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Trends in Coal Utilization and Coal Combustion Product Production in Kentucky: Results of the 2012 Survey of Power Plants

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A B S T R A C T

The University of Kentucky Center for Applied Energy Research has conducted a survey of Kentucky's utility coal-fired power plants every 5 years since 1992. The survey includes a collection of the feed coal and the coal combustion products (CCPs). The latest collection was in 2012, with the accompanying information survey covering trends in 2011. Overall coal-fired energy production decreased, and the nature of the CCPs changed for a number of reasons, including but not limited to, increased gas production in the Appalachians, a series of warm winters, energy conservation, depletion of Appalachian coal reserves, and utility responses to regulations. From 2011 to 2012, Kentucky's coal-fired generation decreased from 91.656 to 82.762 GWh, while gas-fired generation rose from 1.163 to 2.401 GWh. About 10% of the CCPs produced in 2011 were sold compared with 30% in 2006. Some of this can be attributed to an increase in the amount of CCPs in certain categories, primarily flue-gas desulfurization (FGD) gypsum. The latter increase was due to regulations requiring the installation of FGD, while stagnation and decreases in sales were due to multiple factors, including the slowdown in housing construction and to the saturation of the Ohio River Valley market. Overall, comparing 2011 with 2006, all categories of CCPs experienced a decline in sales. The change from low-S to high-S coal with the installation of wet-FGD units has resulted in a shift from low-Fe to high-Fe fly ashes.

A R T I C L E I N F O

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Keywords: fly ash; bottom ash; flue-gas desulfurization; regulations; utilization

1. Introduction

The University of Kentucky has conducted a survey of the utility coal-fired power plants every 5 years since 1992. A less-comprehensive survey was also done in 1978. Each survey has consisted of a collection of feed coal, pulverizer rejects, fly ash, and other coal combustion products (CCPs) at the power plant. In the more recent collections, this has evolved into a system of collecting the fly ash from individual electrostatic precipitator (ESP) or baghouse/fabric filter (FF) hoppers from as many rows as possible. Where possible, we attempt to collect fly ash from the same hoppers sampled in previous studies. The physical collection has been supplemented with a survey of coal sources, coal-quality parameters, CCP production and sales or disposal disposition, changes in the pollution-control system since the previous survey, and anticipated changes by the time of the next 5-year survey. The results of the previous collections and surveys have been published by Hower et al. (1996, 1999a,b, 2005, 2009).

2. Methods

Samples analyzed for this study were collected as part of a 2012 survey of all utility coal-fired power plants. Coal quality analyses of coal collected for the survey were done at the Center for Applied Energy Research (CAER). Proximate, ultimate, heating value, and sulfur forms analyses were conducted following the appropriate ASTM procedures. Ash chemistry was analyzed by X-ray fluorescence on a Phillips PW2404 X-ray spectrometer following procedures outlined by Hower and Bland (1989).

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Table 1
Amounts of coal combustion products produced, utilized, and disposed of in Kentucky in 2011

	Disposal landfill (Mt)	Disposal ponds (Mt)	Sold (Mt)	Used on-site (Mt)	Used off-site (Mt)	Stored on-site (Mt)	Total (Mt)	% sold	% sold + used
Fly ash	1.910	1.437	0.253	0.000	0.073	0.000	3.672	6.89	8.86
Bottom ash/ slag	0.621	0.558	0.269	0.097	0.027	0.000	1.571	17.10	24.96
FGD gypsum	0.757	1.601	0.635	0.059	0.248	0.627	3.927	16.16	39.97
FGD sulfite	2.421	0.000	0.000	0.000	0.000	0.000	2.421	0.00	0.00
Total	5.709	3.595	1.156	0.156	0.348	0.627	11.591	9.98	19.73

Note: FGD = flue-gas desulfurization.

3. Results and Discussion

3.1. Trends in CCP utilization

As noted in the "Introduction," the physical sample collection is supplemented by an information survey. The return of questionnaires was not as complete as in the past, so we had to rely on information reported to the U.S. Energy Information Administration (EIA, 2014). In reality, the basic CCP production and utilization information provided to us directly by the utility is the same as is on the EIA forms, with the exception of the nuances of the tonnages going to different end uses and the insight into anticipated changes.

In 2011, the information year accompanying the 2012 sample collection, 42.47 Mt of coal with an average 9.99% ash yield and 2.60% S (both as received) were combusted to produce 91.656 GWh at Kentucky power plants rated at 15.432 GW capacity. As an indication of the state of the coal-fired power industry in Kentucky, to be discussed in more detail herein, in 2012, the coal-fired generation fell to 82.762 GWh, while natural gas generation rose from 1.163 GWh in 2011 to 2.401 GWh in 2012 (EIA, 2014). Kentucky does not yet have a large natural gas–generating capacity, so the latter numbers are lower than many other states, but they do reflect the national trend. The reasons for the 2011 to 2012 fall in coal-fired power generation are varied and include wider availability of natural gas coincident with the expansion of production in Appalachian gas shales; a warm winter (2011–2012); energy conservation, including the use of increasingly energy efficient appliances; depletion of the thickest, highest, quality, and most accessible Central Appalachian coal reserves following over 100 years of mining; and utility responses to U.S. Environmental Protection Agency (EPA) regulations.

In 2011, Kentucky sold 9.98% of all of the CCPs produced (Table 1), a marked decline from the 30.1% sold in 2006. Comparing 2011 with 2006 (Table 2), every category of CCP, including flue-gas desulfurization (FGD) sulfite, which is almost never sold, saw a decline in sales. Some of the decline in the percentage is a function of the increased production of CCPs, but that does not account for the entire decline. For example, FGD gypsum sales to the wallboard manufacturing industry were impacted by the slowdown in housing construction, as well as by the saturation of the regional market with the construction of new scrubbers in the Ohio River Valley area. The total FGD gypsum sold, used on-site and off-site, and stockpiled in anticipation of future sales in 2011 (1.57 Mt) is less than the 1.753 Mt sold in 2006.

Fly ash sales, generally not as high as FGD gypsum or bottom ash/slag sales, were also hindered by the uncertainty in the EPA's prolonged discussion of a Resource Conservation and Recovery Act (RCRA) subtitle D (nonhazardous) versus subtitle C (hazardous) classification. In February 2014, following a January 2014 consent decree in the United States District Court for the District of Columbia in the case of Appalachian Voices et al. v. Gina McCarthy ordering EPA action (Walton, 2014), the EPA's Office of Solid Waste & Emergency Response ruled that fly ash and FGD gypsum, as encapsulated in concrete and wallboard, were not hazardous (EPA, 2014a). Some aspects of the background for the latter ruling were based on studies by Yost et al. (2010), Garrabrants et al. (2014), and Kosson et al. (2014).[1] According to the EPA, it is unlikely that there will be a review of unencapsulated uses in the near future because each use constitutes a unique case (Hegstead, 2014). Now that the ruling has been issued, it remains to be seen if the market for fly ash returns to levels experienced prior to the December 2008 ash spill at the Tennessee Valley Authority's Kingston power plant in Tennessee (EPA, 2014b).

[1] EPA has been criticized by environmental groups for not submitting the complete ruling for peer review, with the EPA counterarguing that the peer-reviewed studies cited here were the foundation for the ruling (Hegstead, 2014). An additional objection was raised with respect to the Yost et al. (2010) article dealing with wallboard gypsum, because one of the authors is employed by Georgia-Pacific, a manufacturer of wallboard.

Table 2
Amounts of coal combustion products produced, utilized, and disposed of in Kentucky, 1978–2011

Year	MW rating	Fly ash production (Mt)	% sold	Slag/bottom ash production (Mt)	% sold	FGD gypsum (Mt)	% sold	FGD sulfite (Mt)	% sold	Total production (Mt)	% sold
2011	15955	3.672	6.90	1.571	17.10	3.923	16.20	2.421	0.00	11.591	9.98
2006	15000	3.098	11.40	1.283	47.50	2.245	78.10	1.466	0.30	8.092	30.10
2001	15000	3.414	3.60	1.213	36.30	1.979	61.50	2.070	0.00	8.676	20.50
1996	15240	3.237	4.00	1.081	42.60	1.498	11.20	1.707	0.00	7.523	10.10
1991	16000	2.519	4.80	1.386	52.70	0.617	0.00	1.997	0.00	6.519	1.30
1978	11500	2.807		1.424		na		na		4.231	

Note: FGD = flue-gas desulfurization; na = not applicable.

Table 3

Coal quality parameters for coal burned at Kentucky utilities in 2012: proximate and ultimate analysis, heating value (HV), and Cl on as-received basis; major oxides by percent in 750°C ash; mercury on whole coal basis; and minor elements in parts per million in 750°C ash; groupings are based on the amount of S in the feed coal

S code		Ash	Mois	VM	FC	C	H	N	S	O	S_{py}	S_{sulf}	S_{org}	HV (MJ/kg)	Cl
<1%	Avg.	8.43	8.10	31.56	46.42	66.55	5.62	1.25	0.70	17.46	0.15	0.03	0.53	27.26	36
	St. Dev.	1.98	8.03	5.68	6.73	9.89	0.66	0.30	0.37	11.88	0.13	0.01	0.23	3.89	50
	Count	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1–2%	Avg.	10.92	3.31	36.64	49.13	66.49	4.89	1.48	1.84	14.39	0.90	0.11	0.84	28.86	519
	St. Dev.	0.93	0.47	1.40	0.93	5.98	0.17	0.04	0.13	6.99	0.16	0.02	0.05	0.52	733
	Count	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2–3%	Avg.	10.93	3.95	37.22	47.90	67.68	5.11	1.42	2.82	12.04	1.27	0.13	1.42	28.37	222
	St. Dev.	2.17	1.35	1.75	1.76	2.19	0.19	0.19	0.41	1.89	0.44	0.08	0.43	0.87	383
	Count	15	15	15	15	15	15	15	15	15	15	15	15	15	15
>3%	Avg.	13.42	4.24	35.59	46.76	66.49	5.05	1.22	3.38	10.44	1.85	0.13	1.40	27.64	170
	St. Dev.	3.14	1.80	2.39	4.24	3.53	0.15	0.29	0.39	2.50	0.48	0.08	0.48	1.38	213
	Count	9	9	9	9	9	9	9	9	9	9	9	9	9	9

S code		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	SO_3	Hg
<1%	Avg.	48.67	27.35	6.20	6.44	1.82	0.50	1.61	0.35	1.28	5.80	0.08
	St. Dev.	6.18	7.23	1.00	7.47	1.20	0.64	1.04	0.41	0.42	7.59	0.05
	Count	2	2	2	2	2	2	2	2	2	2	2
1–2%	Avg.	49.78	24.69	15.11	3.00	1.02	0.47	2.29	0.14	1.18	2.59	0.11
	St. Dev.	0.41	4.91	1.86	2.00	0.04	0.52	0.13	0.10	0.16	2.47	0.02
	Count	2	2	2	2	2	2	2	2	2	2	2
2–3%	Avg.	48.50	21.99	18.93	3.12	1.15	0.51	2.44	0.17	1.04	3.01	0.15
	St. Dev.	2.04	2.09	3.36	1.96	0.17	0.18	0.28	0.08	0.05	2.42	0.22
	Count	15	15	15	15	15	15	15	15	15	15	14
>3%	Avg.	49.48	22.24	20.35	2.38	1.15	0.40	2.50	0.20	1.03	2.25	0.11
	St. Dev.	1.98	1.28	3.14	1.09	0.15	0.14	0.30	0.15	0.06	1.29	0.02
	Count	9	9	9	9	9	9	9	9	9	9	9

S code		V	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Zr	Mo	Cd	Sb	Ba	Pb
<1%	Avg.	377	129	174	31	168	144	319	63	43	1877	2	58	1.0	0.5	1758	73
	St. Dev.	193	49	18	16	36	30	147	25	5	1244	0	18	0.0	0.7	1315	22
	Count	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1–2%	Avg.	536	166	248	53	113	130	235	106	5	629	9	41	1.0	3.0	618	66
	St. Dev.	234	6	64	1	1	95	29	40	7	734	5	4	0.0	1.4	266	26
	Count	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2–3%	Avg.	469	170	243	60	141	86	266	114	18	266	13	32	1.0	4.6	624	57
	St. Dev.	143	27	33	10	54	31	67	33	27	145	1	16	0.0	1.1	294	13
	Count	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
>3%	Avg.	614	171	240	63	160	78	271	110	58	240	15	16	1.0	5.9	680	52
	St. Dev.	767	40	25	9	161	20	183	28	39	98	1	16	0.0	0.9	314	10
	Count	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9

Note: Mois = moisture; VM = volatile matter; FC = fixed carbon.

3.2. State of the Kentucky coal-fired power-generation industry, 2014–2016

Several of the power plants sampled in 2012 have announced plans to close by the end of 2015. These decisions are driven by EPA regulations governing emissions of SO_2, NO_x, and Hg. It is generally anticipated that controls on CO_2 emissions for existing plants will be added to the latter list. For new plants, limits of 1100 lb (498.95 kg) CO_2/MWh gross over a 12-month operating period or 1000–1050 lb (453.59–476.27 kg) CO_2/MWh gross over an 84-month operating period were proposed (EPA, 2013c). As has been the case with previous EPA regulations, EPA authority is being challenged in U.S. courts, in this case, the U.S. Supreme Court (Liptak, 2014).

Changes seen from the time of the 2007 collection up to the end of 2012 were a consequence of responses to EPA's Cross-State Air Pollution Rule (CSAPR) (EPA, 2013a) and EPA's Mercury and Air Toxics Standards (MATS) (EPA, 2012). Under CSAPR, Kentucky power plants are required to reduce emissions of NO_x during the May through September ozone season, reduce annual emissions of SO_2 and NO_x by the guidelines of the 1997 Annual $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS) and the 2006 24-hour $PM_{2.5}$ NAAQS (EPA, 2013b), and make significant additional reductions in SO_2 emissions by 2014 in order to eliminate their contribution to air-quality problems in downwind areas. The construction of wet FGD units to control SO_2 emissions resulted in a shift of coal supply from low-S Central Appalachian coals to high-S Illinois Basin coals. Further changes include the outright closing of certain plants, usually small, old plants, and the conversion to gas turbine power generation at additional plants. Overall, we estimate that the 2012 coal-fired capacity of >15.9 GW in Kentucky will be reduced to <13 GW in 2016.

3.3. Coal, pulverizer rejects, and fly ash quality

3.3.1. Coal

Compared with the feed coals collected in 2007 (Hower et al., 2009), there are fewer coals in the <1% S and 1–2% S categories in

Table 4

Coal quality parameters for pulverizer rejects at Kentucky utilities in 2012: proximate and ultimate analysis, and Cl on as-received basis; major oxides on percent in 750°C ash; mercury on whole coal basis; and minor elements in parts per million in 750°C ash; groupings are based on the amount of S in the feed coal

S code		Ash	Mois	VM	FC	C	H	N	S	O	S_{py}	S_{sulf}	S_{org}	Cl
<1%	Avg.	33.19	4.45	31.20	31.17	47.38	4.08	0.89	3.42	11.05	2.72	0.11	0.60	
	St. Dev.	4.41	3.87	1.17	0.63	2.09	0.37	0.08	1.65	7.87	1.85	0.05	0.25	
	Count	2	2	2	2	2	2	2	2	2	2	2	2	
1–2%	Avg.	46.24	1.20	28.15	24.41	30.25	2.40	0.70	24.50	<0.1	21.30	0.28	2.92	30
	St. Dev.	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	
	Count	1	1	1	1	1	1	1	1	1	1	1	1	
2–3%	Avg.	39.94	2.36	30.83	26.87	36.11	2.90	0.73	24.04	9.08	17.92	0.60	5.52	48
	St. Dev.	18.95	1.20	4.25	14.78	21.85	1.51	0.59	16.76	2.81	12.11	0.44	5.01	140
	Count	12	12	12	12	12	12	12	12	5	12	12	12	12
>3%	Avg.	58.70	1.57	28.54	11.19	15.56	1.57	0.48	34.40		28.38	0.43	5.83	27
	St. Dev.	12.50	1.80	4.80	6.23	17.48	1.32	0.44	12.69		11.49	0.40	3.64	54
	Count	4	4	4	4	4	4	2	4		4	4	4	4

S code		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	SO_3	Hg
<1%	Avg.	47.87	14.04	21.76	6.93	1.61	0.24	1.06	0.17	0.82	7.40	0.72
	St. Dev.	1.17	0.12	4.70	3.06	0.51	0.34	0.04	0.13	0.26	3.32	0.01
	Count	2	2	2	2	2	2	2	2	2	2	2
1–2%	Avg.	17.06	5.73	58.61	7.24	0.87	0.75	0.86	1.34	0.39	7.71	1.29
	St. Dev.	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	Count	1	1	1	1	1	1	1	1	1	1	1
2–3%	Avg.	21.01	8.12	55.05	5.11	1.57	0.59	0.96	0.11	0.49	6.88	1.43
	St. Dev.	13.51	6.47	20.51	3.62	1.23	0.23	0.78	0.10	0.27	5.88	1.03
	Count	12	12	12	12	12	12	12	12	12	12	12
>3%	Avg.	13.77	4.90	61.24	7.78	0.87	0.61	0.52	0.56	0.34	8.95	1.67
	St. Dev.	4.24	1.81	22.24	8.15	0.34	0.22	0.22	0.77	0.06	10.51	0.95
	Count	4	4	4	4	4	4	4	4	4	4	4

S code		V	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Zr	Mo	Cd	Sb	Ba	Pb
<1%	Avg.	136	159	747	70	103	120	130	166	44	313	15	0	1.0	7.0	708	65
	St. Dev.	45	93	1	24	44	86	42	58	55	247	1	0	0.0	0.0	460	28
	Count	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1–2%	Avg.	227	162	411	145	132	12	196	276	<1	<1	26	<1	1.0	15.0	433	34
	St. Dev.	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	Count	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2–3%	Avg.	136	174	433	141	128	47	224	391	9	8	24	2	1.3	13.7	488	64
	St. Dev.	123	104	251	43	29	66	192	196	17	21	4	4	0.5	3.7	355	41
	Count	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
>3%	Avg.	72	148	274	151	109	6	73	316	54	0	26	0	1.5	16.0	445	37
	St. Dev.	51	45	71	53	37	6	91	146	109	0	1	0	0.6	1.2	268	13
	Count	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Note: Mois = moisture; VM = volatile matter; FC = fixed carbon; nd = not determined.

the 2012 collection (Table 3). As noted already, this is a function of the switch from low-S to high-S coals coincident with the switch to wet-FGD removal of flue-gas SO_2. A two-unit plant currently burning low-S (<1%) coal will convert at least one unit to natural gas before our next collection (planned for 2017). A 1–2% unit will be connected to an existing dry FGD unit at another plant with no planned change in the coal supply (Melnykovych, 2014).

The relatively high CaO content of the <1% S feed coal reflects the use of a western U.S. bituminous/Powder River Basin subbituminous blend in one power plant. The blending of a high-CaO, low-S coal with high-S Illinois Basin coal in one of the 2–3% S feed coal units is barely evident in the 3.12% CaO in the average of the feed coals.

3.3.2. Pulverizer rejects

The pulverizer rejects, often called ''pyrites' in the power plants, live up to the latter name in having an average of up to 34.5% total S in the >3% S feed coal category (note that the rejects and the fly ash summaries follow the S categories of the feed coals; Table 4). The Fe_2O_3 content, largely from the pyrite, mirrors the high-S content of the rejects. Toxic trace elements, notably As and Hg, are significantly higher in the rejects than in the feed coal. Even though the pulverizer rejects represent a small portion of the raw feed coal, the amount of As and Hg in the rejects can mean a reduction of perhaps 10–15% of the As and Hg in the pulverized feed coal (Mardon and Hower, 2004; Hower et al., 2005, 2006).

3.3.3. Fly ash

While up to five rows of ESP and FF were collected at some power plants, not all plants have that many rows, and even where present, the back rows did not always have fly ash at the time of sampling. The first two rows account for about 96% of the fly ash (based on the rule of thumb stating that each row collects about 80% of the fly ash entering that row), and our comparison is limited to the first two rows (Tables 5 and 6). Aside from the relationship between the chemistry of the feed coal and the resulting fly ash, there is a relationship between the collection point (ESP or FF row) and the concentration of trace elements (Meij, 1994; Bool and Helble, 1995; Robl et al., 1995; Hower et al., 1997, 1999c,d,e, 2005, 2006, 2009, 2010; Sakulpitakphon et al.,

Table 5
First-row electrostatic precipitator or fabric filter fly ash at Kentucky utilities in 2012: ash, moisture (Mois), carbon, and sulfur on as-received basis; major oxides on percent in 750°C ash; and minor elements in parts per million in 750°C ash; groupings are based on the amount of S in the feed coal

S code		Ash	Mois	C	S
<1%	Avg.	96.12	0.18	2.02	0.25
	St. Dev.	2.22	0.06	1.95	0.14
	Count	6	6	6	6
1–2%	Avg.	94.52	0.27	6.30	0.44
	St. Dev.	0.27	0.14	2.08	0.17
	Count	3	3	3	3
2–3%	Avg.	94.17	0.32	4.41	0.63
	St. Dev.	6.23	0.30	5.64	0.58
	Count	31	31	31	31
>3%	Avg.	95.27	0.24	3.66	0.61
	St. Dev.	6.00	0.14	6.55	0.38
	Count	25	25	25	25

S code		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	SO_3
<1%	Avg.	52.02	29.53	6.74	5.18	1.63	0.49	1.80	0.27	1.39	0.21
	St. Dev.	4.64	3.67	1.34	6.51	1.19	0.65	0.69	0.34	0.22	0.37
	Count	6	6	6	6	6	6	6	6	6	6
1–2%	Avg.	51.05	24.54	14.99	3.30	1.15	0.63	2.57	0.14	1.13	0.98
	St. Dev.	1.29	5.24	4.14	1.91	0.11	0.38	0.30	0.11	0.11	0.89
	Count	3	3	3	3	3	3	3	3	3	3
2–3%	Avg.	48.02	21.72	19.20	4.31	1.19	0.84	2.34	0.19	1.03	1.55
	St. Dev.	2.61	2.43	2.99	3.12	0.22	1.13	0.43	0.08	0.09	1.92
	Count	31	31	31	31	31	31	31	31	31	31
>3%	Avg.	48.24	21.34	21.34	3.47	1.13	0.48	2.42	0.17	1.03	1.13
	St. Dev.	3.08	1.11	4.28	1.66	0.18	0.18	0.29	0.10	0.08	1.33
	Count	25	25	25	25	25	25	25	25	25	25

S code		V	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Zr	Mo	Cd	Sb	Ba	Pb
<1%	Avg.	402	137	161	33	108	135	184	68	53	1724	1	58	1.0	0.7	1734	77
	St. Dev.	95	36	30	9	30	24	24	29	20	1169	1	17	0.0	1.0	1174	21
	Count	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
1–2%	Avg.	597	173	271	51	120	93	292	155	24	466	10	43	1.0	3.3	631	88
	St. Dev.	157	14	38	6	12	59	53	134	10	645	6	17	0.0	2.1	345	73
	Count	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
2–3%	Avg.	649	168	267	60	165	73	252	119	53	325	14	28	1.0	6.0	691	57
	St. Dev.	656	36	36	9	119	21	88	50	40	165	3	21	0.0	1.5	322	21
	Count	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
>3%	Avg.	568	172	246	66	151	71	271	125	45	182	15	18	1.0	6.6	615	53
	St. Dev.	466	23	26	12	93	26	191	53	37	114	1	14	0.0	1.3	272	16
	Count	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

2000, 2004; Mardon and Hower, 2004; Mastalerz et al., 2004; Depoi et al., 2008; Levandowski and Kalkreuth, 2009; Meij and te Winkel, 2009). In general, for most volatile trace elements, with exception of Hg (discussed in Hower et al., 2010) and Se (discussed in Hower et al., 2009), the concentration of the element will increase from the first row of the ash collection system through to the last row due to the decrease in flue-gas temperature and the increase in particle surface area (and decrease in particle size) in the same direction. Mercury capture, not addressed in this study due to technical difficulties in the determination of Hg in the CAER laboratories, is a function of the flue-gas temperature (increasing as temperature drops), the amount of carbon in the fly ash (increasing as the C content increases), the surface area of the carbon (increasing with an increase in surface area), and the type of carbon (Hower et al., 2010). Anisotropic carbon has the best Hg capture in fly ashes derived from bituminous coals (Maroto-Valer et al., 2001), but lignite- or subbituminous-derived char has better Hg-capture potential (Kostova et al., 2011).

Among the major oxides, CaO is relatively enriched in the low-S feed coal owing to the use of western U.S. coals, which are typically higher in CaO than eastern U.S. coals, in the feed coal at one plant. Iron oxide is enriched in the fly ashes from >1% S coals; this is not a surprise since a large percentage of the S is associated with pyrite. Volatile trace elements, such as Zn and As, increase from the first to second ESP rows, but the trends are not as evident in the group averages. Among the more significant trends is the increase from 150 to 347 ppm As in a three-row ESP. Zinc increases from 1070 to 1593 ppm in the first two of three ESP rows at a plant burning a small amount of tire-derived fuel (tdf) with the high-S feed coal. Concentrations of >2000 ppm V and up to 648 ppm Ni were observed in two plants burning several 10s percent of petroleum coke with high-S coal. One of the latter plants was scheduled to be idled in February 2014 (Reuters, 2014), but the plans were delayed when a short-term contract to purchase electricity was announced (Associated Press, 2014).

4. Outlook

Over the next few years, there will be a further narrowing of the fly ash quality available in Kentucky. Although one currently unscrubbed unit will be converted to dry-FGD controls with no anticipated change in its current medium-S Central Appalachian

Table 6
Second-row electrostatic precipitator or fabric filter fly ash at Kentucky utilities in 2012: ash, moisture (Mois), carbon, and sulfur on as-received basis; major oxides by percent in 750°C ash; and minor elements in parts per million in 750°C ash; groupings are based on the amount of S in the feed coal

S code		Ash	Mois	C	S
<1%	Avg.	95.55	0.18	2.64	0.44
	St. Dev.	1.72	0.03	1.37	0.35
	Count	5	5	5	5
1–2%	Avg.	92.77	0.38	6.62	0.55
	St. Dev.	1.61	0.10	0.56	0.16
	Count	3	3	3	3
2–3%	Avg.	93.14	0.42	5.23	0.56
	St. Dev.	8.26	0.43	7.40	0.29
	Count	23	23	23	23
>3%	Avg.	93.65	0.30	4.97	0.68
	St. Dev.	6.25	0.16	6.19	0.43
	Count	21	21	21	21

S code		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	SO_3
<1%	Avg.	51.23	29.27	6.44	6.08	1.79	0.59	1.72	0.33	1.36	0.48
	St. Dev.	5.33	3.79	0.86	7.04	1.29	0.71	0.74	0.38	0.23	0.66
	Count	5	5	5	5	5	5	5	5	5	5
1–2%	Avg.	48.95	24.03	15.62	3.75	1.17	0.64	2.58	0.17	1.12	1.22
	St. Dev.	1.27	5.02	4.27	2.29	0.13	0.37	0.37	0.13	0.10	1.00
	Count	3	3	3	3	3	3	3	3	3	3
2–3%	Avg.	48.36	22.85	18.62	3.99	1.27	0.44	2.48	0.24	1.09	1.14
	St. Dev.	1.80	2.74	3.19	3.48	0.20	0.22	0.48	0.09	0.10	1.03
	Count	23	23	23	23	23	23	23	23	23	23
>3%	Avg.	47.29	21.09	21.79	3.82	1.13	0.48	2.35	0.17	1.02	1.61
	St. Dev.	3.08	1.14	5.06	1.76	0.21	0.20	0.25	0.09	0.05	1.72
	Count	21	21	21	21	21	21	21	21	21	21

S code		V	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Zr	Mo	Cd	Sb	Ba	Pb
<1%	Avg.	394	130	155	31	105	133	190	58	65	1860	2	56	1.0	1.0	1902	72
	St. Dev.	92	34	20	9	32	21	21	11	20	1259	1	18	0.0	1.4	1291	14
	Count	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
1–2%	Avg.	640	177	301	53	159	92	332	202	31	435	11	42	1.0	3.7	667	105
	St. Dev.	167	9	21	6	48	59	74	195	17	616	6	18	0.0	2.3	381	98
	Count	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
2–3%	Avg.	447	165	249	60	135	88	302	168	36	427	13	40	1.0	5.4	776	76
	St. Dev.	89	27	34	10	45	24	139	79	30	146	2	25	0.0	1.5	371	32
	Count	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
>3%	Avg.	619	175	255	67	165	68	247	131	34	176	15	23	1.0	6.3	582	54
	St. Dev.	570	29	33	14	119	13	91	31	39	120	2	20	0.0	1.4	264	10
	Count	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21

coal supply, the low-Fe fly ashes derived from Central Appalachian coals will continue to decrease with the conversion to gas of one of the last power plants burning low-S Appalachian coals. The high-Zn fly ash from tdf + coal combustion should remain on the market, but the unit is small and does not have a great impact in overall fly ash quality. The fate of the two plants regularly burning petroleum coke with coal is uncertain. Aside from the latter exceptions, the "typical" fly ash from Kentucky will resemble what is now seen in the fly ashes derived from 2–3% and >3% S feed coals.

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