Emission characterizations from a pilot-scale combustor operating on a variety of coals

Tiffany L.B. Yelverton, Angelina T. Brashear, David G. Nash, James E. Brown, Carl F. Singer, Peter H. Kariher, & Jeffrey V. Ryan

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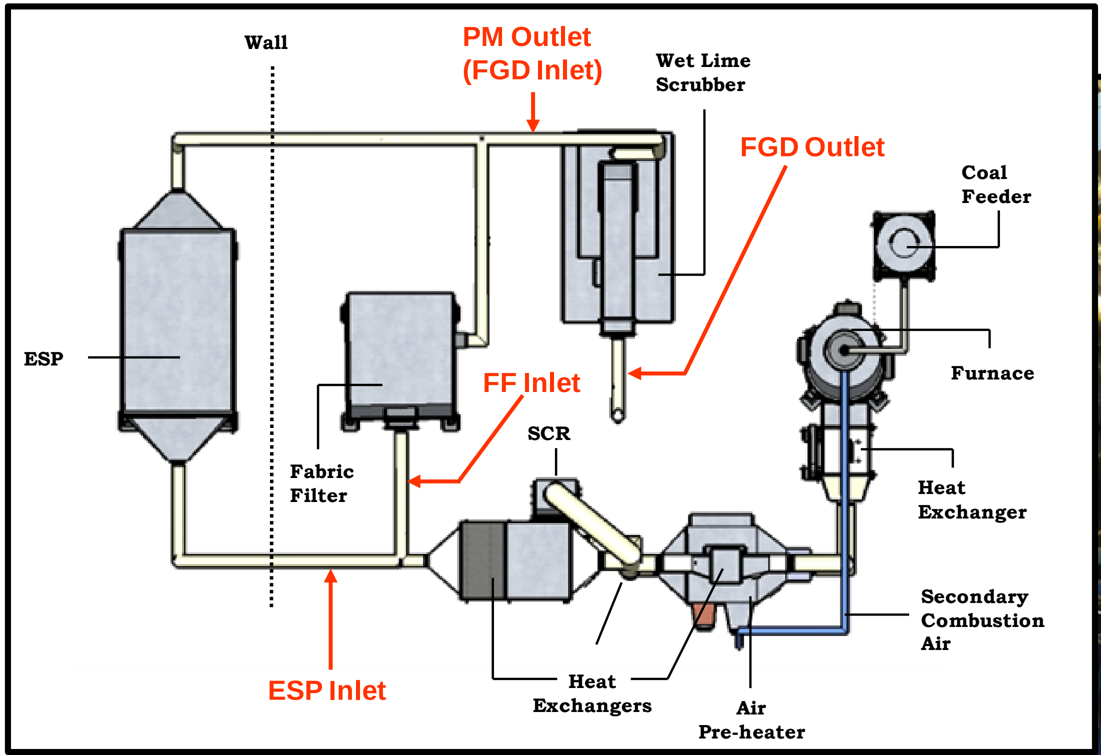
EPA

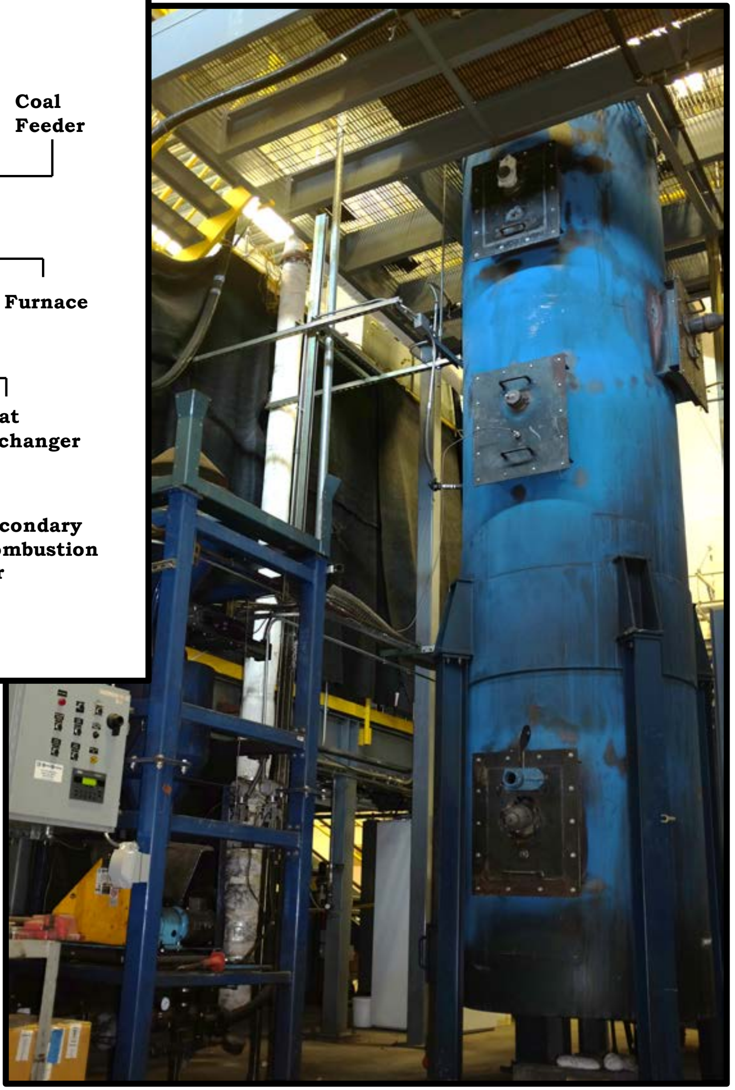
Why study coal emissions?

- Environmental and human health:
  - Many health studies have linked exposure to gaseous and particulate emissions from coal-fired combustion to negative health impacts
    - Among them carcinogenic and mutagenic compounds
  - This study focuses on four of the six EPA criteria pollutants as well as HAPs

- Platform for instrument/method comparison
  - This study compares traditional EPA Reference Methods to FTIR methods (using modified ASTM D6348) for stack emissions

Multipollutant Control Research Facility (MPCRF)





Detailed description of facility available in: T.L.B. Yelverton, D.G. Nash, J.E. Brown, C.F. Singer, J. Ryan, P. Kariher (2016) Dry sorbent injection of trona to control acid gases from a pilot-scale coal-fired combustion facility. *AIMS Environmental Science, 3(1): 45-57.*

- 4 MMBtu/hr capable pilot-scale facility
  - Typical operation for these tests at 2.4 MMBtu/hr (nominally 1.2 stoichiometric ratio)
  - Down-fired combustor
  - ~200 lbs/hour coal feed rate
  - Series of heat exchangers to simulate time-temperature profile of full-scale utility
- Pre- and post-combustion controls used:
  - Low-NO_X burner
  - ESP (FF available but not used for this series of testing)
  - Wet-lime scrubber

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Coal type and emissions

Three coals tested

- Pennsylvania bituminous
- Texas lignite
- Powder River Basin (PRB) sub-bituminous

Emissions sampled & reported

- Gaseous
  - CO, CO_2, NO_X, SO_2
  - CO, HCl, HF, NO, NO_2, SO_2, SO_3
- Particulate
  - $PM_{2.5}$ (mass, number concentration, PSD) , EC, OC, BC

	Moisture (%)	Volatiles (%)	Fixed Carbon (%)	Ash (%)	Sulfur (%)	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	HHV (Btu/#)
Bituminous	1.32	35.82	51.12	11.74	1.75	72.18	5.02	1.52	6.47	13173
Lignite	20.90	34.44	31.94	12.73	0.77	48.07	3.33	0.97	13.25	8184
Sub-bituminous	21.34	33.12	38.84	6.71	0.33	53.88	3.49	0.86	13.41	9160

Methods and instrumentation

Measurement of Interest	Current Method	Approximate Sampling Interval
PM		
mass	modified EPA Method 5	time-integrated
particle number	SMPS	2-minute scan
particle size distribution	SMPS	2-minute scan
OC	time-integrated filter analysis with NIOSH5040	~20 minute
EC	time-integrated filter analysis with NIOSH5040	~20 minute
BC	Aethalometer	1 minute
Gas Phase*		
Aldehydes	FTIR	~1 minute average
VOCs	FTIR	~1 minute average
CH_4	FTIR	~1 minute average
Hydrogen Halides and Halogens	FTIR and/or gas-filter correlation	~1 minute average
CEM Bench		
CO	EPA Method 10	continuous
CO_2	EPA Method 3A	continuous
O_2	EPA Method 3	continuous
NO_X	EPA Method 7E	continuous
SO_2	EPA Method 6C	continuous
TOC	EPA Method 25A	continuous

- Moved toward many online, real-time sampling techniques
  - Can better characterize combustion “events”
  - Comparison of instrumentation to traditional EPA Reference methods
- Successful testing that compares measurement techniques

Gaseous emissions

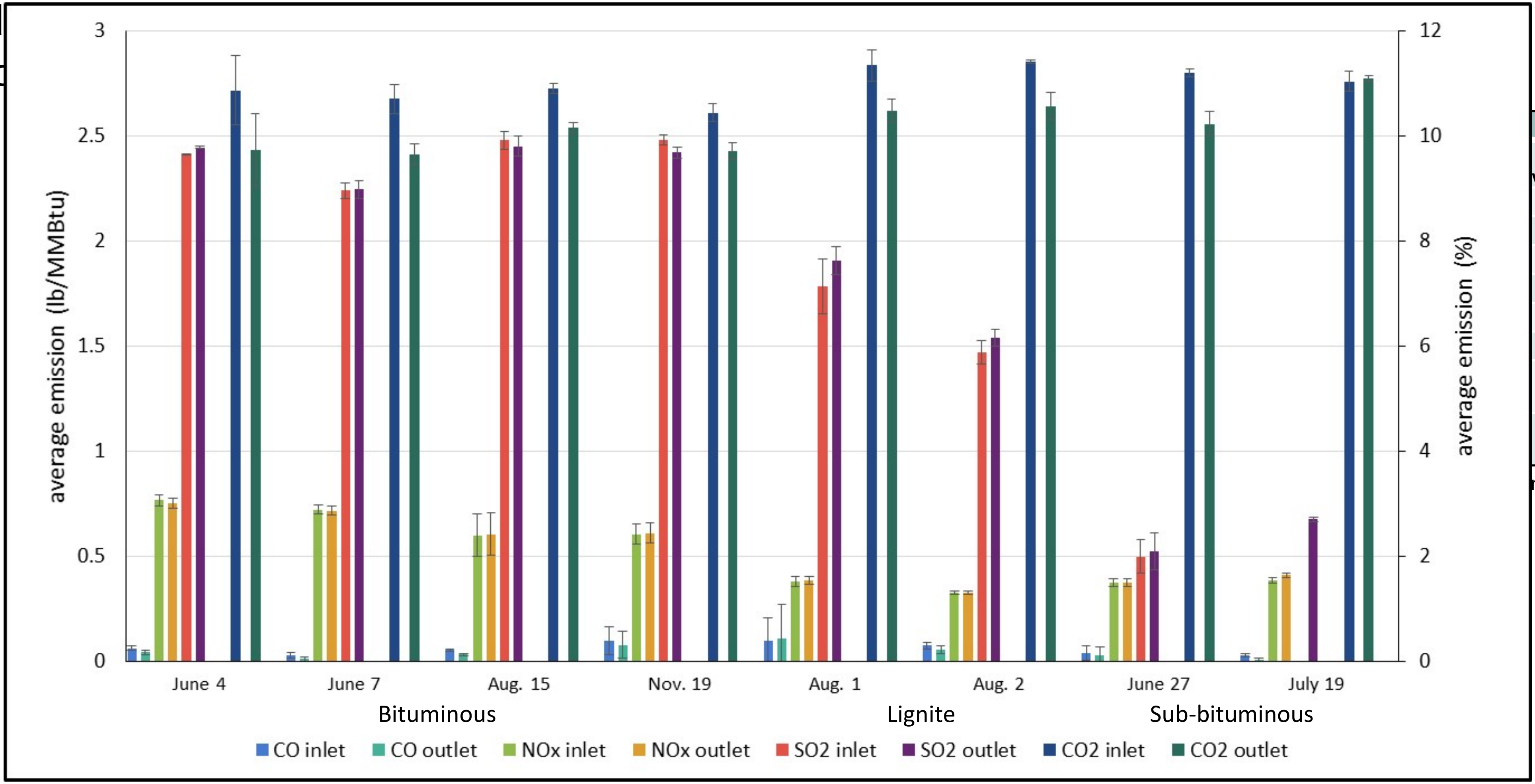
- EPA Reference Methods
  - 10 (CO), 7E (NO_X), 6C (SO_2)
- FTIR (modified ASTM Method D6348)
  - MKS model 2030 analyzed using "EGU" recipe

Test Date	Coal Type	CO inlet average (lb/MMBtu)	CO inlet Std Dev	CO outlet average (lb/MMBtu)	CO outlet Std Dev	NO_X inlet average (lb/MMBtu)	NO_X inlet Std Dev	NO_X outlet average (lb/MMBtu)	NO_X outlet Std Dev	SO_2 inlet average (lb/MMBtu)	SO_2 inlet Std Dev	SO_2 outlet average (lb/MMBtu)	SO_2 outlet Std Dev	CO_2 inlet average (%)	CO_2 inlet Std Dev	CO_2 outlet average (%)	CO_2 outlet Std Dev
June 4	Bituminous	0.063	0.011	0.044	0.011	0.766	0.027	0.755	0.024	2.413	0.003	2.444	0.005	10.867	0.654	9.726	0.686
June 7	Bituminous	0.031	0.013	0.012	0.010	0.722	0.020	0.717	0.021	2.239	0.039	2.244	0.040	10.707	0.275	9.654	0.194
Aug. 15	Bituminous	0.054	0.005	0.033	0.005	0.601	0.100	0.605	0.102	2.478	0.044	2.451	0.048	10.892	0.096	10.163	0.094
Nov. 19	Bituminous	0.097	0.066	0.080	0.065	0.605	0.048	0.611	0.048	2.481	0.022	2.421	0.026	10.443	0.171	9.712	0.161
Aug. 1	Lignite	0.100	0.106	0.108	0.161	0.381	0.023	0.387	0.019	1.784	0.128	1.906	0.068	11.340	0.304	10.475	0.230
Aug. 2	Lignite	0.075	0.018	0.057	0.018	0.327	0.009	0.327	0.009	1.471	0.057	1.538	0.039	11.404	0.032	10.564	0.255
June 27	Sub-bituminous	0.041	0.035	0.027	0.044	0.375	0.018	0.377	0.018	0.500	0.081	0.524	0.090	11.200	0.067	10.226	0.235
July 19	Sub-bituminous	0.030	0.008	0.008	0.008	0.388	0.013	0.410	0.009	N/A	N/A	0.677	0.011	11.035	0.192	11.085	0.053

Yelverton et al., 2017 (under review, *Fuel*)

Gaseous emissions

- EPA Reference Methods
  - 10 (CO), 7E (NO_X), 6C (SO_2)
- FTIR (mod
  - MKS mod



CO_2 outlet	
verage (%)	Std Dev
9.726	0.686
9.654	0.194
10.163	0.094
9.712	0.161
10.475	0.230
10.564	0.255
10.226	0.235
11.085	0.053

nder review, ***Fuel***)

Gaseous emissions

- EPA Reference Methods
  - 10 (CO), 7E (NO_X), 6C (SO_2)
- FTIR (modified ASTM Method D6348)
  - MKS model 2030 analyzed using "EGU" recipe

EGU Recipe		
Compound	**Chemical Formula**	**CAS No.**
acetaldehyde	CH_3CHO	75-07-0
acetylene	C_2H_2	74-86-2
ammonia	NH_3	7664-41-7
benzaldehyde	C_6H_5CHO	100-52-7
benzene	C_6H_6	71-43-2
ethane	C_2H_6	74-84-0
ethylene	C_2H_4	74-85-1
formaldehyde	CH_2O	50-00-0
hydrochloric acid	HCl	7647-01-0
hydrogen bromide	HBr	10035-10-6
hydrogen cyanide	HCN	74-90-8
hydrogen fluoride	HF	7664-39-3
methane	CH_4	74-82-8
methanol	CH_3OH	67-56-1
nitric acid	HNO_3	7697-37-2
nitric oxide	NO	10102-43-9
nitrogen dioxide	NO_2	10102-44-0
nitrous oxide	N_2O	10024-97-2
propane	C_3H_8	74-98-6
propylene	C_3H_6	115-07-1
sulfur dioxide	SO_2	7446-09-5
sulfur trioxide	SO_3	7664-41-9
sulfuric acid	H_2SO_4	7664-93-9
water	H_2O	7732-18-5

Test Date	Coal Type	CO inlet average (lb/MMBtu)	CO inlet Std Dev	CO outlet average (lb/MMBtu)	CO outlet Std Dev	NO… averag… (lb/MME…	…₂ inlet …(%)	…₂ inlet Std Dev	CO_2 outlet average (%)	CO_2 outlet Std Dev
June 4	Bituminous	0.063	0.011	0.044	0.011	0.766	7	0.654	9.726	0.686
June 7	Bituminous	0.031	0.013	0.012	0.010	0.722	7	0.275	9.654	0.194
Aug. 15	Bituminous	0.054	0.005	0.033	0.005	0.601	2	0.096	10.163	0.094
Nov. 19	Bituminous	0.097	0.066	0.080	0.065	0.605	3	0.171	9.712	0.161
Aug. 1	Lignite	0.100	0.106	0.108	0.161	0.381	0	0.304	10.475	0.230
Aug. 2	Lignite	0.075	0.018	0.057	0.018	0.327	4	0.032	10.564	0.255
June 27	Sub-bituminous	0.041	0.035	0.027	0.044	0.375	0	0.067	10.226	0.235
July 19	Sub-bituminous	0.030	0.008	0.008	0.008	0.388	5	0.192	11.085	0.053

… et al., 2017 (under review, *Fuel*)

Gaseous emissions

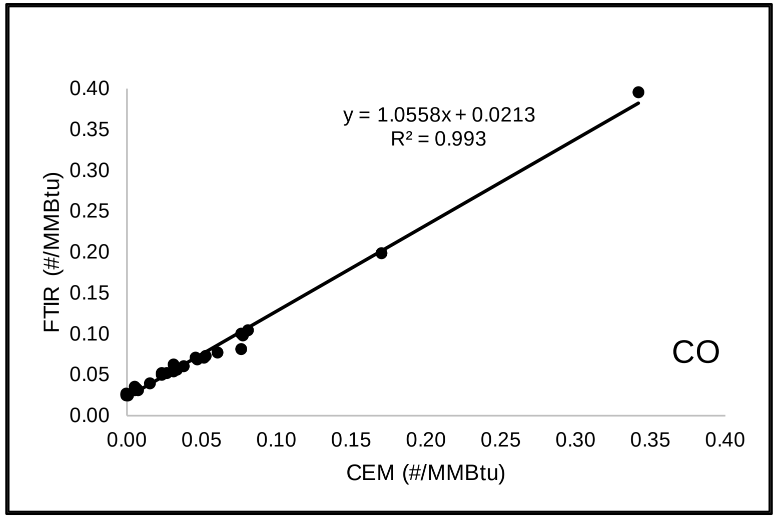
- EPA Reference Methods
  - 10 (CO), 7E (NO_X), 6C (SO_2)
- FTIR (modified ASTM Method D6348)
  - MKS model 2030 analyzed using “EGU” recipe

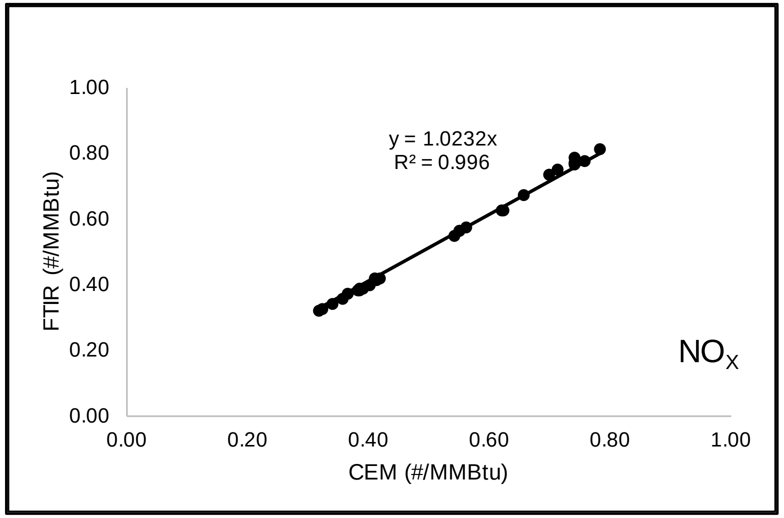
Test Date	Coal Type	CO inlet		CO outlet		NO_x inlet		NO_x outlet		SO_2 inlet		SO_2 outlet		CO_2 inlet		CO_2 outlet	
		average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (%)	Std Dev	average (%)	Std Dev
June 4	Bituminous	0.063	0.011	0.044	0.011	0.766	0.027	0.755	0.024	2.413	0.003	2.444	0.005	10.867	0.654	9.726	0.686
June 7	Bituminous	0.031	0.013	0.012	0.010	0.722	0.020	0.717	0.021	2.239	0.039	2.244	0.040	10.707	0.275	9.654	0.194
Aug. 15	Bituminous	0.054	0.005	0.033	0.005	0.601	0.100	0.605	0.102	2.478	0.044	2.451	0.048	10.892	0.096	10.163	0.094
Nov. 19	Bituminous	0.097	0.066	0.080	0.065	0.605	0.048	0.611	0.048	2.481	0.022	2.421	0.026	10.443	0.171	9.712	0.161
Aug. 1	Lignite	0.100	0.106	0.108	0.161	0.381	0.023	0.387	0.019	1.784	0.128	1.906	0.068	11.340	0.304	10.475	0.230
Aug. 2	Lignite	0.075	0.018	0.057	0.018	0.327	0.009	0.327	0.009	1.471	0.057	1.538	0.039	11.404	0.032	10.564	0.255
June 27	Sub-bituminous	0.041	0.035	0.027	0.044	0.375	0.018	0.377	0.018	0.500	0.081	0.524	0.090	11.200	0.067	10.226	0.235
July 19	Sub-bituminous	0.030	0.008	0.008	0.008	0.388	0.013	0.410	0.009	N/A	N/A	0.677	0.011	11.035	0.192	11.085	0.053

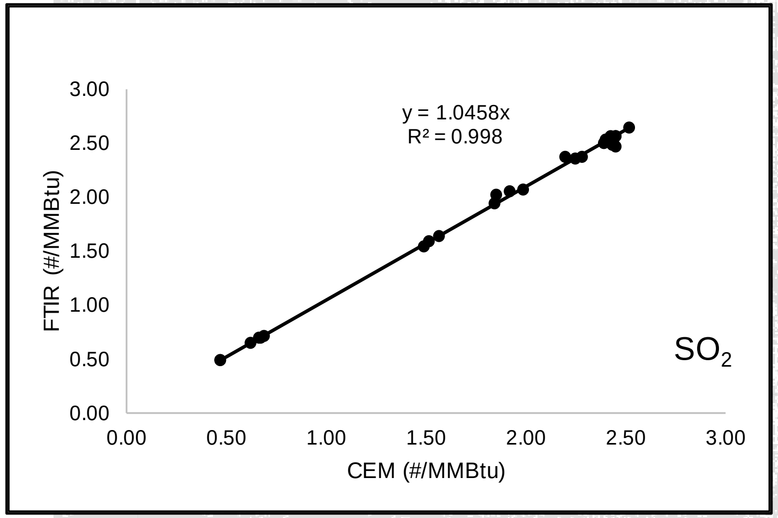
Test Date	Coal Type	CO		HCl		HF		NO		NO_2		SO_2		SO_3	
		average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev
June 4	Bituminous	0.066	0.011	0.042	0.001	0.001	0.000	0.771	0.025	0.010	0.000	2.482	0.010	<MDC	<MDC
June 7	Bituminous	0.038	0.013	0.044	0.001	0.001	0.000	0.745	0.028	0.012	0.001	2.378	0.009	<MDC	<MDC
Aug. 15	Bituminous	0.058	0.005	0.047	0.001	0.002	0.000	0.614	0.105	0.004	0.001	2.577	0.047	<MDC	<MDC
Nov. 19	Bituminous	0.105	0.066	0.049	0.001	0.001	0.000	0.611	0.050	0.006	0.001	2.527	0.026	<MDC	<MDC
Aug. 1	Lignite	0.139	0.174	0.004	0.000	<MDC	<MDC	0.382	0.020	0.008	0.002	2.028	0.055	<MDC	<MDC
Aug. 2	Lignite	0.081	0.014	0.004	0.000	<MDC	<MDC	0.314	0.010	0.013	0.000	1.594	0.043	<MDC	<MDC
June 27	Sub-bituminous	0.044	0.033	0.007	0.001	0.001	0.000	0.363	0.020	0.012	0.002	0.552	0.089	0.007	0.001
July 19	Sub-bituminous	0.033	0.006	0.010	0.000	0.001	0.000	0.399	0.008	0.010	0.001	0.708	0.009	0.007	0.000

Yelverton et al., 2017 (under review, *Fuel*)

Methods comparison







Yelverton et al., 2017 (under review, *Fuel*)

Particulate emissions

Test Date	Coal Type	Fine PM inlet		Fine PM outlet		Fine PM Removal	Total Number Concentration PM inlet		Total Number Concentration PM outlet	
		average (lb/ton)	Std Dev	average (lb/ton)	Std Dev	average (%)	average (#/cm³)	Std Dev	average (#/cm³)	Std Dev
June 4	Bituminous	1.989	1.489	0.139	0.174	93	38831519	2519616	1037288	44307
June 7	Bituminous	1.748	1.319	0.100	0.049	94	42652679	1541716	1818085	623885
Aug. 15	Bituminous	1.033	0.122	0.040	0.029	96	35196140	814217	953045	46848
Nov. 19	Bituminous	1.479	0.611	0.133	0.195	91	26648855	2765526	229272	27293
Aug. 1	Lignite	0.853	0.116	0.039	0.034	95	33060268	499638	79933	117899
Aug. 2	Lignite	0.342	0.041	0.042	0.019	88	30198701	1410992	530052	288769
June 27	Sub-bituminous	0.630	0.124	0.150	0.127	76	30878108	875990	60006	4742
July 19	Sub-bituminous	0.629	0.103	0.148	0.036	77	32351476	188169	53651	5328

Yelverton et al., 2017 (under review, *Fuel*)

Particulate emissions

Test Date	Coal Type	Fine PM inlet		Fine PM outlet		Fine PM Removal	Tota Conce
		average (lb/ton)	Std Dev	average (lb/ton)	Std Dev	average (%)	averag (#/cm³
June 4	Bituminous	1.989	1.489	0.139	0.174	93	3883151
June 7	Bituminous	1.748	1.319	0.100	0.049	94	4265267
Aug. 15	Bituminous	1.033	0.122	0.040	0.029	96	3519614
Nov. 19	Bituminous	1.479	0.611	0.133	0.195	91	2664885
Aug. 1	Lignite	0.853	0.116	0.039	0.034	95	3306026
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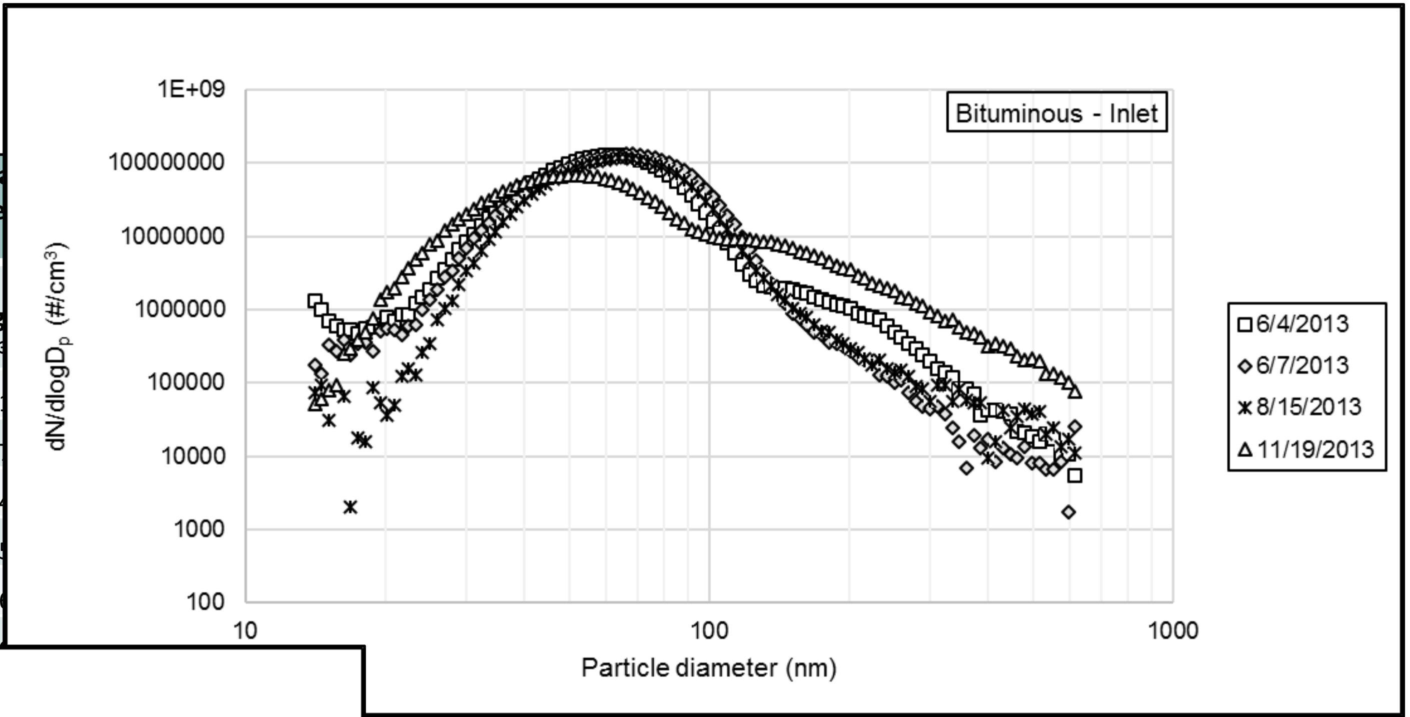

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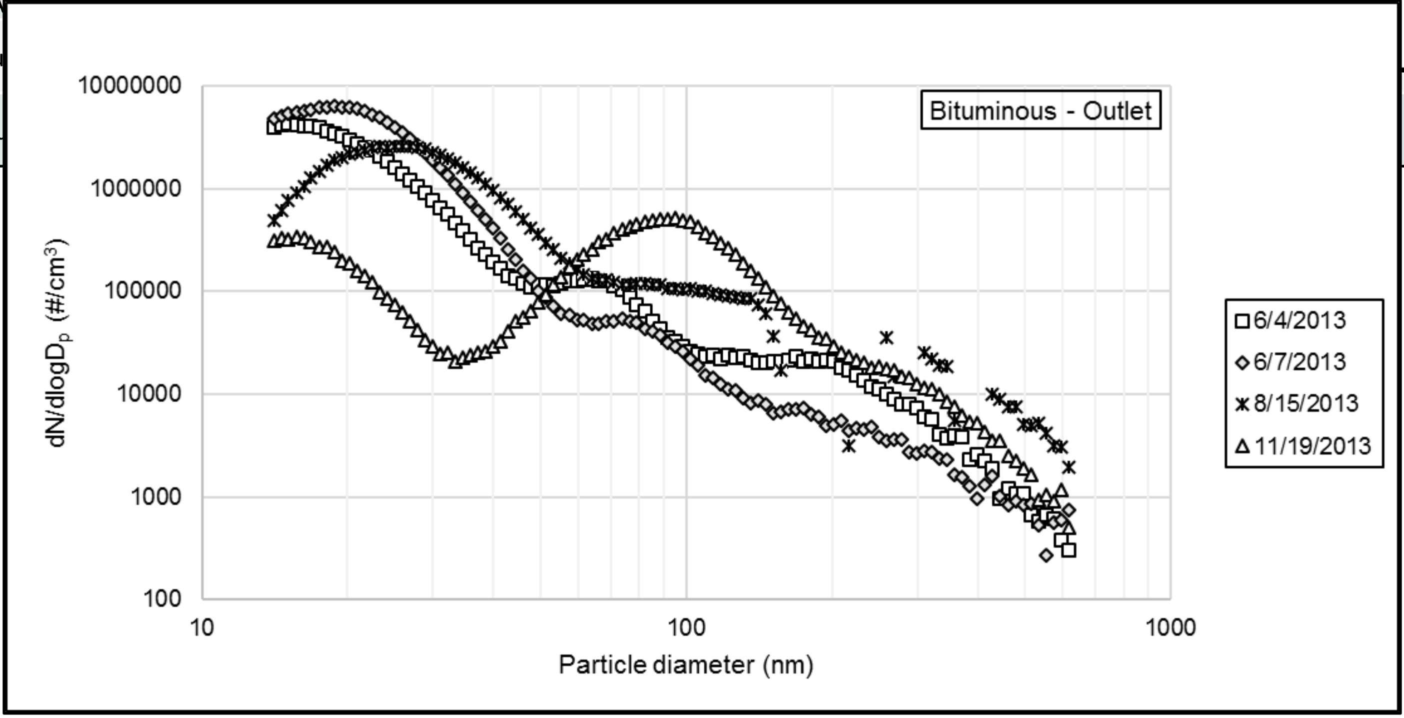
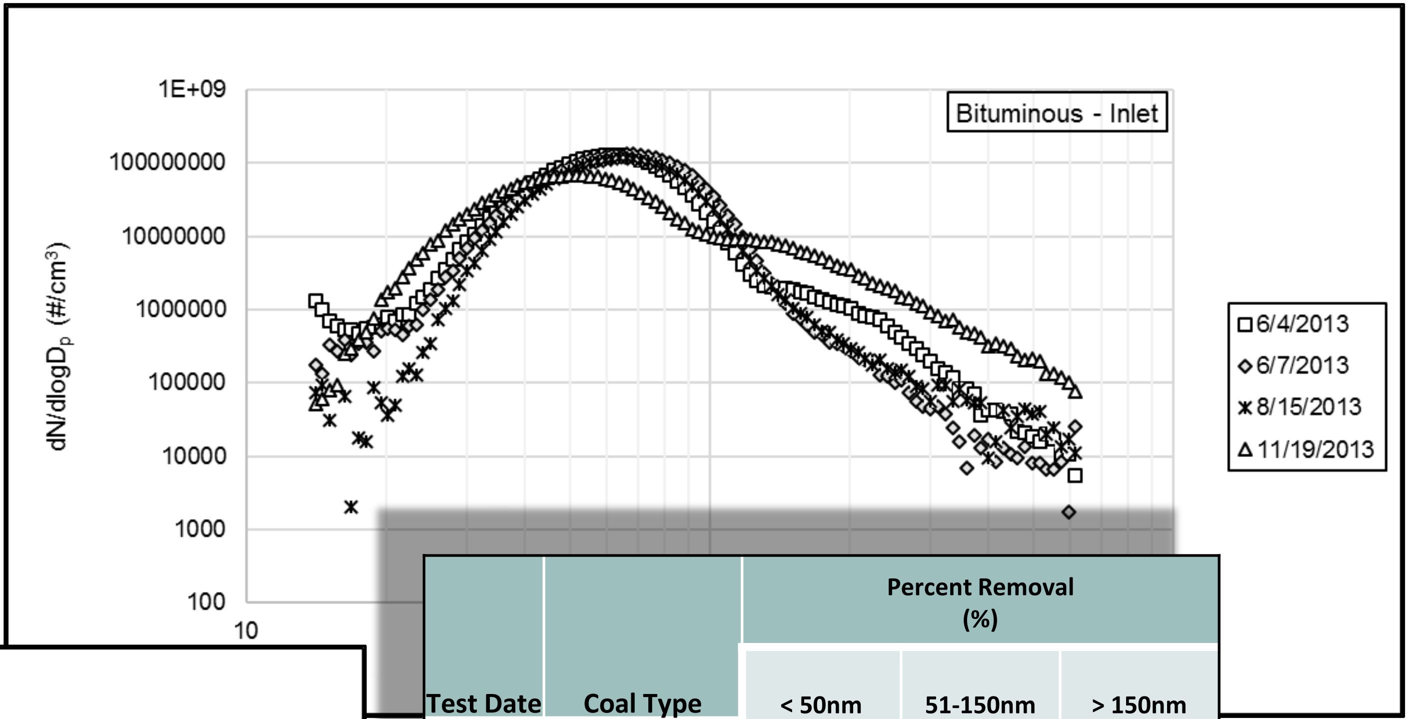


Particulate emissions



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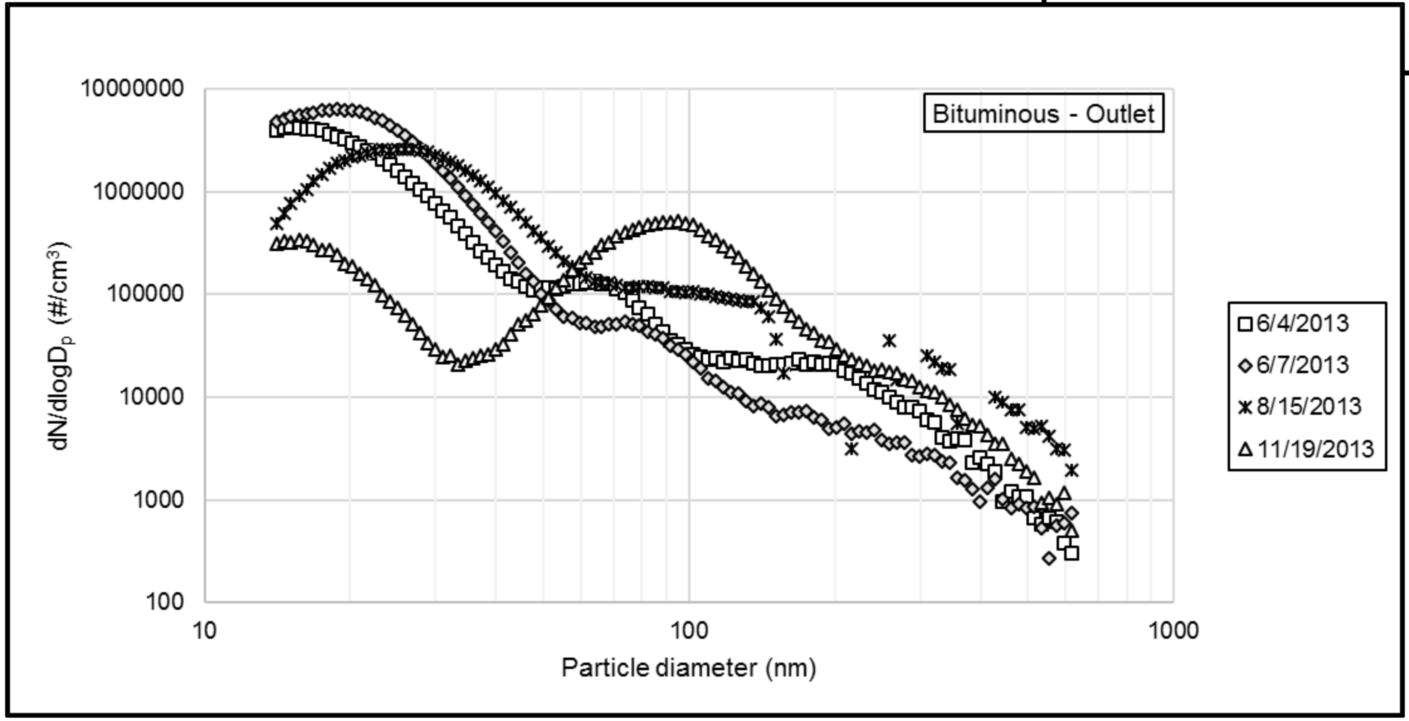


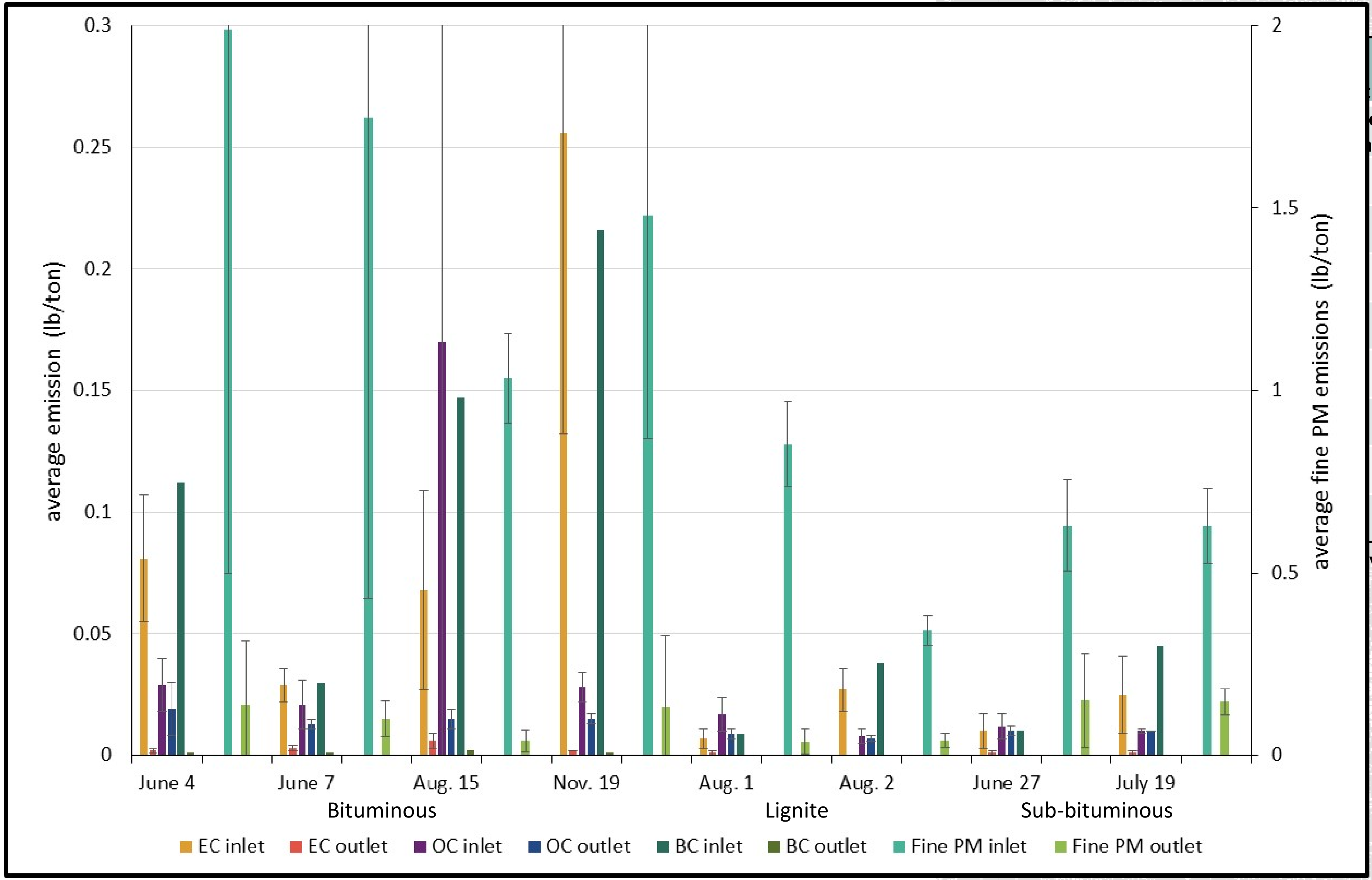
Test Date	Coal Type	Percent Removal (%)		
		< 50nm	51-150nm	> 150nm
June 4	Bituminous	91	100	98
June 7	Bituminous	81	100	98
Aug. 15	Bituminous	88	100	97
Nov. 19	Bituminous	99	99	99
Aug. 1	Lignite	100	100	59
Aug. 2	Lignite	100	100	N/A
June 27	Sub-bituminous	100	100	98
July 19	Sub-bituminous	100	100	99

Particulate emissions (cont'd)

Test Date	Coal Type	EC inlet		EC outlet		EC Removal	OC inlet		OC outlet		OC Removal	BC inlet	BC outlet	BC Removal
		average (lb/ton)	Std Dev	average (lb/ton)	Std Dev	average (%)	average (lb/ton)	Std Dev	average (lb/ton)	Std Dev	average (%)	average (lb/ton)	average (lb/ton)	average (%)
June 4	Bituminous	0.081	0.026	0.002	0.001	97	0.029	0.011	0.019	0.011	35	0.112	0.001	99
June 7	Bituminous	0.029	0.007	0.003	0.001	91	0.021	0.010	0.013	0.002	40	0.030	0.001	98
Aug. 15	Bituminous	0.068	0.041	0.006	0.003	92	0.170	0.267	0.015	0.004	91	0.147	0.002	99
Nov. 19	Bituminous	0.256	0.124	0.002	0.000	99	0.028	0.006	0.015	0.002	47	0.216	0.001	99
Aug. 1	Lignite	0.007	0.004	0.001	0.001	89	0.017	0.007	0.009	0.002	44	0.009	0.000	95
Aug. 2	Lignite	0.027	0.009	0.000	0.000	99	0.008	0.003	0.007	0.001	9	0.038	0.000	99
June 27	Sub-bituminous	0.010	0.007	0.001	0.001	91	0.012	0.005	0.010	0.002	19	0.010	0.000	96
July 19	Sub-bituminous	0.025	0.016	0.001	0.001	94	0.010	0.001	0.010	0.000	2	0.045	0.000	>99

Yelverton et al., 2017 (under review, *Fuel*)

Particulate emissions (cont'd)

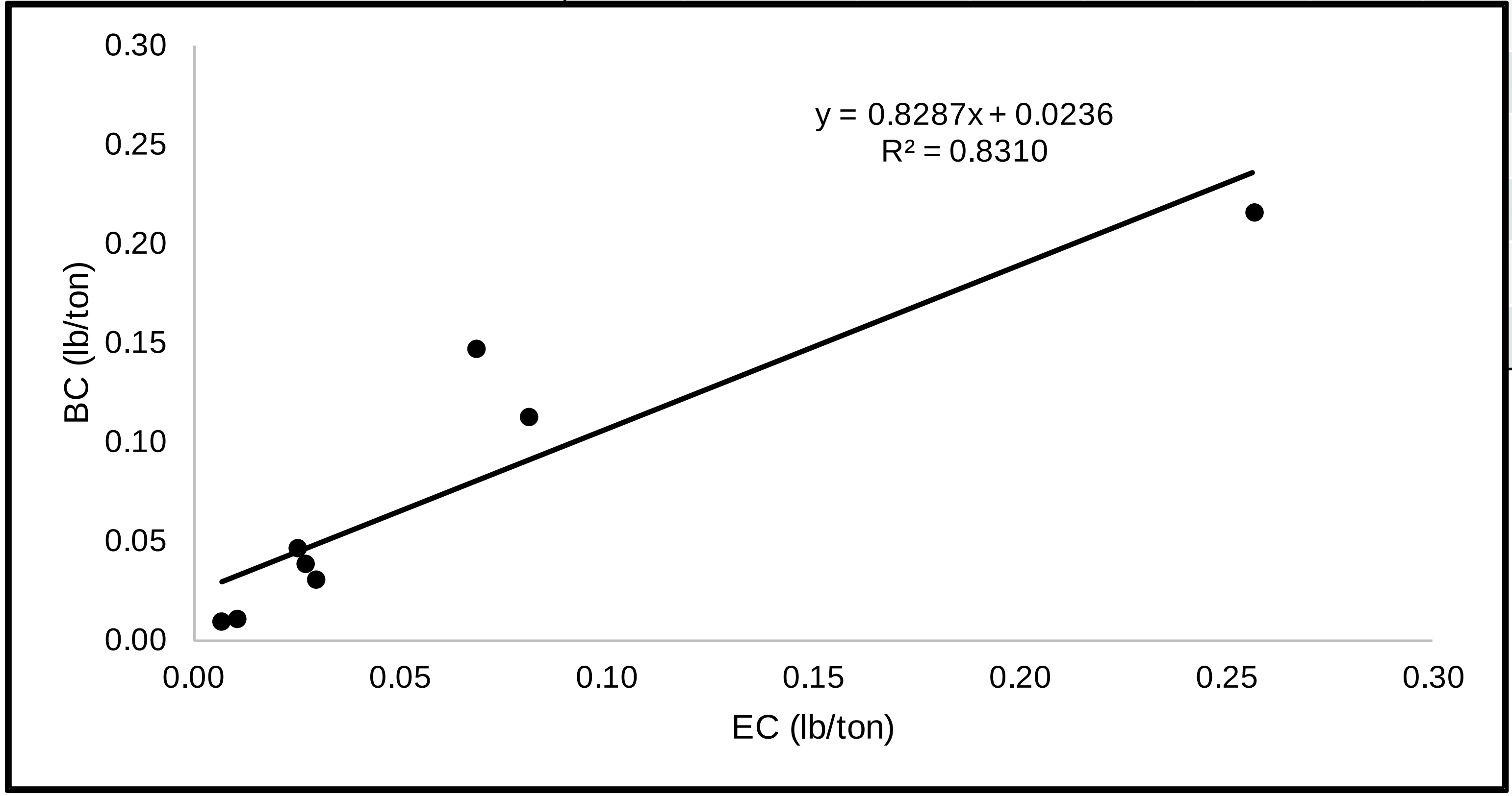


BC Removal average (%)
99
98
99
99
95
99
96
>99

view, ***Fuel***)

Particulate emissions (cont'd)

Test Date	Coal Type	EC inlet		EC outlet		EC Removal	OC inlet		OC outlet		OC Removal	BC inlet	BC outlet	BC Removal
		average (lb/ton)	Std Dev	average (lb/ton)	Std Dev	average (%)	average (lb/ton)	Std Dev	average (lb/ton)	Std Dev	average (%)	average (lb/ton)	average (lb/ton)	average (%)
June 4	Bituminous	0.081	0.026	0.002	0.001	97	0.029	0.011	0.019	0.011	35	0.112	0.001	99
June 7	Bituminous	0.029	0.007	0.003	0.001	91	0.021	0.010	0.013	0.002	40	0.030	0.001	98
								0.267	0.015	0.004	91	0.147	0.002	99
								0.006	0.015	0.002	47	0.216	0.001	99
								0.007	0.009	0.002	44	0.009	0.000	95
								0.003	0.007	0.001	9	0.038	0.000	99
								0.005	0.010	0.002	19	0.010	0.000	96
								0.001	0.010	0.000	2	0.045	0.000	>99



Yelverton et al., 2017 (under review, *Fuel*)

Conclusions

- A better understanding of particulate emissions:
  - Coal type/rank was found to have a relatively small influence on EC/OC ratio of the fine PM, as compared to variations between replicate tests (i.e. combustion characteristics)
  - PSD are bi-modal, resulting in peak number concentrations for all three coals between 50-70nm when measured prior to PM control
  - Exceptional overall fine PM removal provided by ESP (particle count removal >98%, PM mass removal >88%), but particles of smallest diameter (<50nm) have the lowest average percent removal across nearly all test conditions
    - Removal of particles with diameters between 51-150nm are much greater than expected, likely due to the smallest particles passing through the ESP and escaping as larger agglomerated particles

- A better understanding of gaseous emissions measurement techniques:
  - EPA Reference Methods 6C (SO_2), 7E (NO_X), and 10 (CO) have high correlation with FTIR measurements via ASTM D6348
    - Given this correlation, using the MKS EGU recipe, it is assumed other gaseous emissions measured (which are typically very difficult to measure via other techniques) are reasonable as well

Future direction: co-firing of coal and biomass

- Use of biomass as a drop-in replacement for coal has been considered a potential solution to needed reductions in GHG emissions
  - EPA Report (2010) prepared by OAR/OAQPS/SPPD
- Need for characterization of emissions from combustion of biomass/agricultural byproducts and energy crops
  - Initial aim for 40% biomass blend (by mass)
    - Completed successfully
  - After proof-of-concept, moved toward 80% biomass blend (by mass) with both processed (torrefied) and unprocessed biomass
    - White pine, yellow pine, corn stover, sorghum stover, miscanthus, and arundo

Sorghum – stover is one of the biomass materials used for the current investigation

Special THANKS to all of our partners and the MPCRF Team!!

- EPA's Region 4 Program Office (RARE Grant):
  - Dale Aspy, Katy Lusky, Tom Baugh (retired), and Dawn Taylor
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  - Nick Hutson, Christian Fellner, Steve Fruh, and Bob Wayland
- MPRCF Team:
  - (EPA) Ed Brown, Dave Nash, Peter Kariher, and Jeff Ryan
  - (SSC) Alina Brashear
  - (JTI) Carl Singer, Calvin Whitfield, Daniel Janek, and John Nash

EPA

¿¿Questions??

For further information or more in-depth discussion, please contact me:

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