REINHOLD ENVIRONMENTAL Ltd.

2017 NOx-Combustion-CCR Round Table Presentation

February 27 & 28, 2017, in Cleveland, OH / Hosted by FirstEnergy

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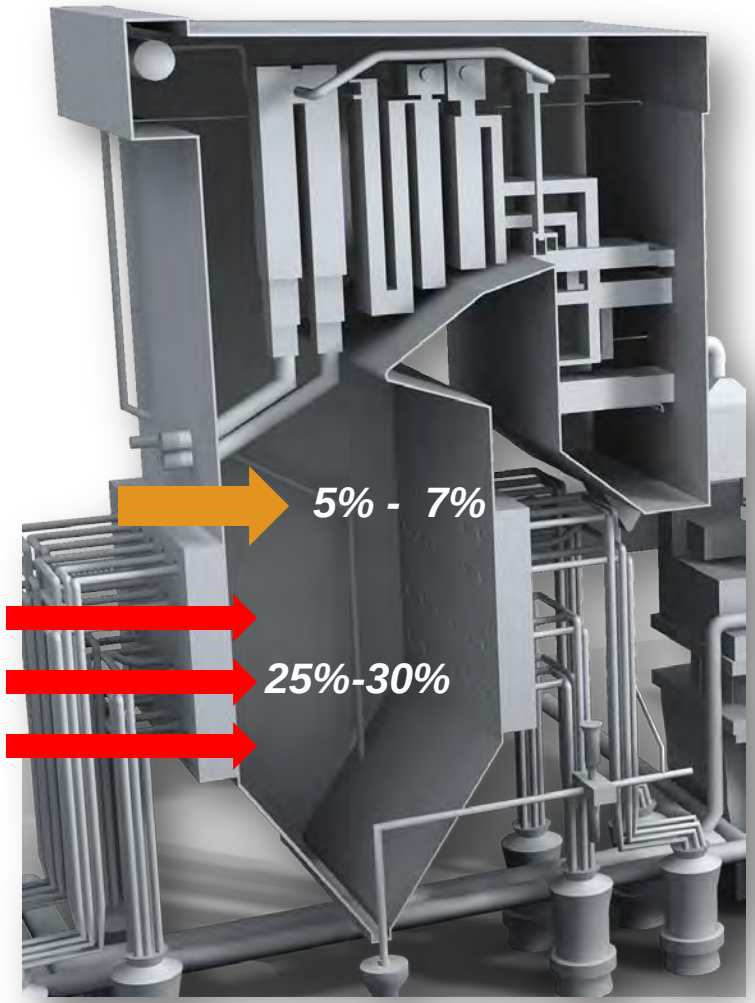
Update on Experience and Applications with Enhanced Gas CoFiring

Presented by: Cal Lockert & Tim McCreary

Date: February 27, 2017

Enhanced Gas CoFiring

Enhanced Cofire Concept

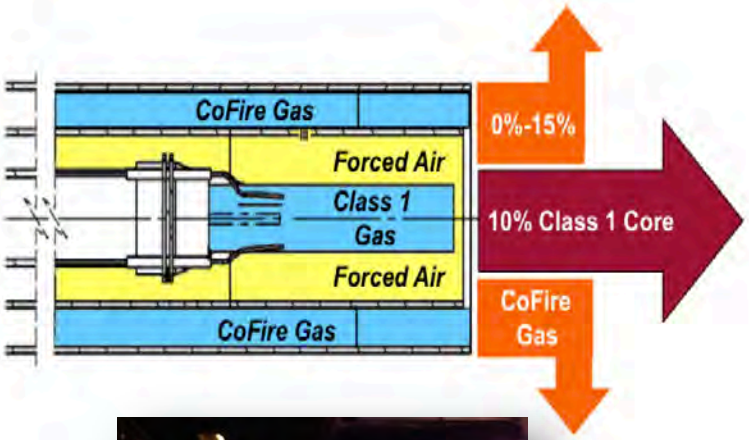


Dual-Use of Natural Gas

1. FLGR Requires 5% - 7% Natural Gas in the Upper Furnace for NOx Control
2. Cofiring places volumes of NG at the igniter, or air bucket, location from 10% of HI (NFPA Class 1) to 30%

Based on Load and Operating Conditions, the gas volume at each location can be adjusted

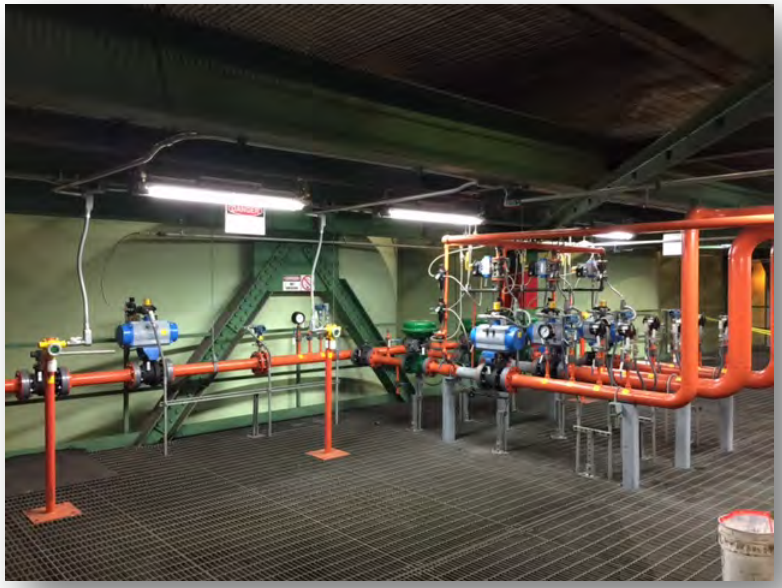
DOC Design



Maximizes Gas flow while maintaining heat proximity to the furnace walls

Cofire gas comes from a higher area secondary annulus

FLGR For Dual Use Gas



Pressure & Flow Control can be adjusted to properly marry gas injection depth/velocity with NOx presence

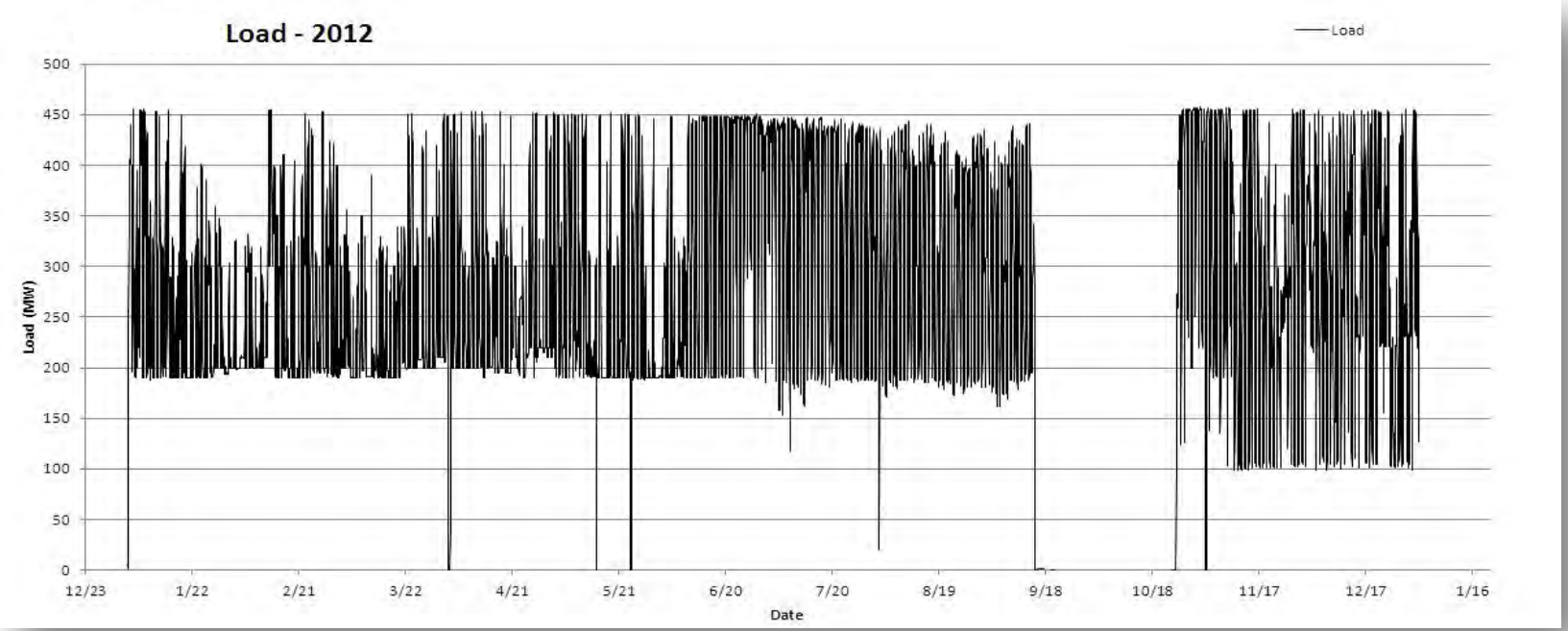
Update on CoFiring

CoFiring Variables

- **465 MW Nominal/Wall-Fired Unit**
  - 30 Burners based on 5 mills – 3 front wall/2 back wall
- **Unit burns 100% Illinois Basin Coal**
  - Natural Gas Igniters
  - Landfill Gas use is variable
  - Can reach full load with 3 mills + Gas

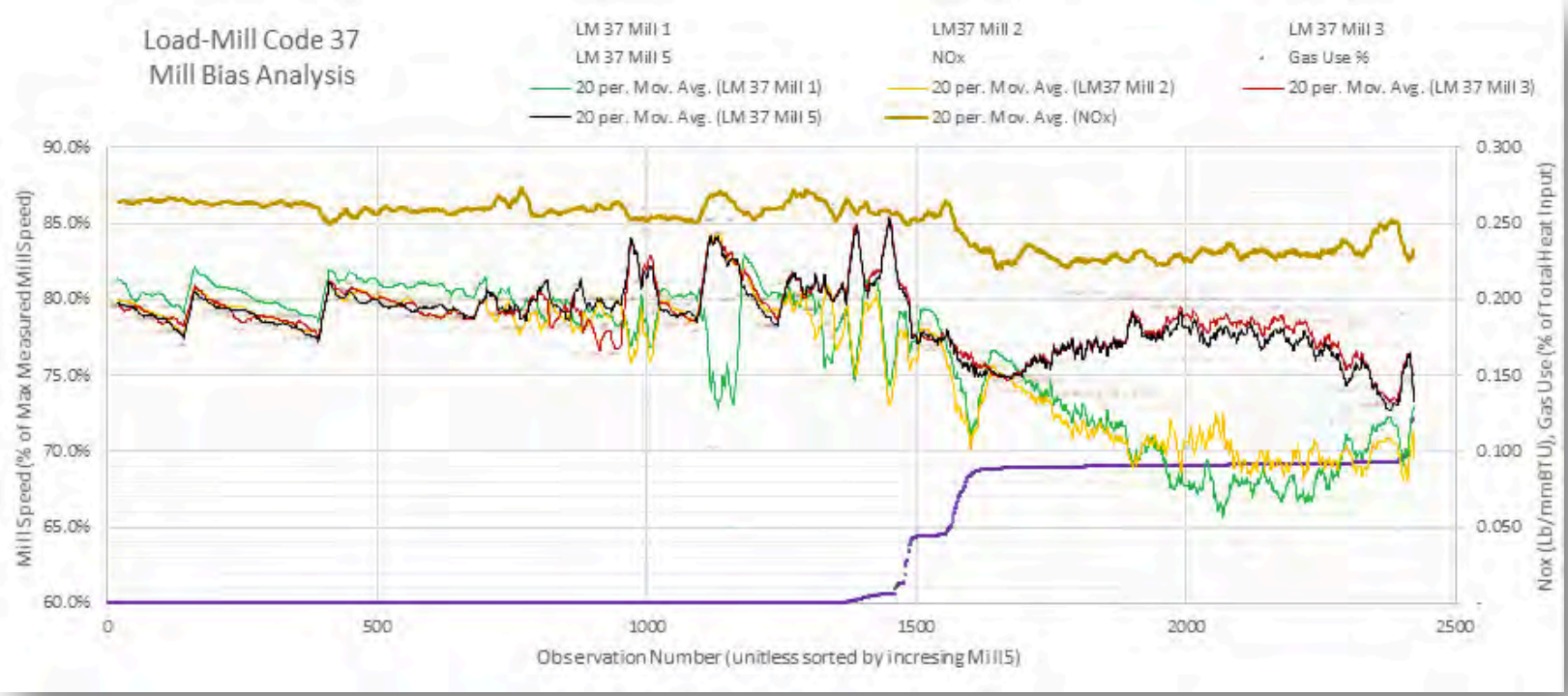
- **Variables:**
  - Mill Count & Configuration
  - Use of Natural Gas
  - Use of Landfill Gas

Load Plot



- High Volume of Gas at Low Load relieves NFPA worries re: two mill operation
- High Volume Gas Dilutes SO3 at SCR inlet relieving concerns over SCR MOT

Mill Bias/Gas Observation Plot



- This Mill Configuration is the most common for this plant at Full Load.
- Utilization of only 9% natural gas (igniter level, no FLGR) allows deep biasing of coal input to the bottom mills and a significant drop in unit NOx

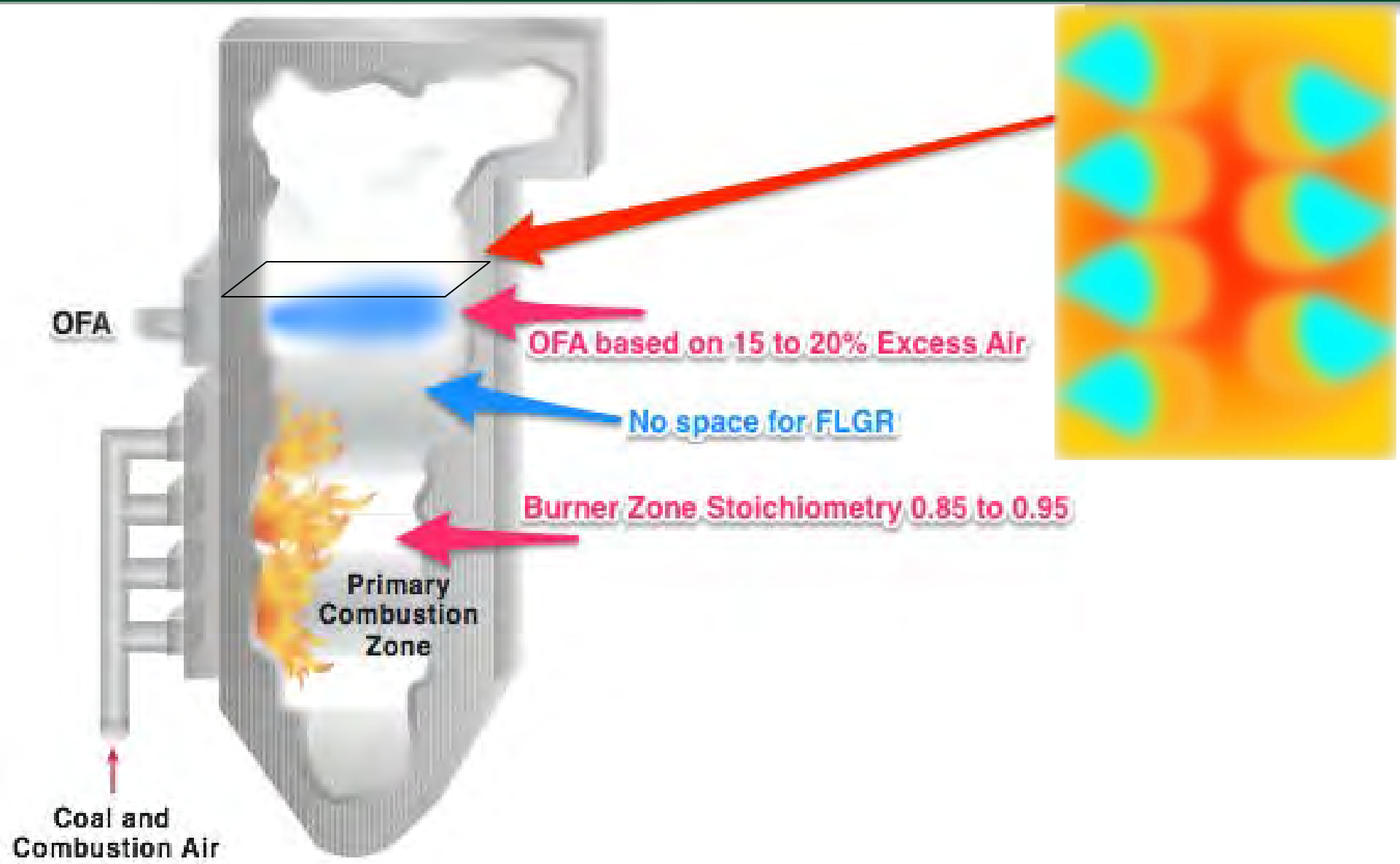
Update on FLGR

Chemistry of FLGR

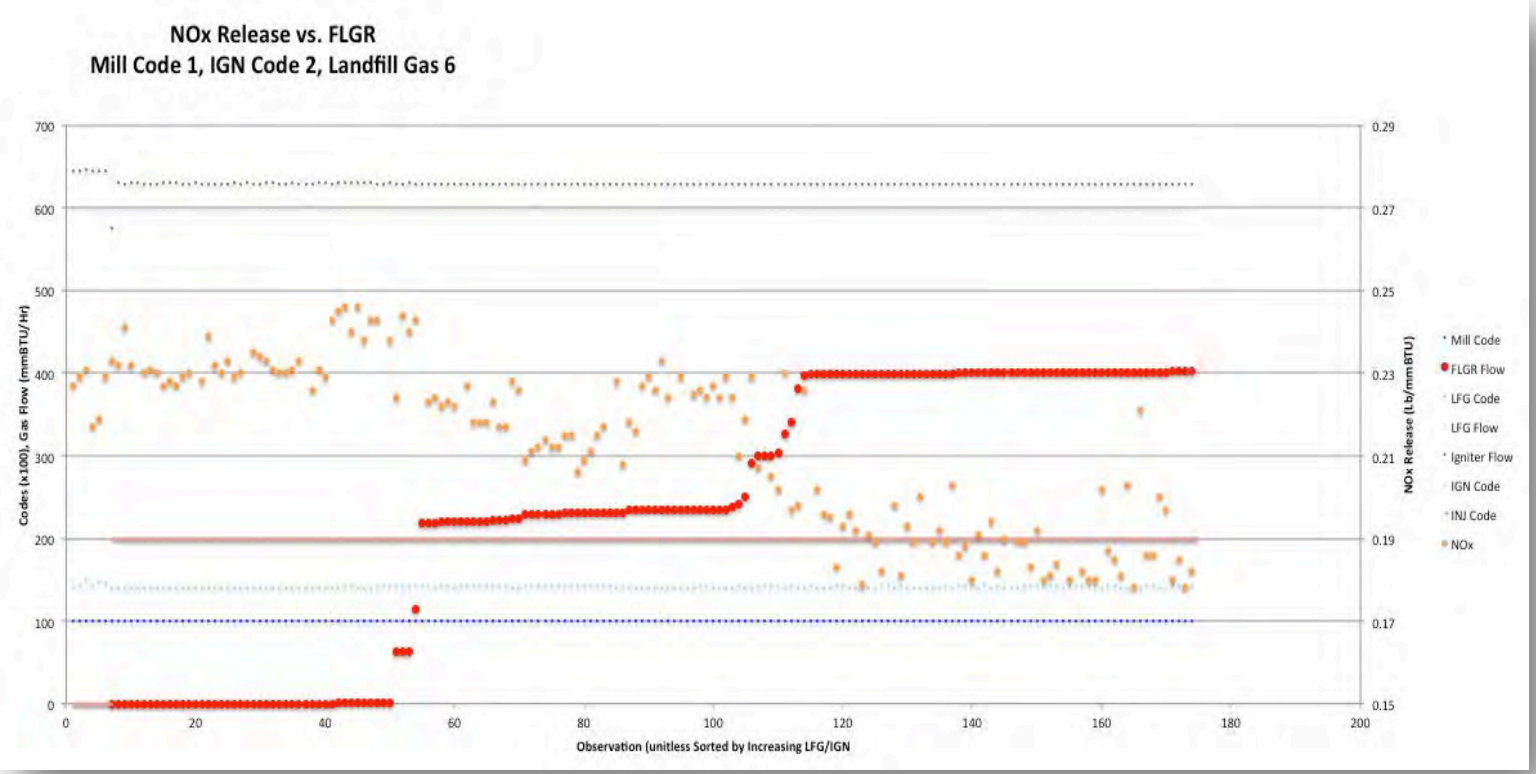
- **Natural Gas is injected via a series of injectors that are designed to create Micro-Swirls in identified higher NO_x zones,**

- **Essentially:**
  - $CH_4 + NO_x = N_2 + H_2O + CO$
- **The N_2 and H_2O parts are simple, the CO reacts with Oxygen in the flue gas to become CO_2 through the backpass of the boiler.**
- **The limiting factor on the amount of Natural Gas used, and the resulting NO_x reduction, is the mixing and residence time required to complete the CO:CO_2 reaction**

Modern Boiler – LNB/OFA

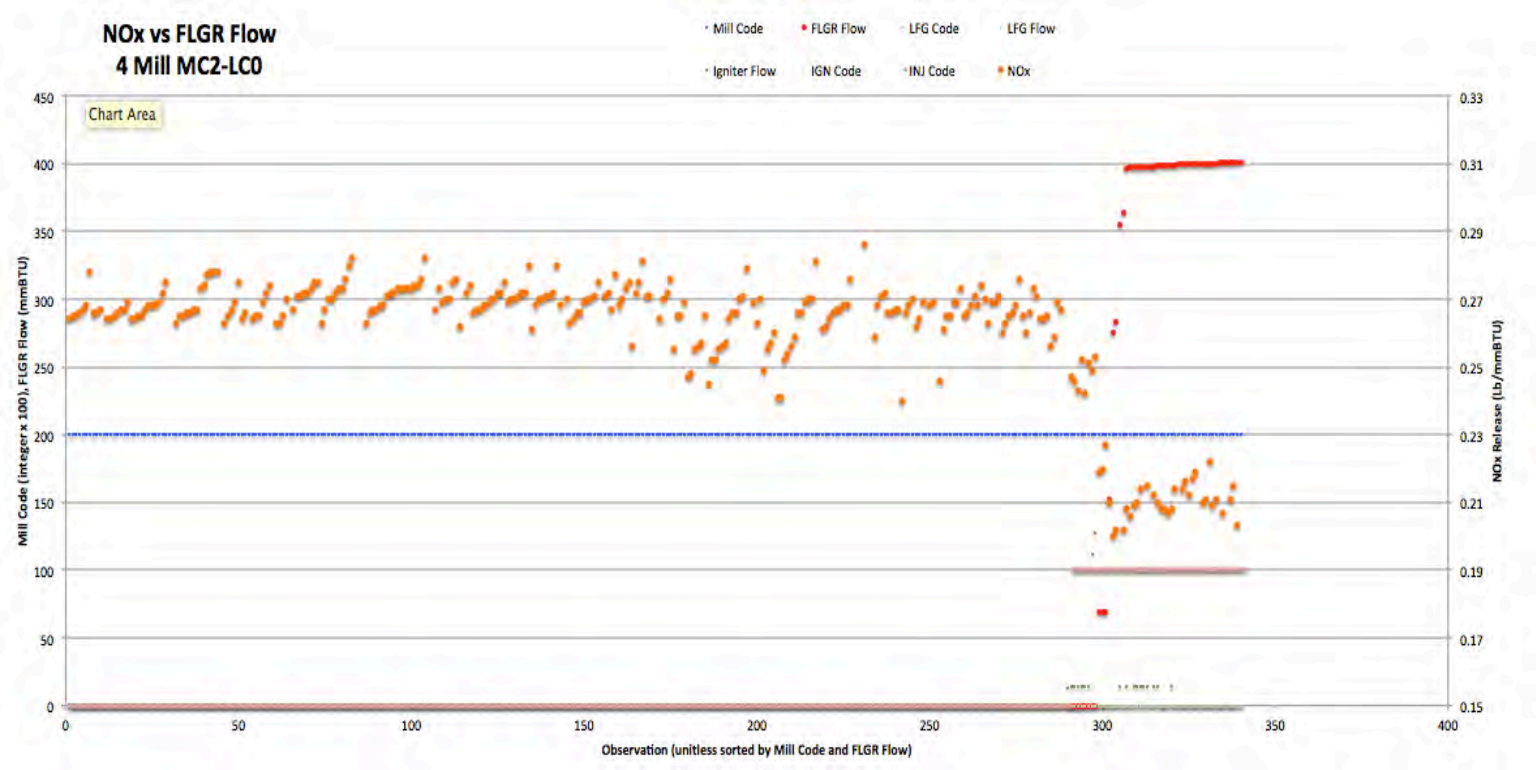


Full Load/3 Mill/2,3,5 FLGR



Initial NOx = 0.230 Lb./mmBTU
FLGR NOx = 0.19 Lb./mmBTU
Reduction = 17%

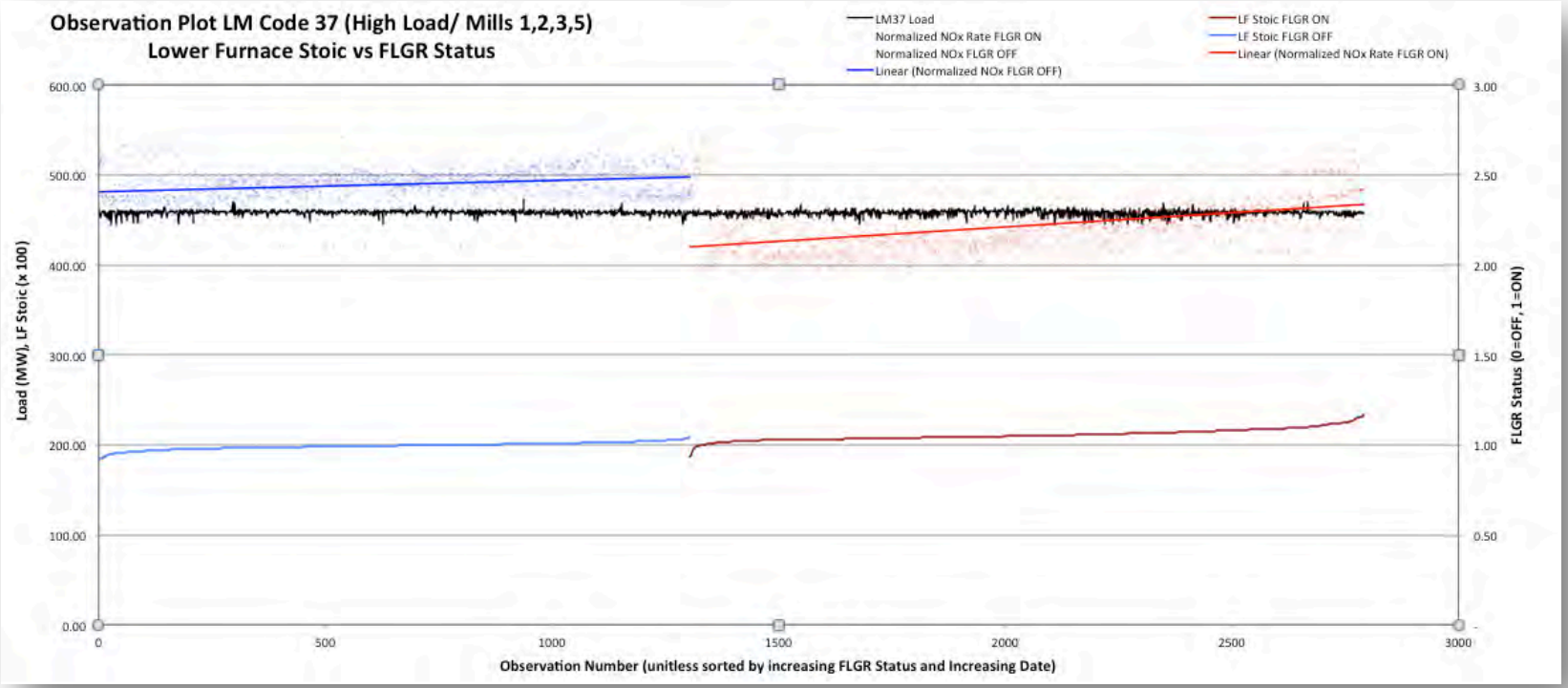
4 Mill Operation/2,3,4,5



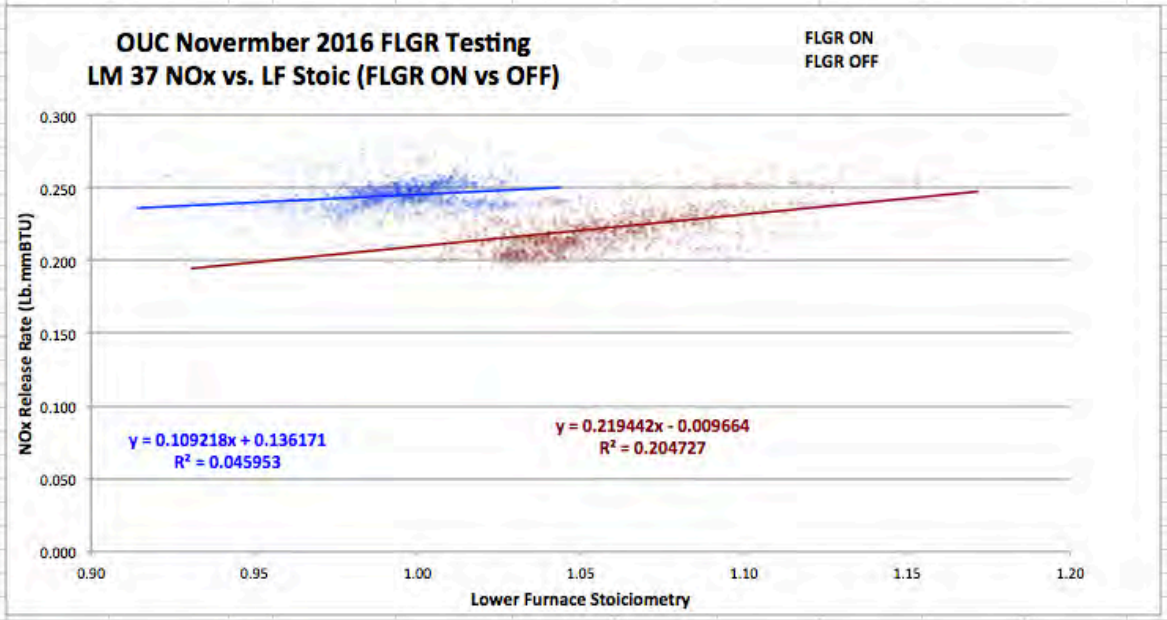
Initial NOx = 0.270 Lb./mmBTU
FLGR NOx = 0.21 Lb./mmBTU
Reduction = 22%

Furnace Stoichiometry Dependence

NOx vs LF Stoic by Stoic



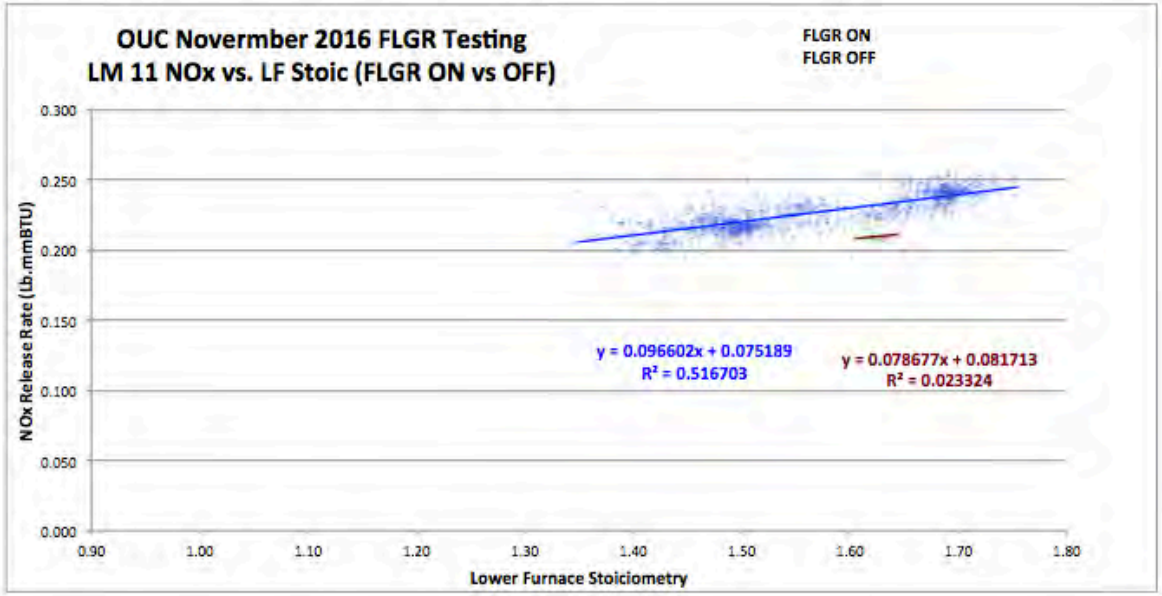
LM37 NOx vs. LF Stoic



"M"	0.109218	0.219442	
"B"	0.136171	-0.009664	

LF Stoichiometry	FLGR OFF NOx Rate	FLGR ON NOx Rate	Nox Reduction
0.95	0.240	0.199	17.1%
0.96	0.241	0.201	16.6%
0.97	0.242	0.203	16.1%
0.98	0.243	0.205	15.5%
0.99	0.244	0.208	15.0%
1.00	0.245	0.210	14.5%
1.01	0.246	0.212	14.0%
1.02	0.248	0.214	13.5%
1.03	0.249	0.216	13.0%
1.04	0.250	0.219	12.5%
1.05	0.251	0.221	12.0%

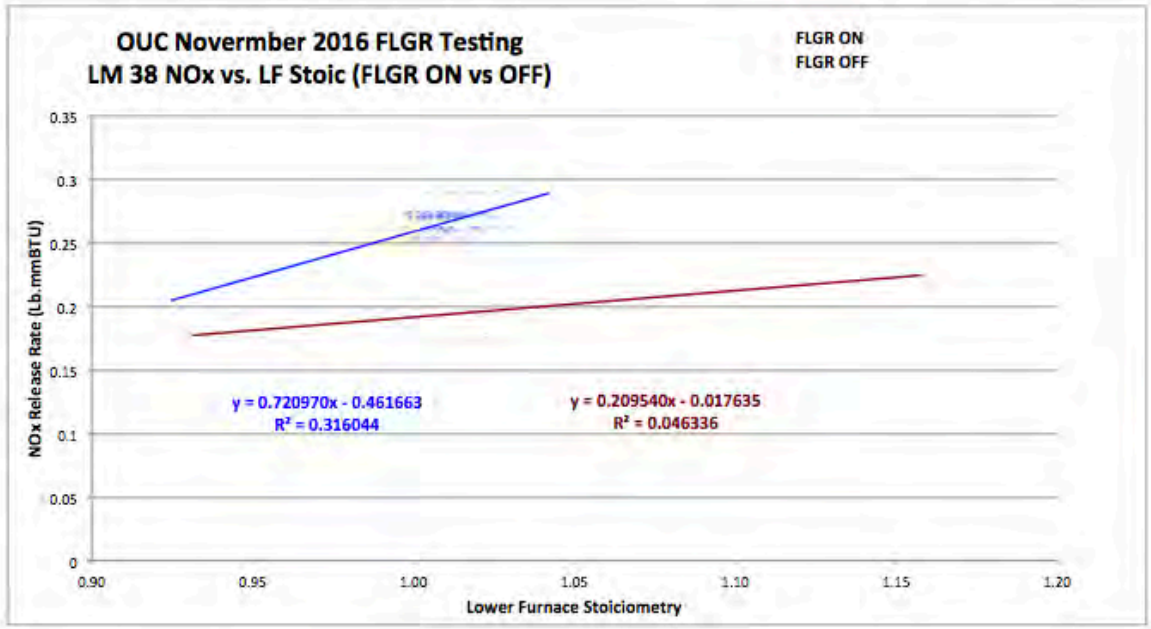
LM11 NOx vs. LF Stoic



"M"	0.096602	0.078677
"B"	0.075189	0.081713

LF Stoichiometry		FLGR OFF NOx Rate	FLGR ON NOx Rate	Nox Reduction
1.40		0.210	0.192	8.8%
1.41		0.211	0.193	8.9%
1.42		0.212	0.193	8.9%
1.43		0.213	0.194	9.0%
1.44		0.214	0.195	9.0%
1.45		0.215	0.196	9.0%
1.46		0.216	0.197	9.1%
1.47		0.217	0.197	9.1%
1.48		0.218	0.198	9.2%
1.49		0.219	0.199	9.2%
1.50		0.220	0.200	9.3%
1.51		0.221	0.201	9.3%
1.52		0.222	0.201	9.3%
1.53		0.223	0.202	9.4%
1.54		0.224	0.203	9.4%
1.55		0.225	0.204	9.5%
1.56		0.226	0.204	9.5%
1.57		0.227	0.205	9.5%
1.58		0.228	0.206	9.6%
1.59		0.229	0.207	9.6%
1.60		0.230	0.208	9.6%
1.61		0.231	0.208	9.7%
1.62		0.232	0.209	9.7%
1.63		0.233	0.210	9.8%
1.64		0.234	0.211	9.8%
1.65		0.235	0.212	9.8%
1.66		0.236	0.212	9.9%
1.67		0.237	0.213	9.9%
1.68		0.237	0.214	9.9%
1.69		0.238	0.215	10.0%
1.70		0.239	0.215	10.0%

LM38 NOx vs. LF Stoic



CO in Compliance/IGN Gass OFF

"M"	0.754909	0.196108
"B"	-0.495382	-0.017195

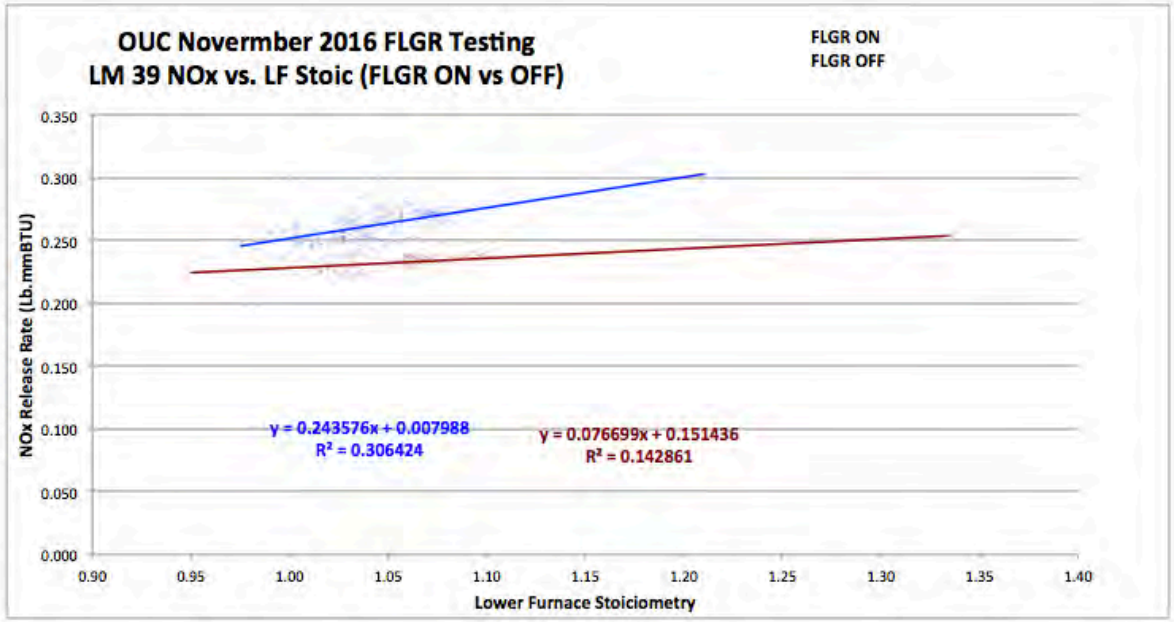
LF Stoichiometry		FLGR OFF NOx Rate	FLGR ON NOx Rate	Nox Reduction
0.95		0.222	0.169	23.8%
0.96		0.229	0.171	25.4%
0.97		0.237	0.173	27.0%
0.98		0.244	0.175	28.4%
0.99		0.252	0.177	29.8%
1.00		0.260	0.179	31.1%
1.01		0.267	0.181	32.3%
1.02		0.275	0.183	33.4%
1.03		0.282	0.185	34.5%
1.04		0.290	0.187	35.5%
1.05		0.297	0.189	36.5%

All Data

"M"	0.72097	0.20945
"B"	-0.461663	-0.017635

LF Stoichiometry		FLGR OFF NOx Rate	FLGR ON NOx Rate	Nox Reduction
0.95		0.223	0.181	18.8%
0.96		0.230	0.183	20.4%
0.97		0.238	0.186	21.9%
0.98		0.245	0.188	23.4%
0.99		0.252	0.190	24.7%
1.00		0.259	0.192	26.0%
1.01		0.267	0.194	27.2%
1.02		0.274	0.196	28.4%
1.03		0.281	0.198	29.5%
1.04		0.288	0.200	30.5%
1.05		0.295	0.202	31.5%

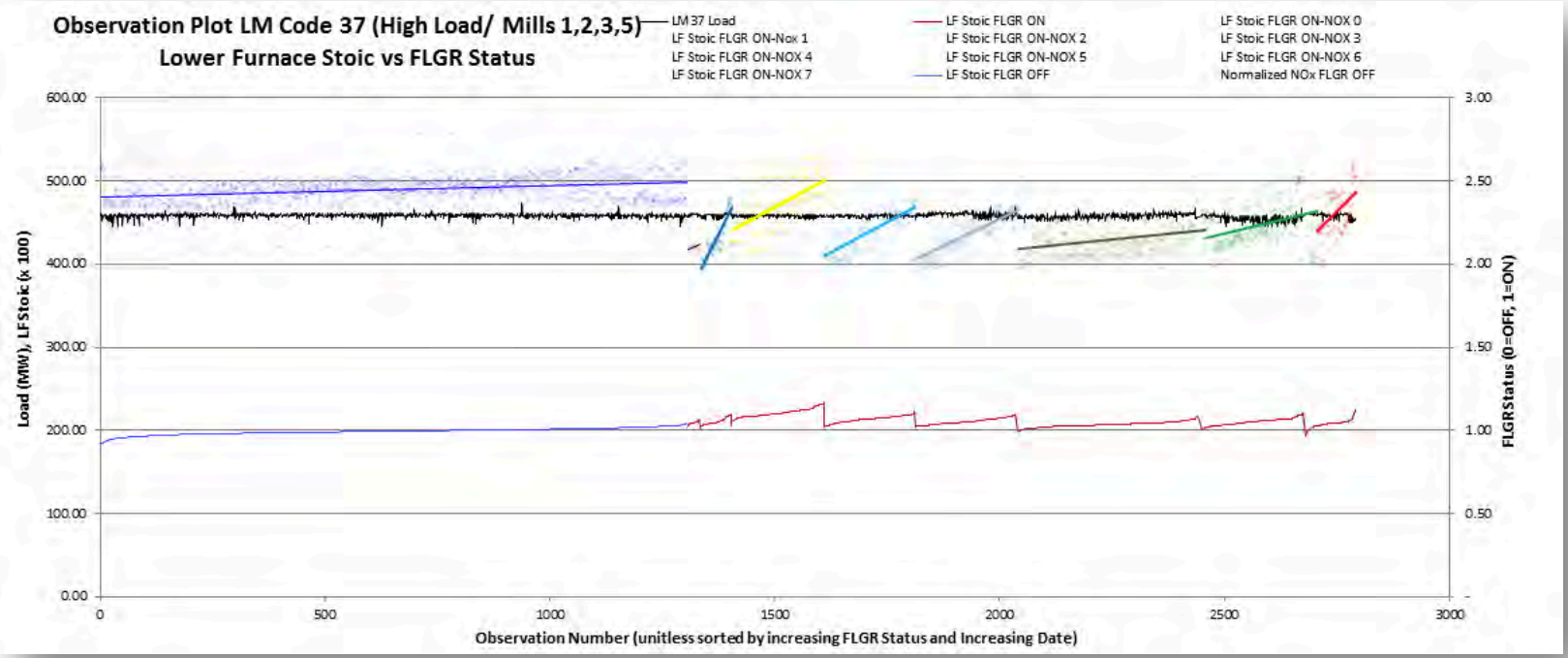
LM39 NOx vs. LF Stoic



"M"	0.243576	0.076699
"B"	0.007988	0.151436

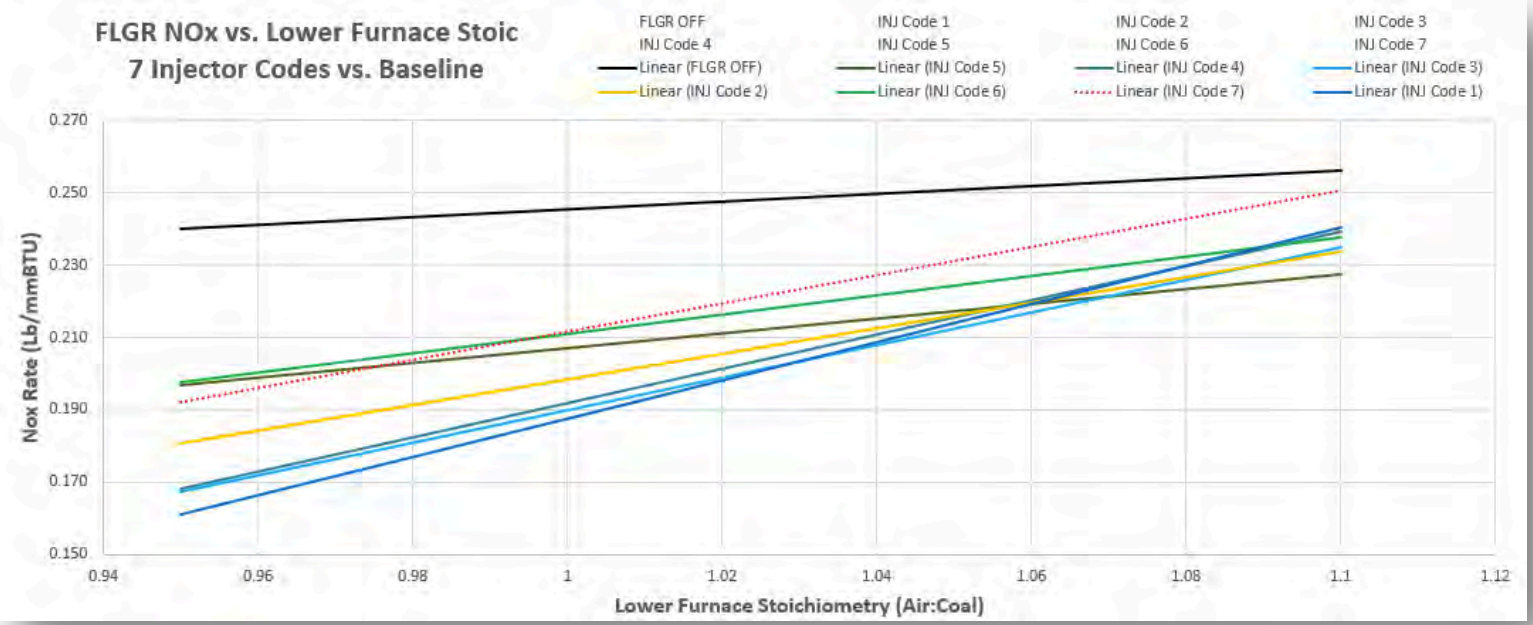
LF Stoichiometry		FLGR OFF NOx Rate	FLGR ON NOx Rate	Nox Reduction
0.95		0.239	0.224	6.3%
0.96		0.242	0.225	6.9%
0.97		0.244	0.226	7.5%
0.98		0.247	0.227	8.1%
0.99		0.249	0.227	8.7%
1.00		0.252	0.228	9.3%
1.01		0.254	0.229	9.9%
1.02		0.256	0.230	10.4%
1.03		0.259	0.230	11.0%
1.04		0.261	0.231	11.5%
1.05		0.264	0.232	12.0%

NOx vs LF Stoic by Stoic w/Inj Codes



Same approach but with FLGR “ON” data segregated by Injector Codes and FLGR Flow Rate below 200 SCFM eliminated (< 30 data points)

NOx v LF Stoic by Injector Code



FLGR Injector Setup Codes

1 Side Walls: Long, Straight, 7.5% Flow & Long, 22.5° to Front Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 9% Flow & Short, 22.5° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

2 Side Walls: Long, Straight, 9% Flow & Long, 45° to Front Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 7.5% Flow & Short, 22.5° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

3 Side Walls: Long, Straight, 9% Flow & Long, 45° to Front Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 9% Flow & Short, 22.5° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

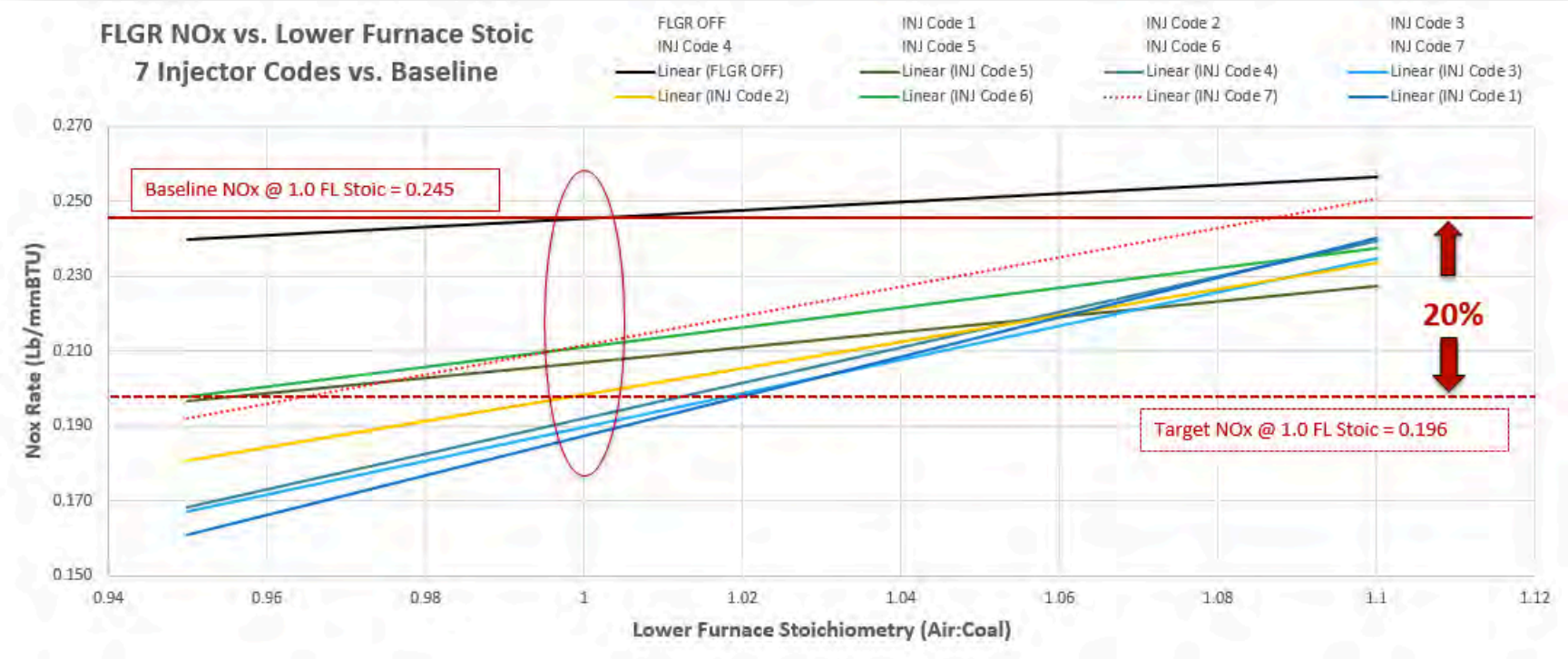
4 Side Walls: Long, Straight, 7.5% Flow & Long, 45° to Front Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 9% Flow & Short, 22.5° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

5 Side Walls: Long, Straight, 7.5% Flow & Long, 22.5° to Rear Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 9% Flow & Short, 22.5° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

6 Side Walls: Long, Straight, 7.5% Flow & Long, 45° to Rear Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 9% Flow & Short, 45° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

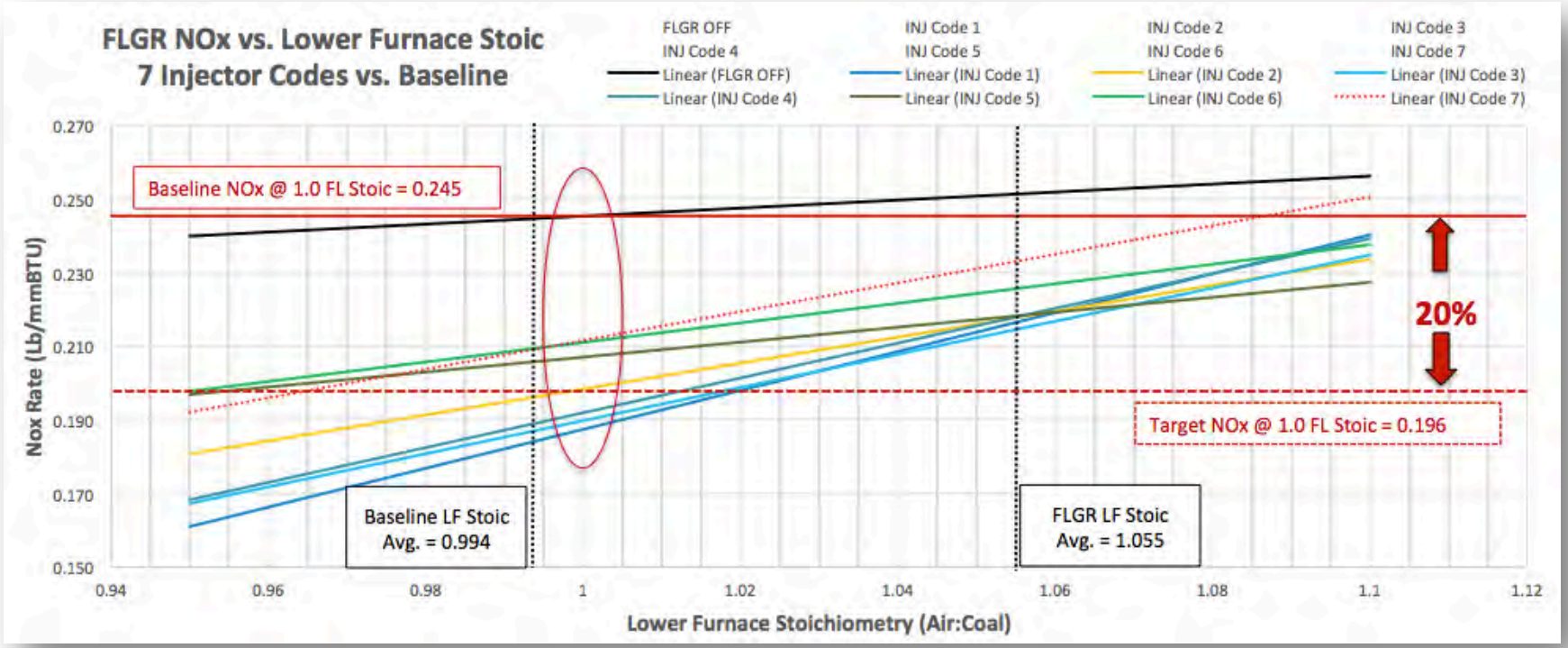
7 Side Walls: Long, Straight, 9% Flow & Long, 45° to Rear Wall, 7.5% Flow
Front Wall Corners: Short, Straight, 7.5% Flow & Short, 22.5° to Center, 9% Flow
Center - Short, Straight 12% Flow - Short 45° to edge, 11% Flow

NOx vs. LFS w/Injector Codes



Yellow and Blue Codes hold the most promise for the next round of testing

LFS vs NOx w/Avg. LF Stoic



Performance must be normalized to current Lower Furnace Stoichiometry conditions.

Normalized LFS vs. FLGR NOx

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State	FLGR OFF	INJ Code 1	INJ Code 2	INJ Code 3	INJ Code 4	INJ Code 5	INJ Code 6	INJ Code 7
"M"	0.109218	0.528980	0.352819	0.450597	0.473520	0.203632	0.265832	0.390200
"B"	0.136171	-0.341586	-0.154459	-0.260822	-0.281615	0.003402	-0.054802	-0.178634

LFS	FLGR OFF	INJ Code 1	INJ Code 2	INJ Code 3	INJ Code 4	INJ Code 5	INJ Code 6	INJ Code 7
0.95	0.240	0.161	0.181	0.167	0.168	0.197	0.198	0.192
0.96	0.241	0.166	0.184	0.172	0.173	0.199	0.200	0.196
0.97	0.242	0.172	0.188	0.176	0.178	0.201	0.203	0.200
0.98	0.243	0.177	0.191	0.181	0.182	0.203	0.206	0.204
0.99	0.244	0.182	0.195	0.185	0.187	0.205	0.208	0.208
1.00	0.245	0.187	0.198	0.190	0.192	0.207	0.211	0.212
1.01	0.246	0.193	0.202	0.194	0.197	0.209	0.214	0.215
1.02	0.248	0.198	0.205	0.199	0.201	0.211	0.216	0.219
1.03	0.249	0.203	0.209	0.203	0.206	0.213	0.219	0.223
1.04	0.250	0.209	0.212	0.208	0.211	0.215	0.222	0.227
1.05	0.251	0.214	0.216	0.212	0.216	0.217	0.224	0.231
1.06	0.252	0.219	0.220	0.217	0.220	0.219	0.227	0.235
1.07	0.253	0.224	0.223	0.221	0.225	0.221	0.230	0.239
1.08	0.254	0.230	0.227	0.226	0.230	0.223	0.232	0.243
1.09	0.255	0.235	0.230	0.230	0.235	0.225	0.235	0.247
1.10	0.256	0.240	0.234	0.235	0.239	0.227	0.238	0.251
0.99	0.245	0.184	0.196	0.187	0.189	0.206	0.209	0.209
1.06	0.251	0.216	0.218	0.215	0.218	0.218	0.226	0.233
Normalized Redux @ 0.99		24.7%	19.8%	23.6%	22.7%	15.9%	14.4%	14.5%
Normalized Redux @ 1.055		13.9%	13.4%	14.7%	13.3%	13.2%	10.2%	7.3%

FLGR Lessons Learned

1. **Maintenance of ORIGINAL Furnace Air/Fuel Stoichiometry is critical when moving FLGR gas into the upper furnace,**
2. **Gas Usage in the Upper Mill Igniters can help bias coal lower and improve NOx**

3. **Dual use of gas in upper AND lower furnace at different times can provide significant Unit Turndown, NOx, Particulate, Hg, SO_2 and CO_2 benefits for the single cost of the coal/gas price differential**

Next Steps

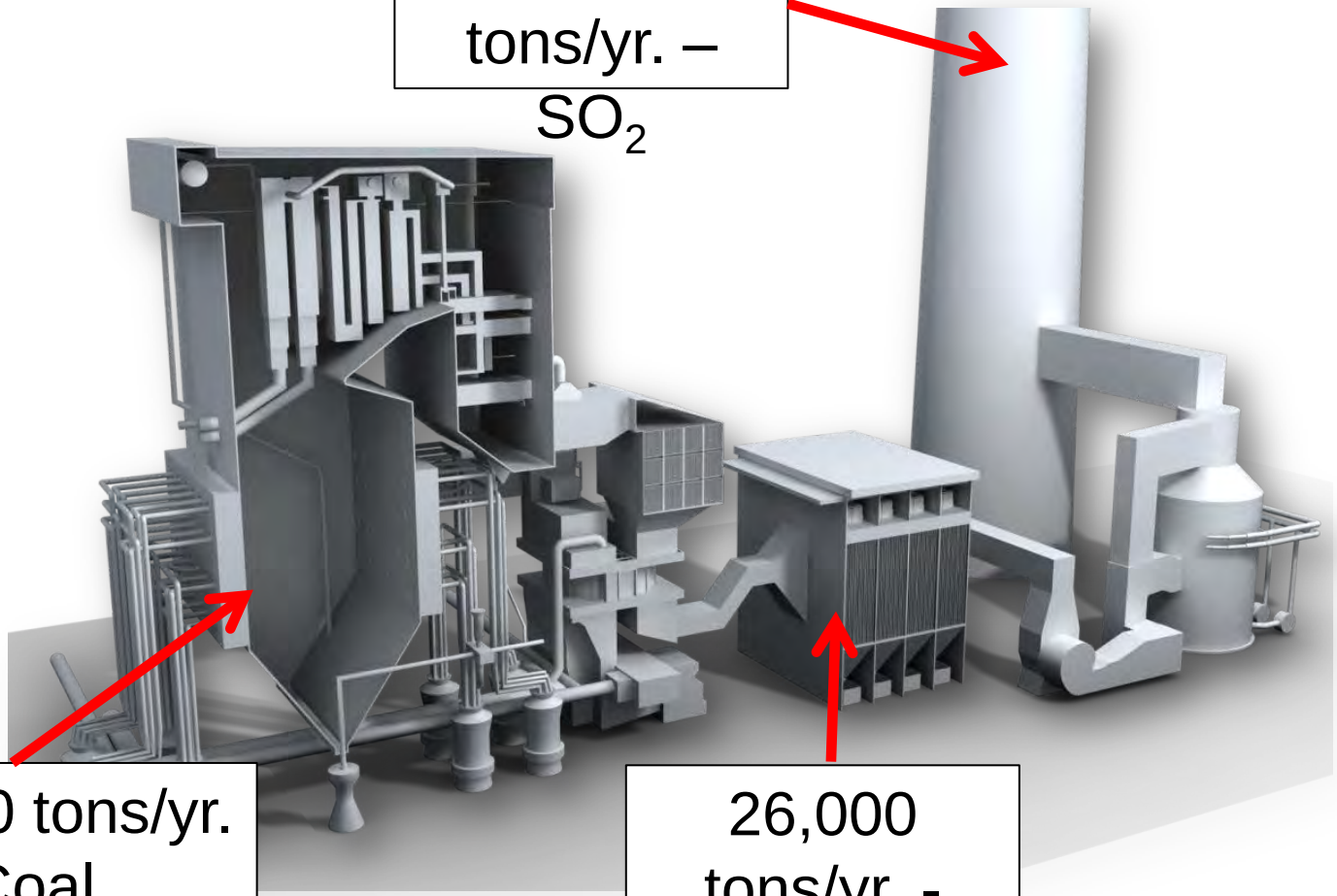
(OR) WHAT IS THIS GOOD FOR?

Non-Hypothetical Plant

- **350 MW, Subbituminous Fuel, NG Ignition**
- **No SCR**
- **No FGD**
- **Cold Side ESP for Particulate Control**

- **How do you reduce SO_2 85% without major capital expense?**

Current Operations

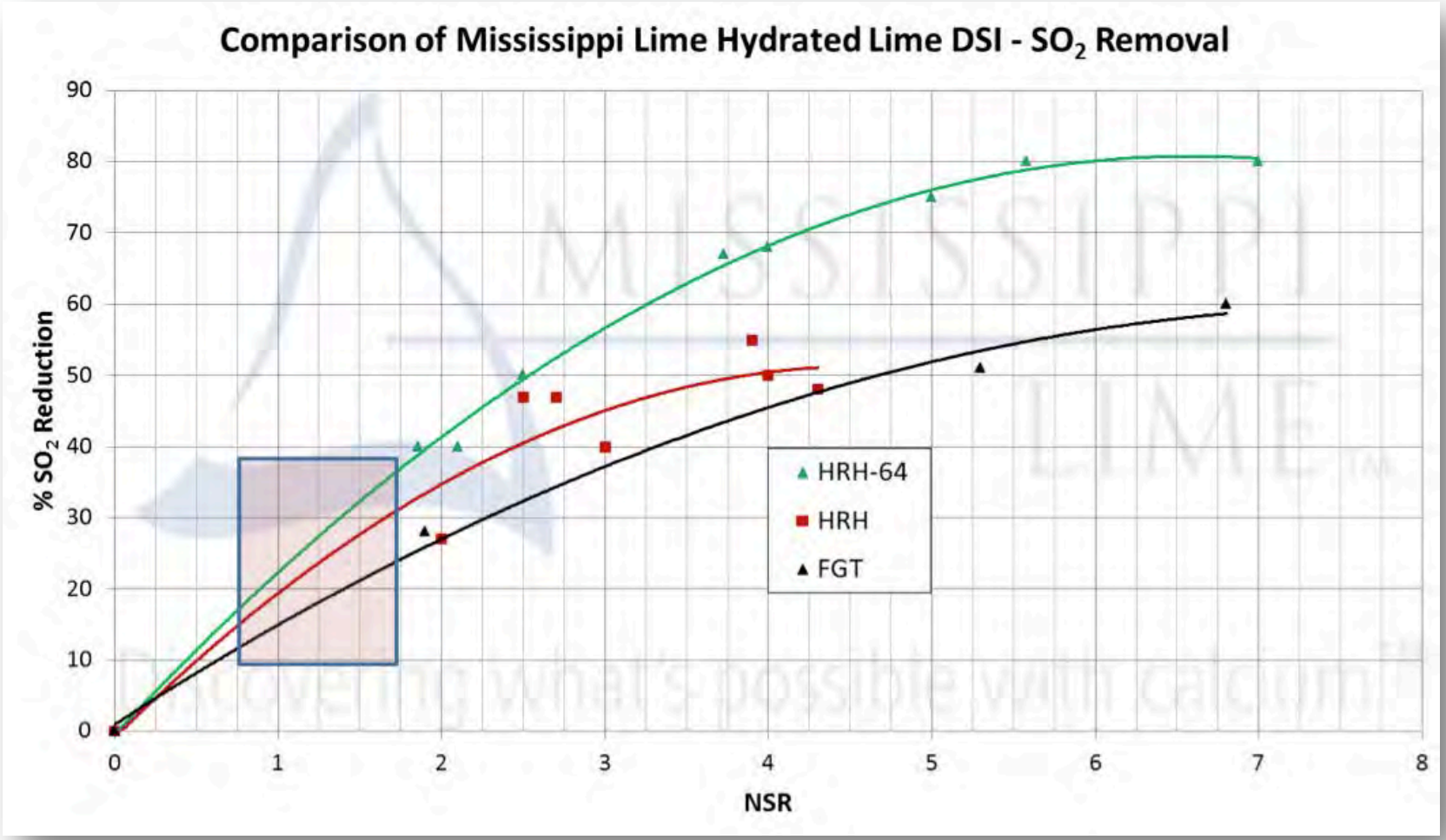


3,777 tons/yr. – SO_2

870,000 tons/yr. - Coal

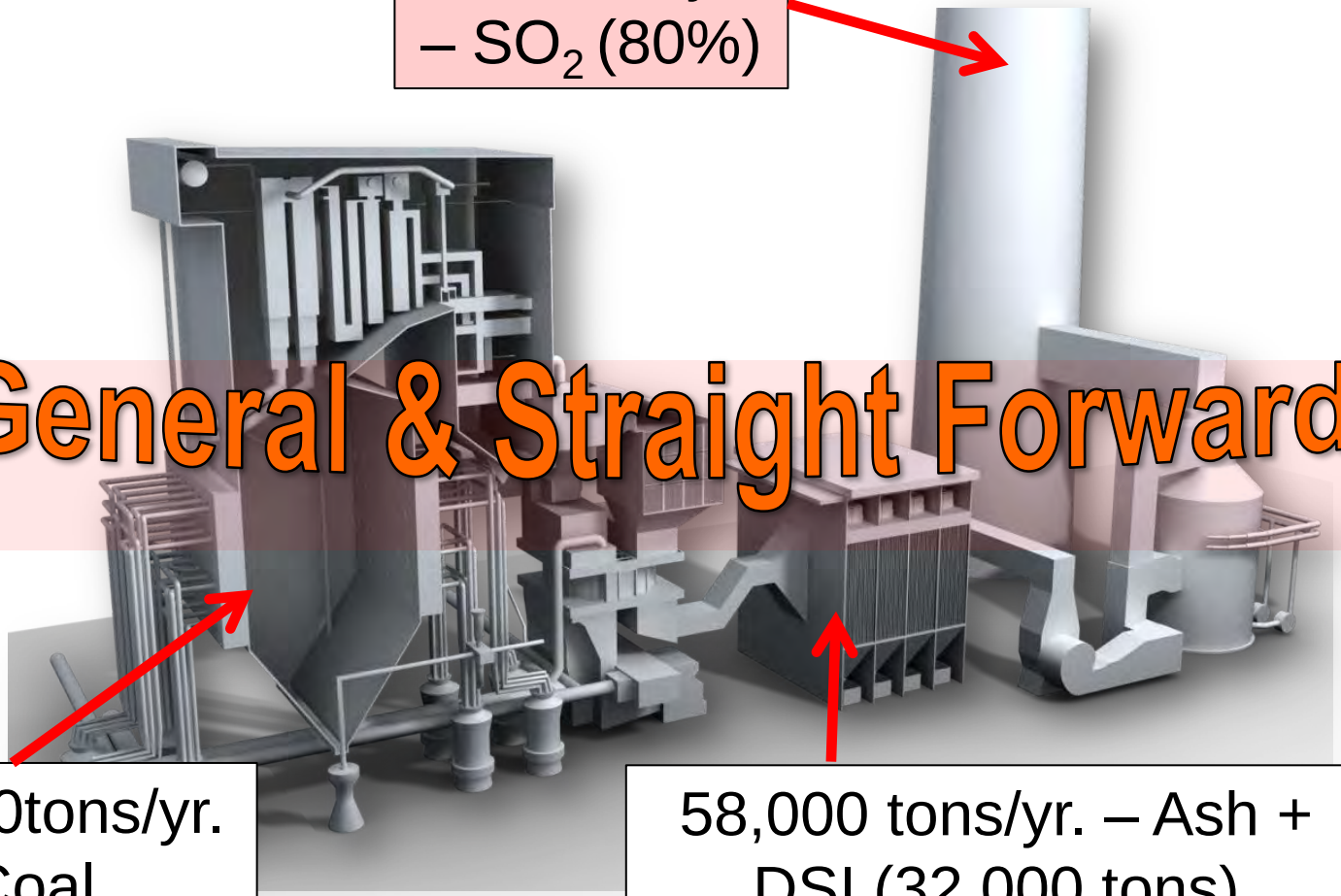
26,000 tons/yr. - Ash

Published SO_2 Capture with HRH-64



Traditional DSI FF Solution

754 tons/yr. – SO_2 (80%)



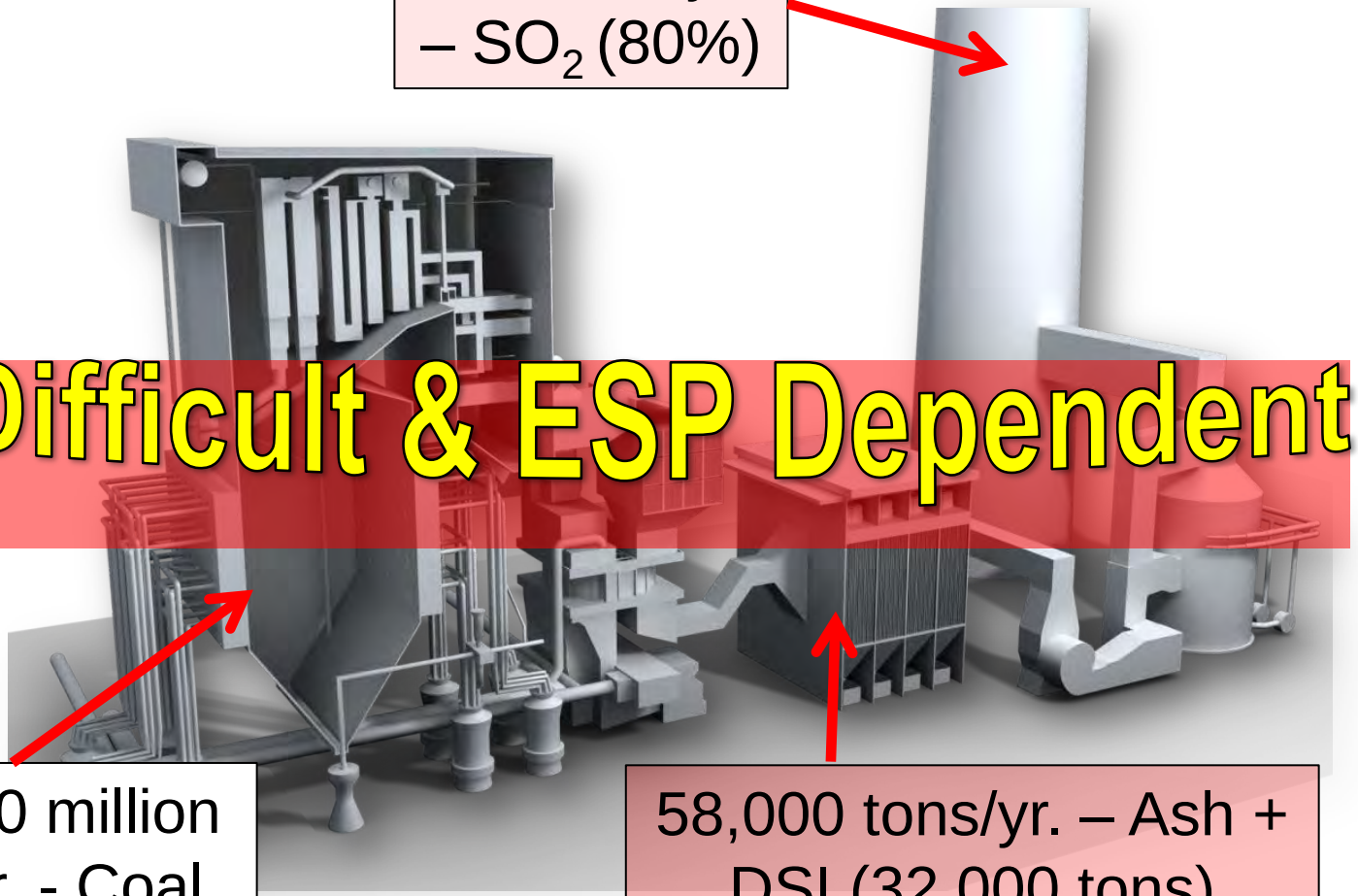
General & Straight Forward

870,000tons/yr. - Coal

58,000 tons/yr. – Ash + DSI (32,000 tons)

Traditional DSI ESP Solution

754 tons/yr. – SO_2 (80%)



Difficult & ESP Dependent

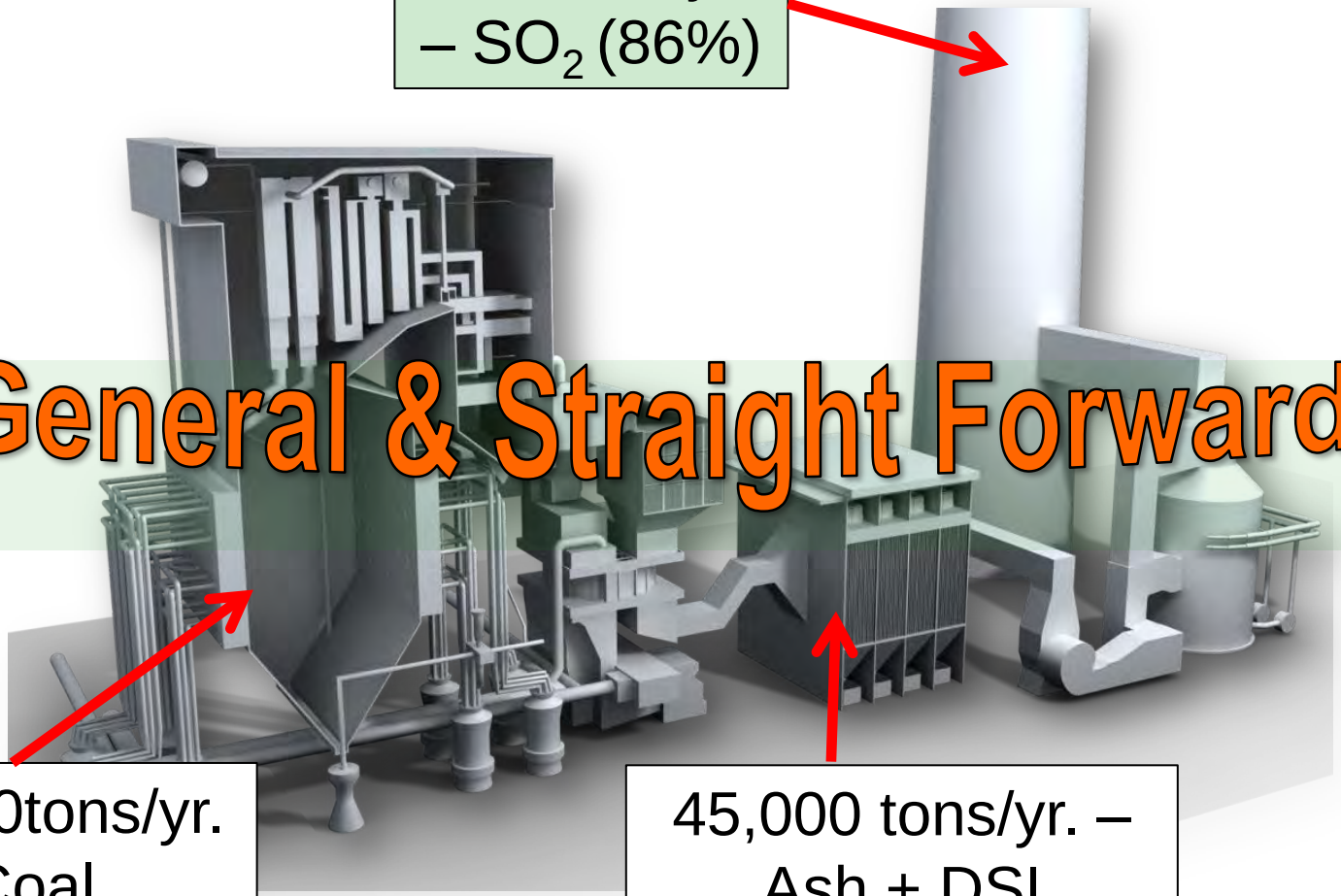
870,000 million tons/yr. - Coal

58,000 tons/yr. – Ash + DSI (32,000 tons)

Gas CoFire/DSI Solution

- **Add 30% Gas Cofire through the Igniter/Burner location**
- **Only operate Gas at loads above Minimum Range**

Gas CoFire/DSI FF Solution



Gas /DSI Solution/Non-Min Load Only

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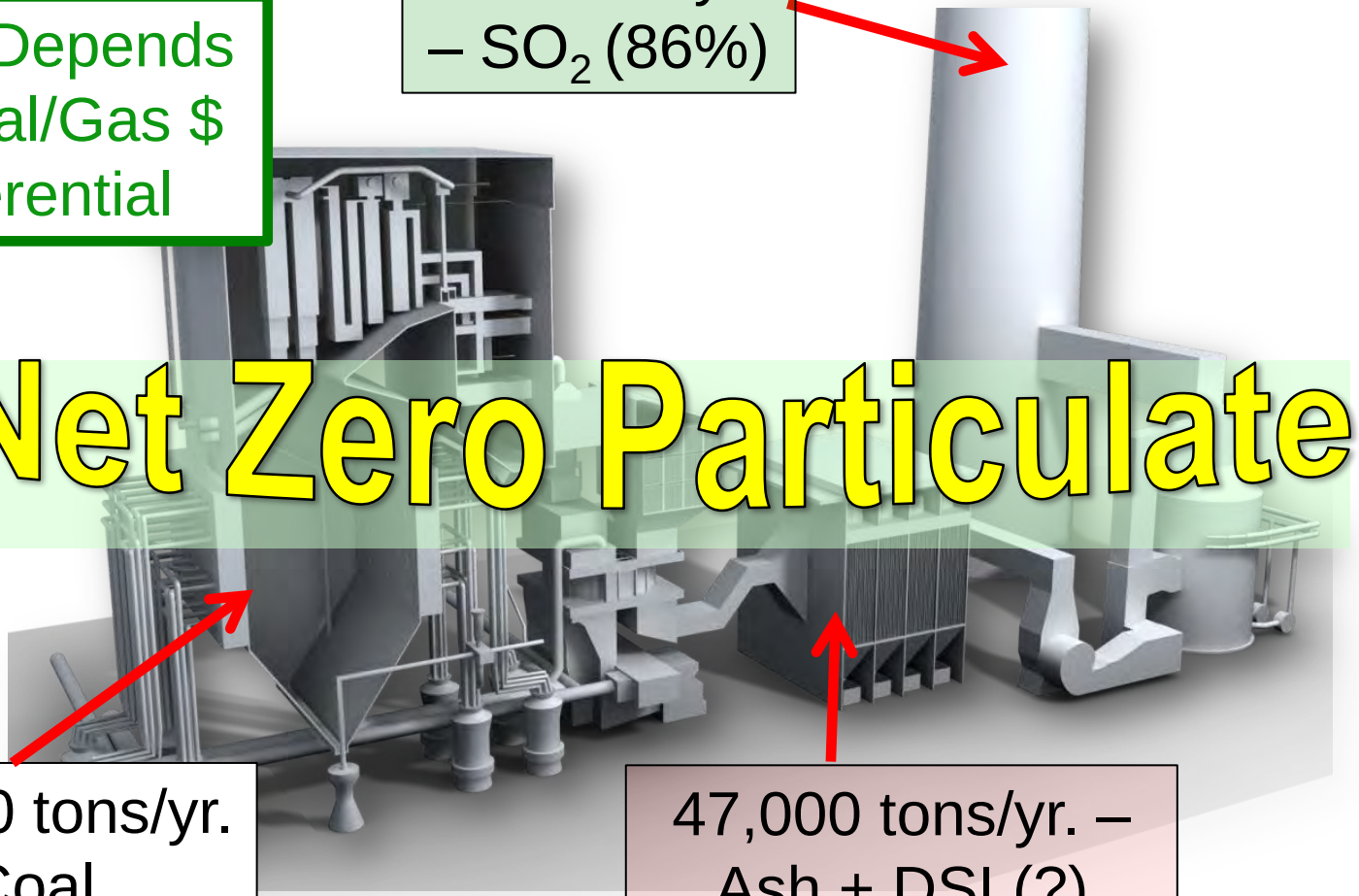
Value Depends on Coal/Gas $ Differential

529 tons/yr. – SO_2 (86%)



Net Zero Particulate

704,000 tons/yr. - Coal

47,000 tons/yr. – Ash + DSI (?)

CoBenefits/Gas+DSI (Non-Min Load)

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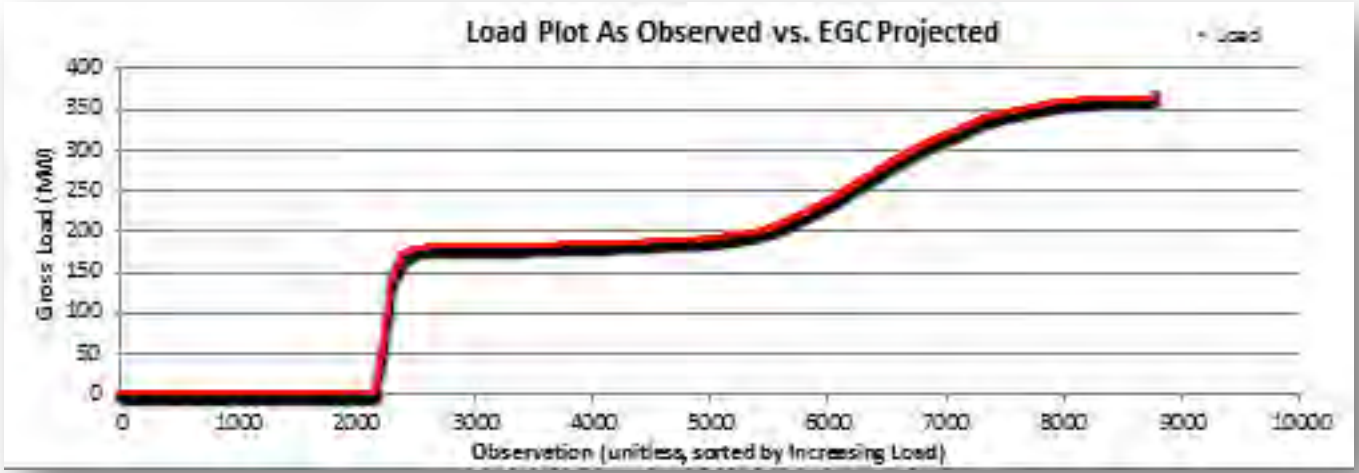
ENVIRONMENTAL BENEFITS

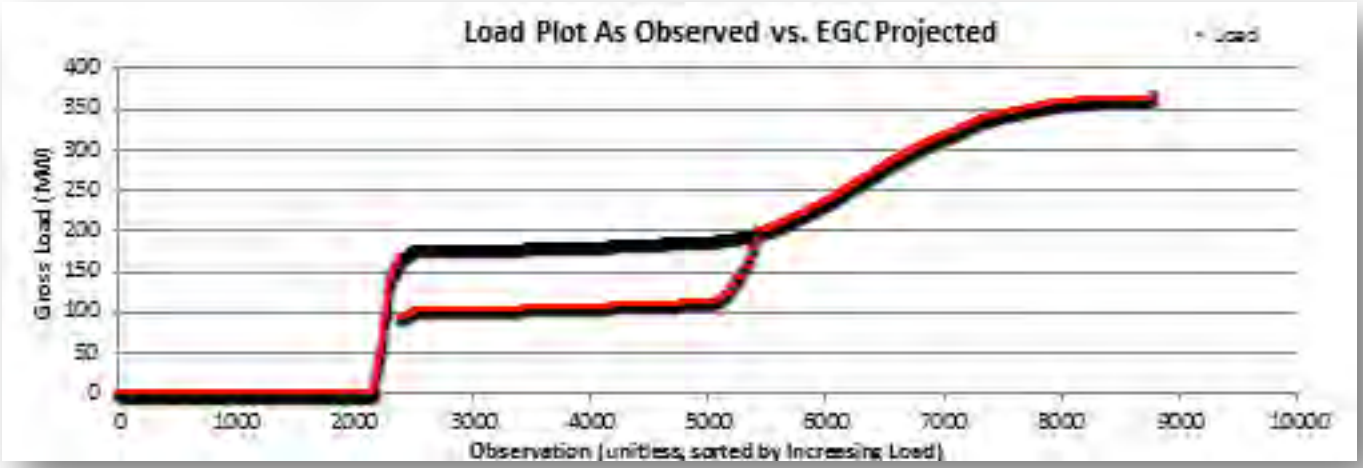
	Hisorical Total	EGC Total	Benefit	% Reduction
SO2-EGC	3,777	3,061	716	19.0%
SO2-DSI	3,061	682	2,380	77.7%
DSI Required (NSR/Tons)		5.78	20,465	
Outlet NOx	1,143	1,143	-	0.0%
SCR Inlet NOx	1,143	985	159	13.9%
Mercury				
Particulate	26,203	42,758.08	(16,555)	-63.2%
CO2	1,620,858	1,522,608	98,250	6.1%
Coal (mmBTU)	15,476,902	12,531,587	2,945,316	19.0%
Coal (tons)	870,023	704,454	165,569	19.0%

MEASUREABLE SAVINGS

Oil/Gas - Ignition/Stabilization Conversion		0	$/yr
Non-Min LoadCoal/Gas Cost Penalty		-3,877,575	$/yr
MSL Reduction	93	0	$/yr
Pulverizer Operating Cost		58,405	$/yr
SCR Operating Cost		0	$/yr
Fly Ash Disposal Avoidance		97,764	$/yr
FGD Operating Cost		0	$/yr
DSI-SO2		-5,116,350	$/yr
DSI-HCl		0	$/yr
DSI-SO3		0	$/yr
Coal Yard Parasitic Cost		3,826	$/yr
TOTAL CALCULATED SAVINGS		**-8,833,931**	**$/yr**

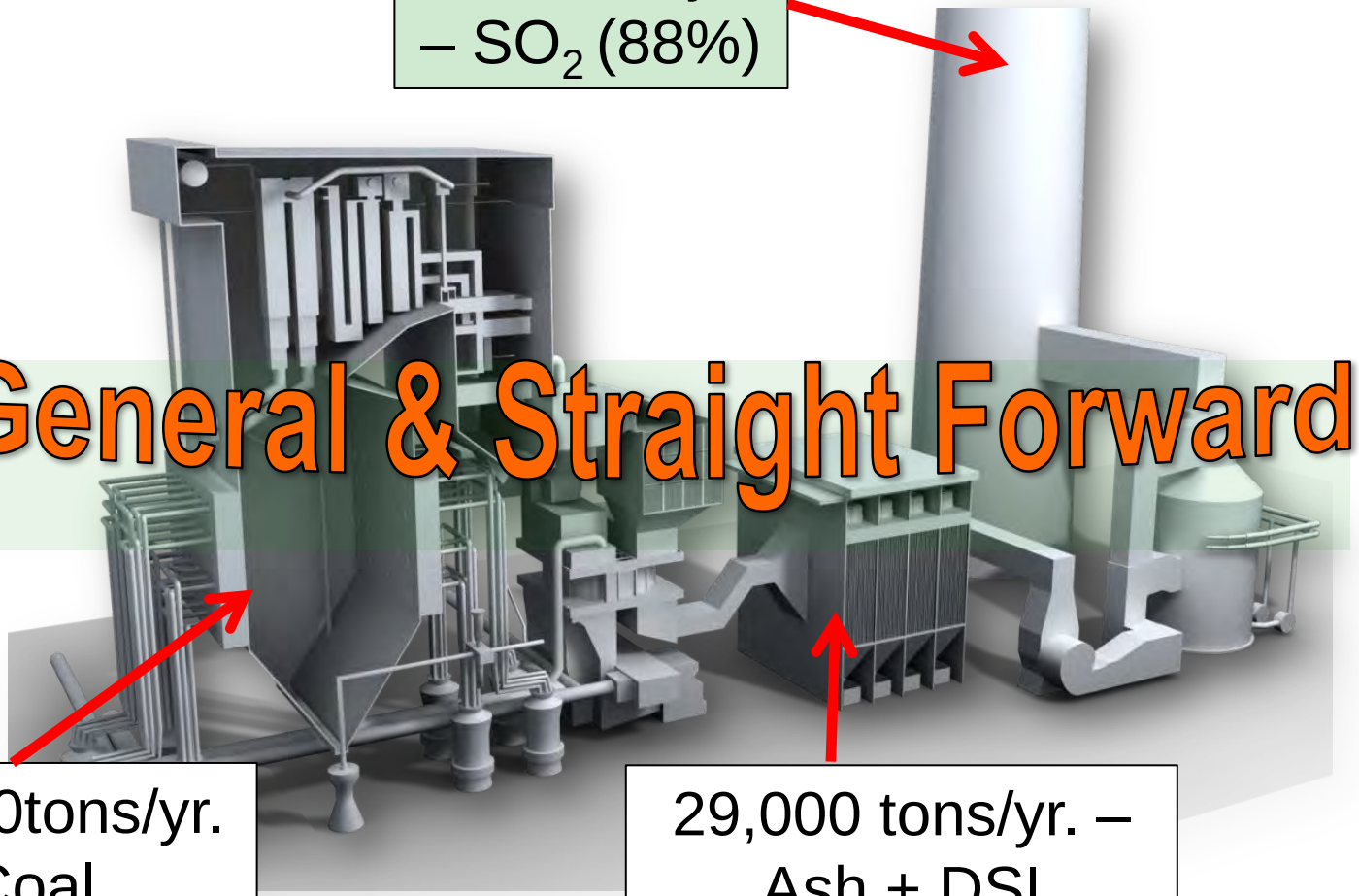
Full Range Gas/DSI Solution





Gas CoFire/DSI FF Solution

475 tons/yr.
– SO_2 (88%)



General & Straight Forward

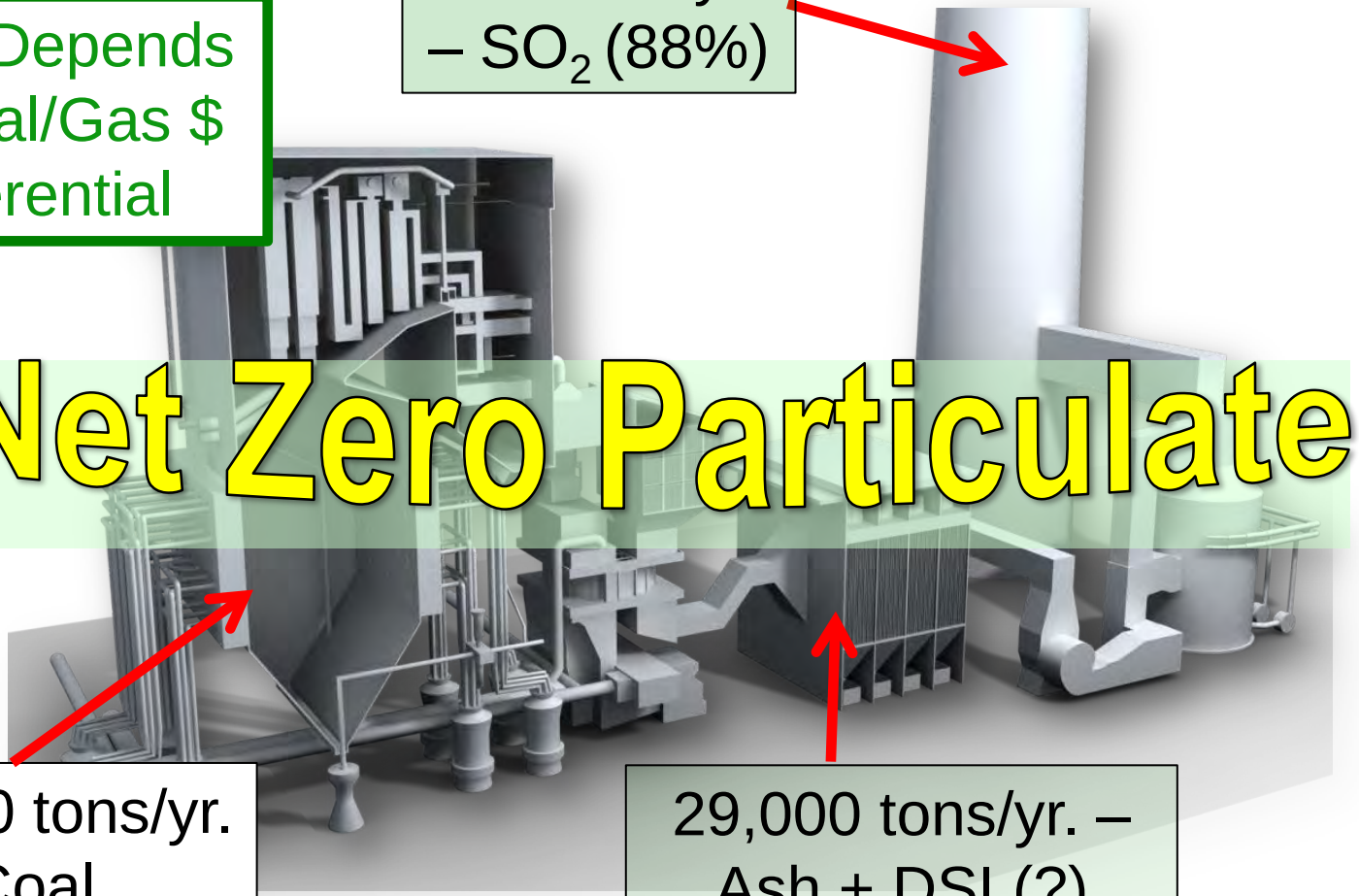
503,000tons/yr.
- Coal

29,000 tons/yr. –
Ash + DSI

Gas /DSI Solution/Non-Min Load Only

475 tons/yr. – SO_2 (88%)

Value Depends on Coal/Gas $ Differential



Net Zero Particulate

503,000 tons/yr. - Coal

29,000 tons/yr. – Ash + DSI (?)

CoBenefits for Free

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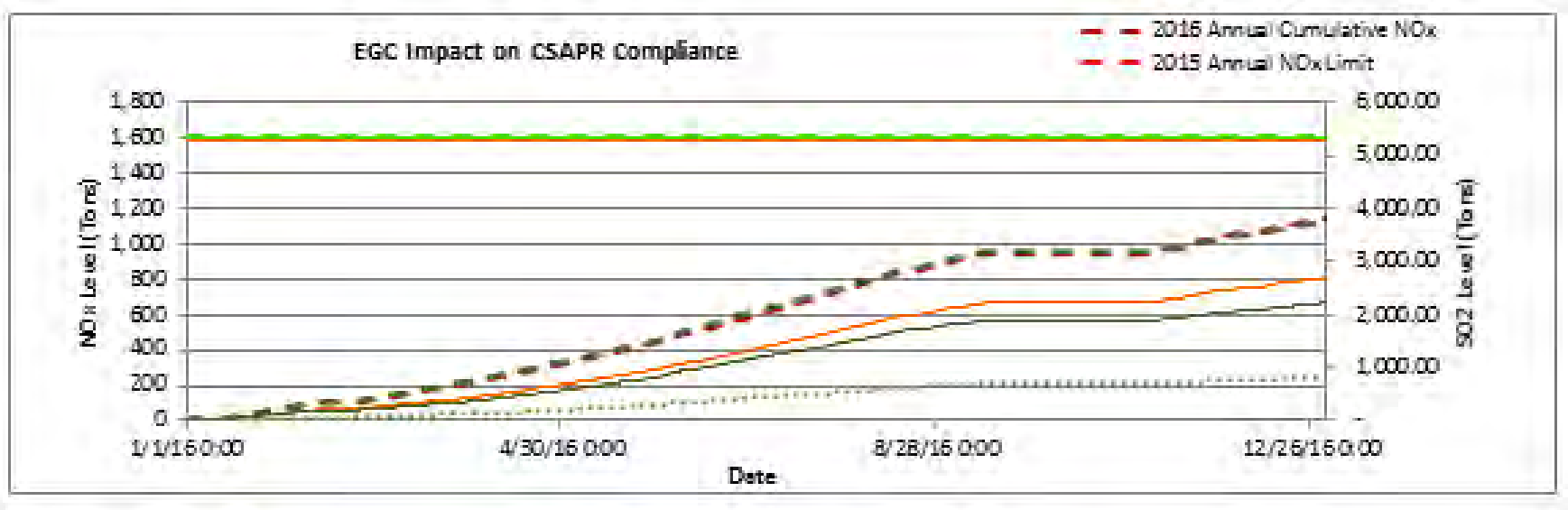
ENVIRONMENTAL BENEFITS

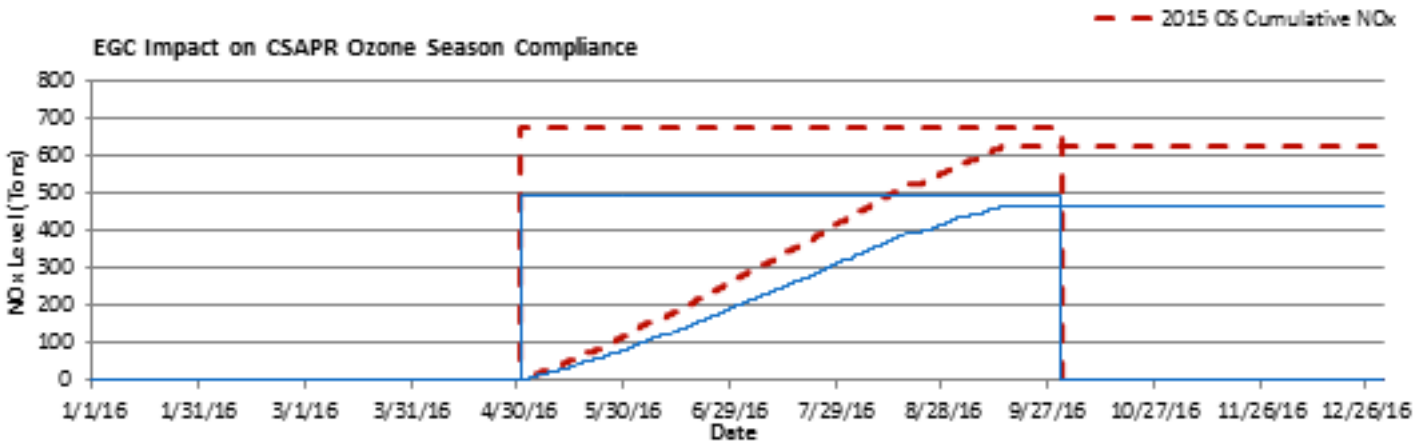
	Hisorical Total	EGC Total	Benefit	% Reduction
SO2-EGC	3,777	2,209	1,568	41.5%
SO2-DSI	2,209	835	1,374	62.2%
DSI Required (NSR/Tons)		3.95	10,071	
Outlet NOx	1,143	1,143	-	0.0%
SCR Inlet NOx	1,143	849	295	25.8%
Mercury				
Particulate	26,203	25,989.97	213	0.8%
CO2	1,620,858	1,221,841	399,017	24.6%
Coal (mmBTU)	15,476,902	8,954,727	6,522,175	42.1%
Coal (tons)	870,023	503,383	366,639	42.1%

MEASUREABLE SAVINGS

Oil/Gas - Ignition/Stabilization Conversion		0 $/yr
Non-Min LoadCoal/Gas Cost Penalty		-3,877,575 $/yr
MSL Reduction	93	8,863,670 $/yr
Pulverizer Operating Cost		129,641 $/yr
SCR Operating Cost		0 $/yr
Fly Ash Disposal Avoidance		257,098 $/yr
FGD Operating Cost		0 $/yr
DSI-SO2		-2,517,663 $/yr
DSI-HCl		0 $/yr
DSI-SO3		0 $/yr
Coal Yard Parasitic Cost		3,826 $/yr
TOTAL CALCULATED SAVINGS		**2,858,996 $/yr**

Move Gas to FLGR Above Min Load





Comparative Metrics

ENVIRONMENTAL BENEFITS

	Hisorical Total	EGC Total	Benefit	% Reduction
SO2-EGC	3,777	2,231	1,547	40.9%
SO2-DSI	2,231	825	1,406	63.0%
DSI Required (NSR/Tons)		4.02	10,359	
Outlet NOx	1,143	1,143	-	0.0%
SCR Inlet NOx	1,143	809	335	29.3%
Mercury				
Particulate	26,203	26,439.25	(236)	-0.9%
CO2	1,620,858	1,226,227	394,631	24.3%
Coal (mmBTU)	15,476,902	9,045,079	6,431,824	41.6%
Coal (tons)	870,023	508,462	361,560	41.6%

MEASUREABLE SAVINGS

Oil/Gas - Ignition/Stabilization Conversion		0	$/yr
Non-Min LoadCoal/Gas Cost Penalty		-3,852,107	$/yr
MSL Reduction	93	8,863,670	$/yr
Pulverizer Operating Cost		127,845	$/yr
SCR Operating Cost		0	$/yr
Fly Ash Disposal Avoidance		253,080	$/yr
FGD Operating Cost		0	$/yr
DSI-SO2		-2,589,803	$/yr
DSI-HCl		0	$/yr
DSI-SO3		0	$/yr
Coal Yard Parasitic Cost		3,801	$/yr
TOTAL CALCULATED SAVINGS		**2,806,486**	**$/yr**

Gas CoFiring Summary

- **Gas Cofiring provides a stable, reliable fuel flexibility option,**
- **Gas CoFiring provides multiple benefits through Minimum Load Reduction potential**
- **Gas CoFiring provides multiple environmental co-benefits at no additional cost**

- **Current DSI Technology can support future requirements for SO_2 Reduction on units equipped with Fabric Filters,**
- **Current DSI Technology with Gas CoFiring can support future requirements for SO_2 Reduction on units equipped with all types of Particulate Removal Eqpt.**

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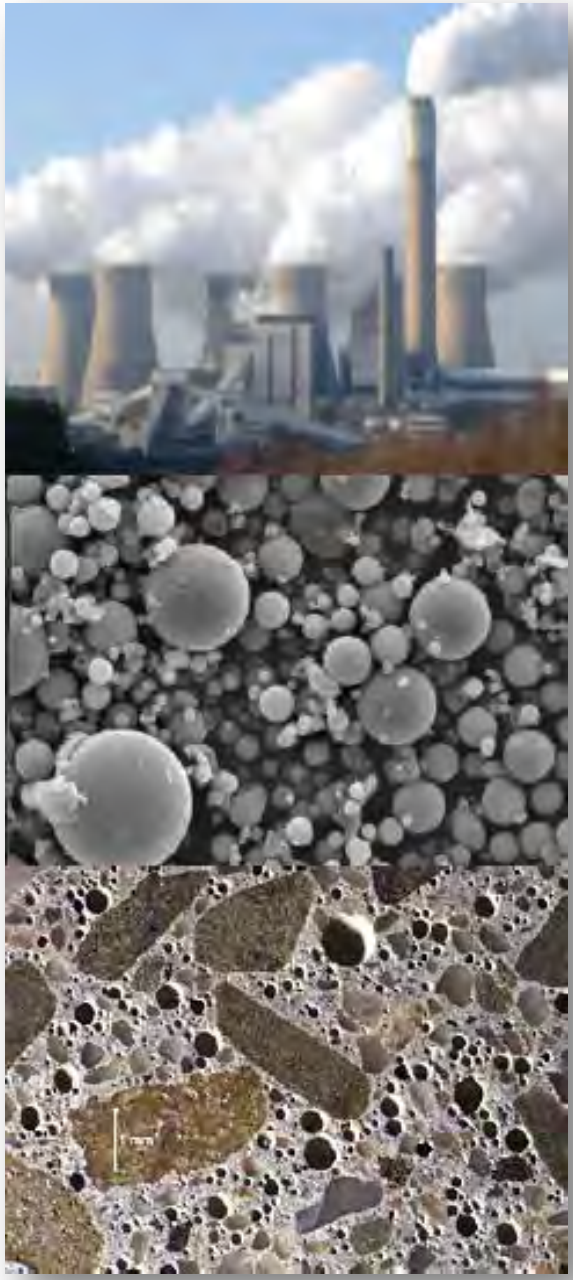
Enhanced Gas Cofiring Experience at Orlando Utilities

Thank you



Presented by: Cal Lockert & Tim McCreary

Date: February 27, 2017