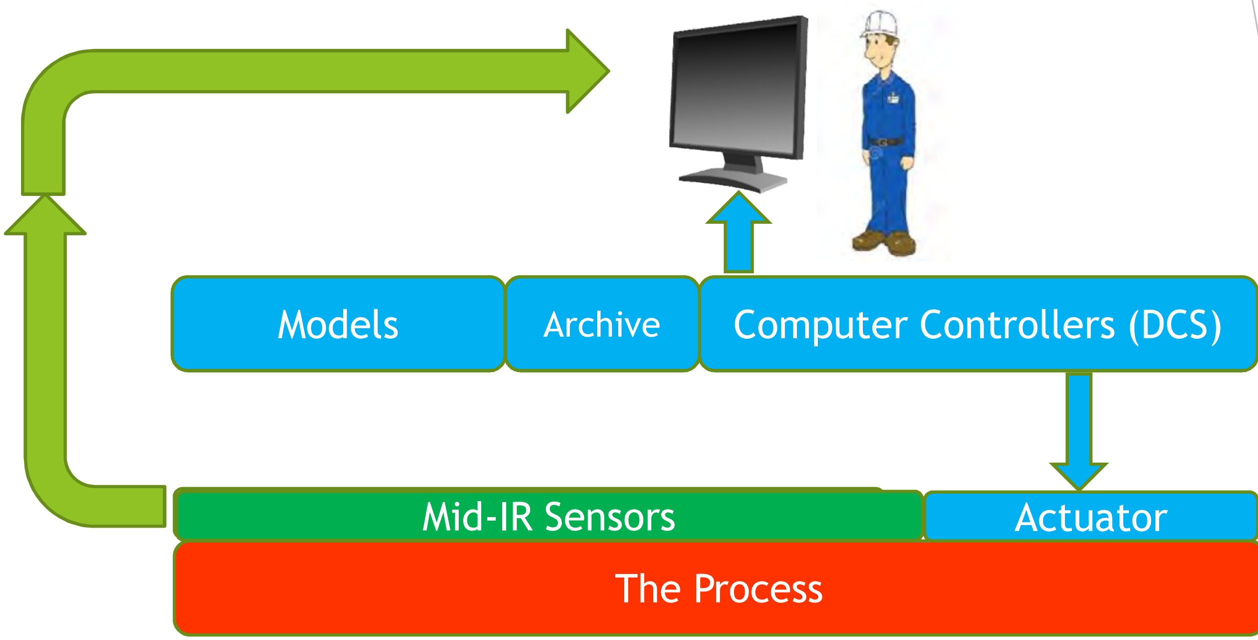
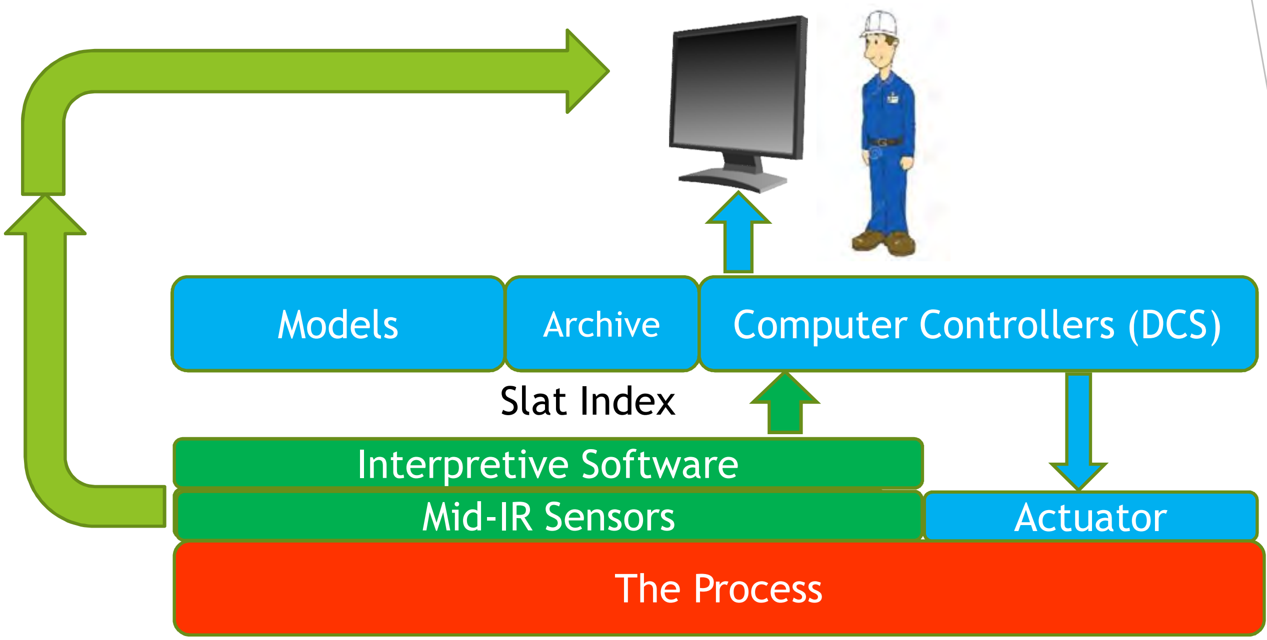
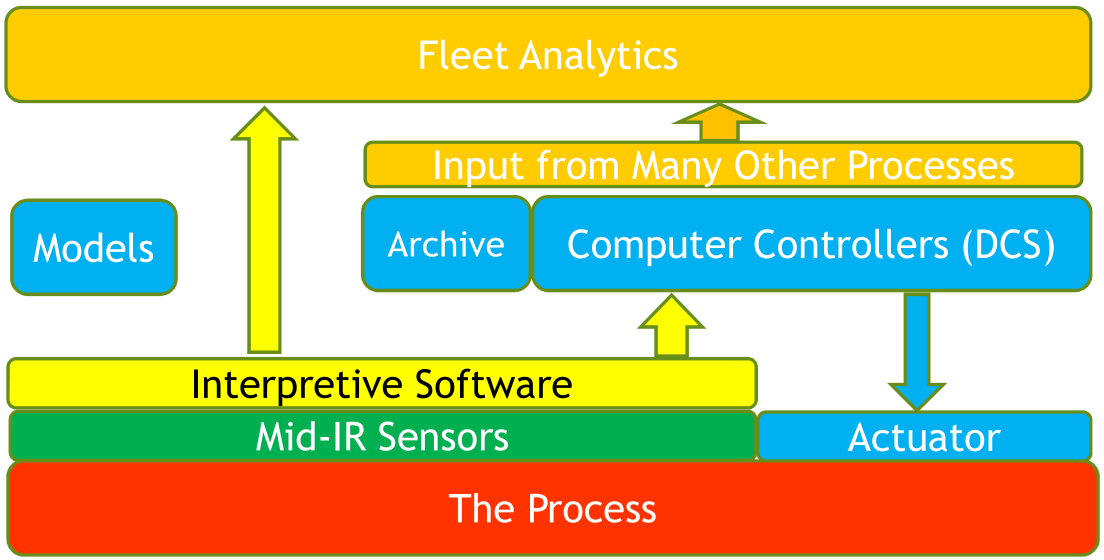
Data Flow 1: Direct Video to Operator



Data Flow 2: Interpretive Software to DCS



Data Flow 3: Fleet Analytics

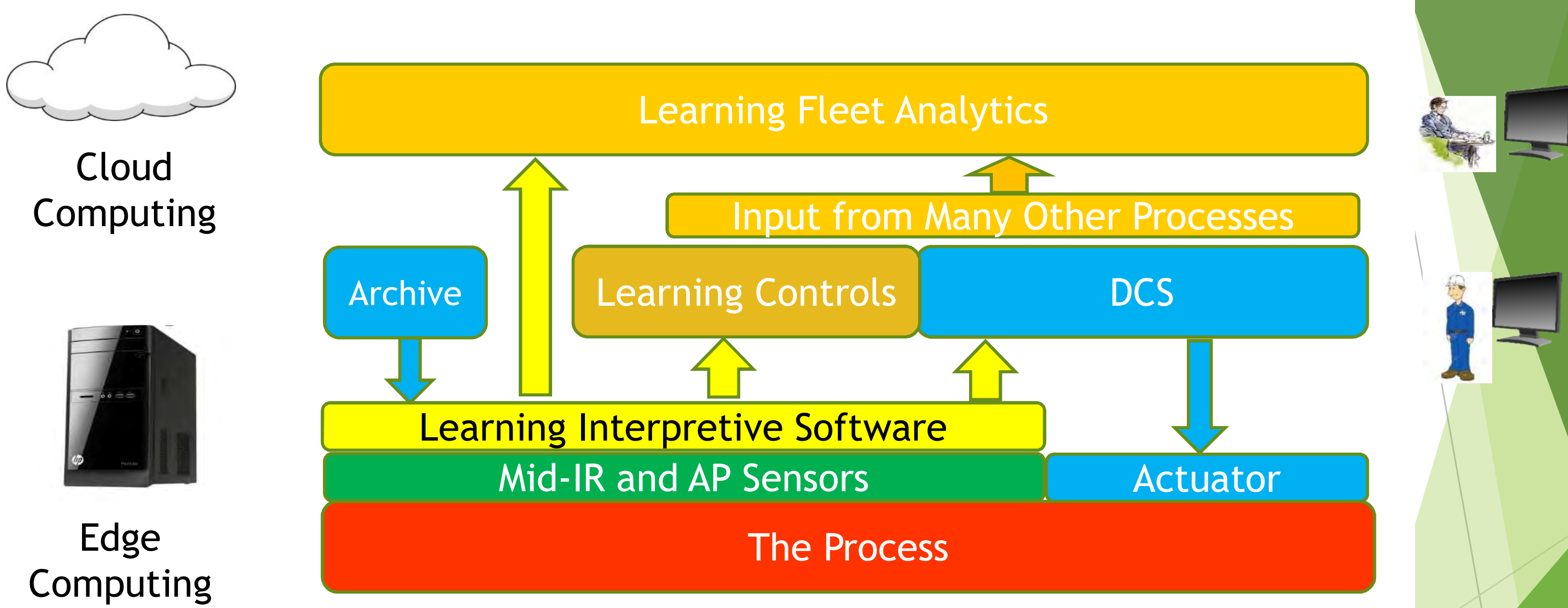


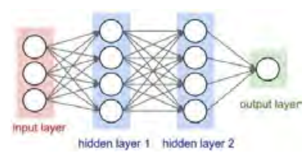
Enabled by Networking

Next Steps

- Phenomena Not Captured by Slag Index
  - Flame Impingement
  - Slagging Outside "Boxes"
  - "Dustiness" of Image
  - Sootblower Behavior
- Combining Slag Indexing and AP Data
  - Lower Furnace Temperatures to Control Slagging
  - Demonstration Project
- Next Step
  - Learning Software

Data Flow 4: Deep Learning





Learning Software: Neural Nets

Questions?

Special Thanks to:

- Duke Energy
  - Stephen Storm
  - Technical Staff at East Bend Generating Station
- Cal Lockert