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A Model of Coal Cleaning for Sulfur Emissions Reduction

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This paper presents results of multivariate regression models developed to estimate the properties and cost of U.S. coals washed for varying degrees of sulfur removal using commercially available physical coal preparation processes. The models allow washed coal characteristics to be predicted from information on coal origin, heating value, ash, and sulfur content. The models were developed by first "processing" each of the 710 coals in the U.S. Bureau of Mines (USBM) coal washability data base through a coal preparation plant computer model which optimizes plant performance to achieve a desired washed coal quality. Washability data are adjusted to account for the inefficiencies of coal washing equipment, and the actual coal sizes treated by various plant wash streams. Since different plant designs may be capable of achieving a given level of sulfur removal, three nominal levels of plant complexity (Levels 2, 3, 4) were included to identify the most economical alternative. The washed coal characteristics thus derived were then analyzed using standard statistical techniques to develop regression equations linking washed coal properties and cost to raw coal properties for each of 18 geographical regions encompassing the entire U.S. These regression models are incorporated in the Advanced Utility Simulation Model (AUSM) to estimate the economic potential of coal washing as a sulfur abatement strategy, in conjunction with other options available to coal-fired power plants. Modeling results for Pennsylvania showed that washed coals frequently were selected as part of a cost-effective control strategy, accounting for 10 to 30 percent of the total emissions reduction, and that "local coal" restrictions significantly increase the use of washed coal as an SO_2 control strategy. Hypothetical requirements for mandatory coal cleaning, however, were found to be costly and ineffective.

Coal beneficiation (also known as coal cleaning or coal preparation) is a generic term for a variety of processes which enhance coal properties by reducing the level of impurities such as ash and sulfur. The majority of the processes (e.g., cyclones, jigs, concentrating tables) exploit the fact that impurities tend to be denser than the combustible material in coal and, hence, can be characterized by a specific gravity of separation. Such "physical" coal preparation is widely practiced in the U.S., Europe, and other coal-producing regions of the world. Its primary objective has been to remove ash and other noncombustible materials in order to lower transportation costs and achieve a coal quality suitable for combustion. The reduction of pyritic sulfur also can be achieved with physical coal cleaning, though this generally has not been done since it increases cost. However, as a result of recent proposals to curb emissions of sulfur dioxide associated with coal combustion,[1] there has been growing interest in the contribution enhanced coal preparation might make to reducing sulfur emissions.

In the U.S., various computer models have been used to examine the roles which switching to low sulfur coals and installing flue gas desulfurization (FGD) equipment might play in reducing SO_2 emissions nationally.[1–4] In addition, studies have been undertaken of the technical potential for SO_2 reductions through enhanced coal preparation.[5,6] So far, however, it has not been possible to make a comprehensive assessment of the *economic* potential for increased levels of coal preparation, measured in the same terms as coal switching and FGD. To date, models have relied on exogenously specified coal preparation costs and performance, often related to arbitrary assumptions about possible washing practices.

As part of the development of the Advanced Utility Simulation Model (AUSM),[7,8] we have developed a method for inferring the washed characteristics and costs of coals subjected to different degrees of sulfur removal through physical coal cleaning, given information about coal rank, geographical origin and basic seam properties (ash, sulfur, heating value, and moisture). This method can be used to establish a structured data base of washed coal properties and costs, which can be used to assess the economic potential of coal preparation as a sulfur reduction strategy (either alone, or in combination with other measures). This paper describes the development of the method, and briefly indicates its utilization.

Methodology Overview and Rationale

The motivation for the method described here was to estimate the properties and cost of coals subject to various degrees of washing for use in a large-scale simulation model of the U.S. electric utility sector. The method chosen was influenced very much by the nature of available data describing the "washability" of U.S. coals, and by the requirements for implementing it in the larger modeling framework. Nevertheless, the method developed also can be used in a "stand-alone" fashion to estimate coal washing potential.

The main source of information on washability characteristics was the U.S. Bureau of Mines (USBM) washability data base.[9] This contains data on the characteristics of 710 U.S. coals from float-sink analyses conducted under laboratory conditions (i.e., with a very sharp specific gravity of separation) for three or four different specific gravities. Washing was carried out after crushing to three different topsizes (1.5-in., 3/8-in., and 14 mesh), corresponding roughly to the top, medium and fine size streams of commercial coal preparation plants. The process yield, ash content and sulfur content were measured for each float-sink analysis, while the higher heating value was inferred from an empirical equation derived by USBM. Table I shows an example of the type of data reported by the USBM.

In the AUSM, a number of "characteristic coals" from each of 35 U.S. supply regions are defined according to their normalized sulfur content (lb $SO_2/10^6$ Btu). Information

Table I. Example of USBM coal washability data (Reference 9).

Properties	Specific gravity categories			
	<1.3	<1.4	<1.6	<2.2
Size range 1.5″ × 0″				
Yield (%)	64.10	78.40	87.00	100.00
Ash (%)	8.40	8.90	9.90	15.40
Sulfur (%)	2.22	2.45	2.91	5.23
HHV (Btu/lb)	12,831	12,762	12,622	11,855
Size range 0.375″ × 0″				
Yield (%)	51.50	77.70	85.70	100.00
Ash (%)	5.80	7.20	8.20	15.10
Sulfur (%)	1.96	2.12	2.50	5.31
HHV (Btu/lb)	13,194	12,999	12,859	11,897
Size range 0.0464″ × 0″				
Yield (%)	37.20	70.00	84.20	100.00
Ash (%)	5.10	6.60	8.20	15.60
Sulfur (%)	1.94	2.21	2.48	5.35
HHV (Btu/lb)	13,292	13,083	12,859	11,827

also is retained on coal rank, ash content, higher heating value, moisture and minemouth cost. In this framework, the potential contribution of coal preparation as an economical means of sulfur reduction can be assessed by viewing coal cleaning as a way of upgrading a coal from one sulfur category to another. The primary inputs to a coal washing model then must be the sulfur content, ash content, higher heating value and cost of the unwashed coal, plus the desired sulfur content of the washed coal. The outputs which must be determined are the washed coal ash content, higher heating value and cost.

As noted above, the USBM data include three different coal sizes which correspond roughly to the topsize of process streams found in commercial coal preparation plants. Previous coal cleaning studies typically have used the USBM data for a single specific gravity and topsize to estimate sulfur reduction potential. Actual prep plants, however, usually blend coals from two or three process streams washing different coal sizes at different specific gravities of separation, thereby optimizing the overall process so that coal of a target quality is produced as the lowest cost. In addition, commercial coal preparation equipment is less "efficient" than the laboratory float-sink tests used by USBM, in the sense that a perfect separation of material above and below the characteristic specific gravity does not occur. Rather, a certain amount of material (which depends on the washing equipment and the characteristic specific gravity of separation) is "misplaced," either from the float to the sink or vice-versa. For this reason, USBM data could give erroneous results for real preparation plants. Errors also occur from using the USBM data directly in "cumulative" form as reported (i.e., for all sizes below the indicated topsize), since actual plant designs require "noncumulative" data corresponding to specified *ranges* of coal size.

Table II. Definition of coal washability regions.

No.	Coal supply regions	No. of USBM samples
1	East Pennsylvania	143
2	West Pennsylvania	62
3	N.E. West Virginia and Maryland	39
4	Other northern West Virginia	32
5	Southern West Virginia/Virginia	24
6	Ohio	148
7	East Kentucky/north Tennessee	25
8	West Kentucky	37
9	South Tennessee/Alabama	11
10	Illinois	40
11	Indiana	21
12	Iowa	17
13	East Oklahoma/Arkansas	15
14	West Oklahoma/Kansas/Missouri/Texas	30
15	North Colorado/Wyoming	12
16	South Colorado/N.E. New Mexico/Utah	28
17	West New Mexico/Arizona	15
18	North Dakota/Montana/Washington	11

The modeling approach adopted here is to first process the raw USBM data using a coal preparation plant optimization model to derive the properties and costs of washed coals given a nominal plant flowsheet and target sulfur contents.[10] A secondary data base is thus produced which contains estimates of the properties and costs of the 710 USBM coals washed for different degrees of sulfur removal under commercial conditions. Since different plant designs may be capable of achieving a given level of sulfur removal, three levels of plant complexity were included to identify the most economic alternative. The secondary data base then was analyzed using standard statistical techniques to derive empirical equations linking washed coal properties and cost to raw coal input properties for each of 18 geographical regions encompassing the entire United States. Application of these regression equations then allows the washing potential of other U.S. coals to be estimated.

Table III. Nomenclature for coal cleaning model.

a_n = Regression coefficients ($n = 1, \ldots, 6$)
A = Coal ash content (dry wt. fraction)
A' = Normalized ash content (lb/10^6 Btu)
$\Delta A'$ = Fractional reduction in A'
b_n = Regression coefficients ($n = 1, \ldots, 6$)
c_n = Regression coefficients ($n = 1, \ldots, 5$)
C_c = Coal cleaning cost ($/dry raw ton)
C_i = Elements of cleaning cost ($i = 1, \ldots, 5$)
C_R = Run-of-mine coal cost ($/dry ton)
C_W = Washed coal cost ($/dry ton)
d_n = Regression coefficients ($n = 1, \ldots, 5$)
e_n = Regression coefficients ($n = 1, \ldots, 5$)
H = Coal higher heating value (Btu/dry lb)
H' = Lb of dry ash-free coal (/10^6 Btu)
O = Organic sulfur content (dry wt. fraction)
O' = Normalized organic sulfur (lb SO_2/10^6 Btu)
p = Pyritic fraction of total sulfur
P = Pyritic sulfur content (dry wt. fraction)
P' = Normalized pyritic sulfur (lb SO_2/10^6 Btu)
$\Delta P'_M$ = Maximum fractional reduction in P'
R = Subscript indicating raw (run-of-mine) coal
S = Total coal sulfur content (dry wt. fraction)
S' = Normalized sulfur content (lb SO_2/10^6 Btu)
$\Delta S'$ = Fractional reduction in S'
$\Delta S'_M$ = Maximum value of $\Delta S'$
W = Subscript indicating washed coal
Y = Plant dry mass yield (tons out/tons in)
Y' = Plant energy yield (Btu out/Btu in)
Y_B = Mass yield for "basic preparation"
Y_T = Total yield including "basic preparation"

The Coal Preparation Plant Model

Details of the preparation plant model used to derive washed coal properties from the USBM data base are presented elsewhere.[10] Nevertheless, a brief summary is necessary to understand how the raw data were processed.

The first function of the model is to adjust the raw washability data for the separation inefficiency of commerical preparation plant equipment. This is done by hypothesizing linear "partition curves" which relate the fraction of coal transferred to the float to its density and the characteristic specific gravity of separation. Partition curves may be characterized by a "probable error" which is assumed to be a function of the type of washing equipment assumed in the model (here, heavy media separation devices were assumed). This results in a lower potential sulfur reduction and lower process yields relative to the unadjusted USBM data.

The second function of the model is to derive the optimal mode of plant operation which minimizes the cost of achieving a target sulfur content for the final coal. It is assumed that this condition is met when the overall plant process yield is maximized, since the value of coal lost with the plant refuse typically accounts for the major part of coal washing costs. The optimization is achieved by defining coal properties (sulfur, ash and heating value) as functions of the mass or energy yield in each process stream, then using standard Langrangian multiplier techniques to determine the optimal overall process yield, given a constraint on the final coal quality. Separate analyses are carried out for three preparation plant configurations commonly referred to in the literature.[5,6] The first is a Level 2 plant design which washes only coarse coal sizes following crushing and screening. A Level 3 plant additionally washes mid sizes of coal, while a Level 4 plant includes a third stream for washing fine sizes which are also thermally dried. Cumulative USBM data are used to derive noncumulative washabilities for the top and bottom sizes specified for each plant stream.

The final function of the model is to calculate the capital and operting costs of the preparation plant, and the cost of cleaned coal. These are a function of the overall process yield, the preparation plant design level, and various economic/financial parameters included in the model.

Structuring the Analysis

The approach adopted was to exercise the preparation plant model a number of times for each coal in the USBM database, assuming different degrees of sulfur reduction. The number of times the model was exercised for each coal was determined by considering the number of USBM float-sink analyses reported. This led to the selection of 5 percent increments of sulfur removal (i.e., 5 percent, 10 percent, etc., based on equivalent lb $SO_2/10^6$ Btu) up to a maximum feasible reduction which was estimated as part of this work. For Level 2 preparation plants, this gave a total of 2753 sampling points in the secondary data base associated with the 710 coals, or an average of 3.9 per coal. For Level 3 and 4 preparation plants, the number of sampling points was higher due to the greater degree of sulfur removal possible. (The statistical implications of this difference for the subsequent regression analysis is discussed below.)

Ideally, a separate statistical analysis would be carried out to estimate the washed coal properties in each of the 35 AUSM coal supply regions of interest. However, in many cases there were too few coals in a supply regions to provide a statistically meaningful sample. Thus, the following criteria (in order of priority) were adopted for aggregating AUSM coal supply regions: (1) regions in the same USBM producing district; (2) regions in the same state; (3) regions in the same USBM producing region; and (4) regions in broad geographical proximity. This led to the selection of 18 geographical regions used for the statistical analysis. Their identity and the number of USBM coal samples in each are shown in Table II.

Coal Washing Regression Models

The statistical models developed here are intended to provide a means of estimating washed coal properties and cost directly from readily available raw coal characteristics. The following sequence of steps is employed:

- Infer the pyritic sulfur fraction of the feed coal from other coal properties (since only pyritic sulfur can be removed by physical coal cleaning).
- Estimate the maximum extent to which pyritic sulfur can be reduced (to test whether or not a desired degree of sulfur removal is feasible).
- Determine the reduction in ash content associated with a specified reduction in sulfur content.
- Estimate the higher heating value of the washed coal.
- Estimate the energy recovery of the washing process.
- Estimate the costs of coal washing.

All algebraic symbols used in the regression equations are defined in Table III. Some coal properties are normalized on the weight of coal, while others are normalized on energy content. A set of identities links these normalized properties:

$$A' = (A \times 10^6)/H \tag{1}$$

$$S' = (2S \times 10^6)/H \tag{2}$$

$$H' = (10^6/H) - A' \tag{3}$$

Since the sulfur in coal may be divided into its organic and pyritic components, the following identities also obtain:

$$S = O + P \tag{4}$$

$$P = pS \tag{5}$$

$$O = (1 - p)S \tag{6}$$

Also, since physical coal cleaning reduces only the pyritic sulfur in coal, and organic sulfur is an integral part of the coal matrix:

$$O'_W = O'_R \tag{7}$$

$$S'_R - S'_W = P'_R - P'_W \tag{8}$$

The derivation of the regression equations is now described, with key results presented for all 18 regions. Additional statistical parameters (t-statistics, R^2 values and sample size) are given in Reference 8. In all cases, the Durbin-Watson statistic indicated no autocorrelation effects for this analysis.

Pyritic Sulfur Fraction

Pyritic sulfur fraction was found to be significantly correlated with either the sulfur content of the seam quality coal, the ash content, or both. The regression equation selected sets a natural ceiling of 100 percent on the pyritic sulfur fraction:

$$\log(1 - p) = a_1 + b_1 \log S'_R + c_1 \log A'_R \tag{9}$$

Values of the statistically significant coefficients for each region are shown in Table IV. Note that the pyritic sulfur fraction is positively correlated with total sulfur content, confirming the intuitive idea that pyritic sulfur fractions will be higher in "dirtier" coals.

Maximum Sulfur Reduction

The maximum sulfur reduction achievable through coal cleaning depends upon the level of preparation plant assumed. Thus, three separate regression analyses were conducted for each region. The following equation was fitted to link maximum removal of pyritic sulfur to the pyritic sulfur fraction:

$$\Delta P'_M = a_2 + b_2 p \tag{10}$$

The results for each level of cleaning also appear in Table IV. The maximum reduction in total sulfur content (organic plus pyritic) may then be derived from Equation 10 using a simple identity:

$$\Delta S'_M = p(\Delta P'_M) \tag{11}$$

Note that the variable p on the right-hand side of Equation 10 is endogenous, i.e., it is directly related to the depen-

Table IV. Regression coefficients for sulfur reduction (Equations 9, 10).

Region	Equation 9: pyritic sulfur fraction				Equation 10: maximum pyrite removal								
					Level 2			Level 3			Level 4		
	a_1	b_1	c_1	R^2	a_2	b_2	R^2	a_2	b_2	R^2	a_2	b_2	R^2
1	−0.3593	−0.6170	*n*	65.0%	0.0947	0.2837	14.3%	0.2108	0.5751	33.4%	0.2023	0.8152	46.5%
2	−0.3162	−0.5728	*n*	56.3%	0.3991	*n*		0.4117	0.3190	10.8%	0.4558	0.4056	15.2%
3	−0.1430	−0.8268	*n*	78.3%	0.2503	*n*		0.3224	0.2967	11.5%	0.3739	0.4943	23.3%
4	0.1388	−0.2780	0.3165	29.3%	0.3909	*n*		0.6027	*n*		0.4283	0.4473	21.1%
5	−0.1869	−0.5416	*n*	66.2%	−0.0144	0.9924	50.9%	−0.0056	1.4665	62.4%	−0.0259	1.7471	66.4%
6	−0.7891	−0.1460	*n*	4.9%	0.3790	*n*		0.6016	*n*		0.7014	*n*	
7	−0.0918	−0.8290	*n*	84.0%	0.3258	*n*		0.2618	0.4082	27.0%	0.3006	0.4778	24.8%
8	0.1114	*n*	−0.4443	47.7%	0.1458	0.4638	15.4%	0.1644	0.7732	34.8%	0.1642	0.9208	50.8%
9	−0.2468	−0.6582	*n*	97.2%	0.2166	*n*		0.0922	0.7171	34.2%	0.1001	0.8969	41.6%
10	0.3908	*n*	−0.4961	49.2%	0.1249	0.4791	23.7%	0.1519	0.7950	35.9%	0.2116	0.8118	38.7%
11	−0.0076	*n*	−0.4148	26.4%	0.1220	0.4612	27.0%	0.0645	0.8464	48.5%	0.0299	0.9956	42.7%
12	−1.1552	*n*	*n*		0.4185	*n*		0.3743	0.3763	23.4%	0.3288	0.5201	27.7%
13	−0.6539	−0.6641	0.2129	62.5%	−0.0413	0.3932	43.4%	−0.0699	0.7054	53.3%	−0.1259	1.0526	62.0%
14	0.1802	−0.6459	*n*	75.8%	0.0610	0.4563	49.1%	0.1930	0.5241	36.0%	0.1728	0.7126	48.8%
15	−0.2740	*n*	*n*		0.3466	*n*		0.4046	*n*		0.4940	*n*	
16	−0.3735	−0.3777	*n*	52.1%	−0.0280	0.5810	17.7%	0.2291	*n*		0.0567	0.7853	15.4%
17	−0.0036	−0.1421	*n*	48.5%	−0.1787	1.4237	58.8%	−0.2003	1.6938	51.5%	−0.1959	1.7594	43.7%
18	−0.4423	−0.8712	*n*	47.5%	0.5017	*n*		0.7236	*n*		0.7502	*n*	

n = Coefficient not significant at the 95% level.

Table V. Regression coefficients for ash and heating value (Equations 13, 17).

Region	Equation 13: ash content						Equation 17: heating value term				
	a_3	b_3	c_3	d_3	e_3	R^2	a_4	b_4	c_4	d_4	R^2
1	−17.8680	0.7894	0.1287	0.5354	3.7470	80.6%	59.6945	*n*	0.0877	*n*	3.5%
2	7.4500	0.8102	−0.2327	0.6537	−2.1370	76.7%	61.5520	*n*	*n*	*n*	
3	18.6650	0.8113	*n*	0.7079	−5.0390	82.6%	60.3330	*n*	*n*	*n*	
4	−50.9810	0.8632	*n*	0.7512	11.6280	87.4%	64.1310	*n*	*n*	*n*	
5	−0.9454	0.8335	−2.0523	0.7944	*n*	85.6%	60.4910	*n*	*n*	*n*	
6	7.7760	0.8393	0.1995	0.3754	−2.2299	81.4%	93.8900	*n*	0.1414	−0.4547	6.0%
7	−0.7051	0.9468	−0.2883	0.4358	*n*	69.5%	62.2760	*n*	*n*	*n*	
8	−1.1000	0.9135	−0.9310	1.0317	*n*	88.3%	−40.5100	*n*	−0.3300	1.6304	
9	−39.4800	0.8757	*n*	*n*	9.4450	80.1%	64.1620	*n*	*n*	*n*	
10	5.2850	0.8988	−0.5230	1.0091	−1.7040	91.3%	64.8560	*n*	*n*	*n*	
11	−2.8872	0.7900	0.7713	0.3384	*n*	81.0%	77.5260	*n*	−1.1370	*n*	22.4%
12	23.7060	0.8321	0.5806	*n*	−5.9900	90.5%	37.6100	*n*	*n*	−2.3854	32.4%
13	35.0900	0.7171	*n*	1.7981	−9.3170	80.9%	59.2110	*n*	*n*	*n*	
14	37.6960	0.8878	0.3306	0.5444	−9.4330	78.4%	1.9800	*n*	*n*	0.8320	28.7%
15	31.1000	0.3982	*n*	0.7177	−7.6440	55.2%	70.4690	*n*	*n*	*n*	
16	−25.3270	0.7684	−1.0691	*n*	5.9150	80.5%	−11.6900	*n*	*n*	1.0471	18.5%
17	−3.2254	0.7665	−1.6012	1.0575	*n*	75.2%	−170.7800	−5.1530	*n*	3.2060	66.7%
18	91.6300	0.6283	0.4305	1.2533	−22.0120	75.8%	59.4640	6.4620	*n*	*n*	42.0%

n = Coefficient not significant at the 95% level.

Table VI. Regression coefficients for process yield (Equation 18).[a]

Region	Level 2					Level 3					Level 4				
	a_5	b_5	c_5	d_5	e_5	a_5	b_5	c_5	d_5	e_5	a_5	b_5	c_5	d_5	e_5
1	−40.9580	0.8186	*n*	0.2229	9.0600	−53.5430	0.9262	0.1201	0.1523	12.0160	−59.4240	0.8275	0.1504	0.1057	13.3875
2	−3.3826	0.7340	*n*	0.3266	*n*	−3.4735	0.8842	*n*	0.4063	*n*	−18.4730	0.8952	*n*	0.4092	3.5450
3	−2.8682	0.8150	0.7000	*n*	*n*	−33.6100	0.8574	0.5471	*n*	7.3170	−37.2840	0.8127	0.4468	*n*	8.1980
4	−43.6800	1.0092	−0.5290	0.4421	9.8140	−58.4500	1.0650	*n*	*n*	13.3420	−83.2700	1.0400	−0.3281	*n*	19.3410
5	−3.5992	1.2147	−1.2668	0.8145	*n*	−60.2000	1.0145	−1.3890	0.7656	13.4080	−4.3524	0.9528	−1.0107	0.8315	*n*
6	−3.5681	0.9924	*n*	0.5655	*n*	−26.1030	0.9999	*n*	0.6085	5.2610	−31.8600	1.0164	*n*	0.6399	6.5920
7	−71.5400	1.0909	0.5938	*n*	16.2000	−50.3100	1.0786	0.5614	*n*	11.1510	−42.8800	1.0511	0.6032	*n*	9.3640
8	−62.5560	0.9937	*n*	*n*	14.1110	−68.6760	0.9909	*n*	*n*	15.5230	−71.2850	0.9988	*n*	*n*	16.1290
9	−135.4800	1.0155	*n*	1.5298	31.1180	−89.2000	0.9246	0.4685	1.4982	19.9370	−110.6800	0.9716	*n*	1.6752	25.0740
10	−2.8976	0.8800	*n*	*n*	*n*	−2.5012	0.9881	−0.2261	*n*	*n*	−2.5135	0.9687	−0.2614	*n*	*n*
11	−2.7948	1.0495	0.9014	−0.5706	*n*	−4.2308	0.9929	0.8589	*n*	*n*	−4.2720	0.9608	0.8418	*n*	*n*
12	−44.6500	0.8979	*n*	0.8122	9.3340	−29.5470	0.9102	*n*	1.0232	5.6590	−25.8630	0.8505	*n*	1.0916	4.7330
13	23.4100	1.2118	1.3763	1.3568	−6.8890	23.0500	1.1562	1.5190	1.9837	−7.2960	15.5500	1.1400	1.5520	2.1527	−5.6630
14	48.8950	0.9167	*n*	0.5649	−12.4050	34.4760	1.0237	0.4489	0.4887	−9.8780	36.9750	1.0513	0.4091	0.5022	−9.7510
15	−3.7511	0.7381	*n*	*n*	*n*	−3.6614	1.0037	*n*	*n*	*n*	−3.7192	1.0631	*n*	*n*	*n*
16	−81.6800	1.4318	−1.8254	*n*	18.7880	−75.3000	1.2654	−1.9103	*n*	17.2410	−80.3800	1.1620	−1.7362	*n*	18.3520
17	−5.2380	1.1810	−3.6060	1.3020	*n*	−6.0601	1.0878	−3.2300	1.4965	*n*	−6.9450	0.9900	−3.2827	1.7656	*n*
18	102.0500	1.0104	0.8720	1.9635	−25.2860	86.0800	0.8546	0.7122	1.7416	−21.5780	83.9600	0.7365	0.6404	2.0169	−21.2420

n = Coefficient not significant at the 95% level.

[a] The average R^2 values are 58.3% for Level 2, 68.0% for Level 3 and 71.9% for Level 4. All statistics for individual regions appear in Reference 8.

dent variable in Equation 9. The same situation appears in several later results. Ideally, this requires that the system of equations be solved simultaneously, which cannot readily be done since they are highly nonlinear. It is assumed, however, that the consequences of this endogeneity are not severe, as the equations derived are successful in predicting known coal washability patterns. Other equation forms, including more tractable linear models, were rejected in favor of the equations presented here based on physical reasoning and goodness-of-fit.

Ash Content of Washed Coal

The ash content of washed coal is given by the identity:

$$A'_W = A'_R(1 - \Delta A') \qquad (12)$$

In order to allow for the fact that the maximum theoretical removal of ash from any coal is 100 percent, and the maximum removal of sulfur is p (the pyritic sulfur fraction), the following relationship between ash removal, sulfur removal and feed coal properties was postulated:

$$\log\left(\frac{\Delta A'}{1 - \Delta A'}\right) = a_3 + b_3 \log\left(\frac{\Delta S'}{p - \Delta S'}\right) + c_3 \log S'_R + d_3 \log A'_R + e_3 \log H'_R \qquad (13)$$

This regression equation was found to give excellent fits for individual coals. The equation was then fitted to the pooled data for all coals in a given region using a Level 4 preparation plant, with satisfactory results obtained (Table V). In fitting Equation 13 the number of data points in the secondary data base for Level 4 preparation exceeds the number of original USBM laboratory float-sink analyses. (There are a total of 5492 data points associated with the secondary data used for this analysis, compared to only 2753 USBM float-sink analyses.) Therefore, the *t*-statistics, which indicate the significance of individual parameters in the regression equation could, in principle, be overestimated by up to 50 percent (though even here the values obtained would still be significant[8]). However, since the equation can simulate washability curves for *individual* coals with great accuracy, the source of most of the variance in Equation 13 must be associated with the less significant variables (A'_R, S'_W, H'_R), which are coal-specific. Because of this, the unexplained variance (which is largely associated with the differences among coals) will be roughly proportional to the number of data points per coal selected for the secondary data base. Given the definition of the *t*-statistic, it follows that the statistical significance of the fitted equation will be relatively insensitive to the number of data points used.

Heating Value of Washed Coals

As noted earlier, for each individual coal in the washability data base, the USBM has developed an empirical equation linking the heating value of a washed coal to its ash, organic sulfur, and pyritic sulfur contents.[9] The equation developed is of the form:

$$H_W = x - y(A_W + 0.3P_W + 0.5O_W) \qquad (14)$$

Relating this to the properties of completely unwashed coal allows x to drop out of the equation:

$$H_W - H_R = y\left[A_R - A_W) + 0.3(O_R - O_W) + 0.5(P_R - P_W)\right] \qquad (15)$$

Substituting identities (1)–(5) in Equation 15 and re-

Table VII. Regression coefficients for cleaning cost (Equation 19).[a]

Region	a_6	Level 2			Level 3			Level 4		
	b_6	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3
1	*a*	0.6559	0.7651	0.5956	0.6912	1.2349	0.9029	1.1151	1.6215	1.1827
	b	0.	2.7196	1.2943	0.	1.8494	0.9617	0.	1.4498	0.7867
2	*a*	0.6559	0.7752	0.5993	0.6912	1.2265	0.8782	1.1151	1.5627	1.1221
	b	0.	2.5539	1.2168	0.	1.7372	0.9374	0.	1.4807	0.8180
3	*a*	0.6559	0.7670	0.5960	0.6912	1.2534	0.9099	1.1151	1.6596	1.1983
	b	0.	2.6884	1.2768	0.	1.7746	0.9365	0.	1.3812	0.7638
4	*a*	0.6559	0.7769	0.5998	0.6912	1.2225	0.8770	1.1151	1.5589	1.1188
	b	0.	2.5015	1.1978	0.	1.7239	0.9308	0.	1.4551	0.8072
5	*a*	0.6559	0.7546	0.5909	0.6912	1.1742	0.8621	1.1151	1.5158	1.1170
	b	0.	2.7464	1.3109	0.	2.0875	1.0778	0.	1.7082	0.8879
6	*a*	0.6559	0.7700	0.5976	0.6912	1.2125	0.8727	1.1151	1.5652	1.1235
	b	0.	2.6472	1.2565	0.	1.7856	0.9585	0.	1.4515	0.8114
7	*a*	0.6559	0.7665	0.5955	0.6912	1.1946	0.8639	1.1151	1.5368	1.0977
	b	0.	2.6820	1.2804	0.	1.8657	0.9889	0.	1.4532	0.8219
8	*a*	0.6559	0.7715	0.5983	0.6912	1.2121	0.8773	1.1151	1.5549	1.1267
	b	0.	2.6443	1.2590	0.	1.8430	0.9793	0.	1.5180	0.8277
9	*a*	0.6559	0.7658	0.5950	0.6912	1.1997	0.8681	1.1151	1.5574	1.1293
	b	0.	2.5221	1.2119	0,	1.8172	0.9738	0.	1.4954	0.8198
10	*a*	0.6559	0.7623	0.5951	0.6912	1.2066	0.8750	1.1151	1.5399	1.1240
	b	0.	2.8811	1.3596	0.	1.9070	1.0028	0.	1.6285	0.8614
11	*a*	0.6559	0.7622	0.5951	0.6912	1.1965	0.8678	1.1151	1.5323	1.1178
	b	0.	2.7713	1.3082	0.	1.8404	0.9668	0.	1.5600	0.8210
12	*a*	0.6559	0.7655	0.5964	0.6912	1.2020	0.8715	1.1151	1.5355	1.1172
	b	0.	2.8145	1.3255	0.	1.9283	1.0082	0.	1.6328	0.8689
13	*a*	0.6559	0.7573	0.5915	0.6912	1.2268	0.9088	1.1151	1.6241	1.1789
	b	0.	2.6083	1.2498	0.	1.9155	0.9715	0.	1.3732	0.7703
14	*a*	0.6559	0.7723	0.5979	0.6912	1.2268	0.8762	1.1151	1.5876	1.1243
	b	0.	2.6282	1.2496	0.	1.7348	0.9431	0.	1.3851	0.7927
15	*a*	0.6559	0.7496	0.5895	0.6912	1.1829	0.8608	1.1151	1.5505	1.1339
	b	0.	2.9660	1.4096	0.	1.7899	0.9704	0.	1.4132	0.7930
16	*a*	0.6559	0.7532	0.5897	0.6912	1.1855	0.8641	1.1151	1.5211	1.1128
	b	0.	2.4368	1.1836	0.	1.7969	0.9666	0.	1.5603	0.8574
17	*a*	0.6559	0.7459	0.5875	0.6912	1.1616	0.8540	1.1151	1.5185	1.1129
	b	0.	3.1950	1.5298	0.	2.2593	1.1699	0.	1.6235	0.8914
18	*a*	0.6559	0.7598	0.5941	0.6912	1.1671	0.8559	1.1151	1.5202	1.1295
	b	0.	2.5163	1.2154	0.	2.0758	1.0691	0.	1.8121	0.9190

[a] The average R^2 values exceed 99% for all regions (Reference 8).

arranging gives H_W in terms of known quantities (apart from y):

$$\frac{H_W}{H_R} = \frac{(10^6/y) + [A'_R + S'_R(0.25 - 0.1p)]}{(10^6/y) + [A'_W + S'_R(0.25 - 0.1p - 0.15\Delta S')]} \qquad (16)$$

Values for y are given by the USBM for each coal in the washability data base. For each AUSM supply region, the value $(10^6/y)$, used in Equation 16, was regressed against the properties of the unwashed coal:

$$10^6/y = a_4 + b_4 S'_R + c_4 A'_W + d_4 H'_R \qquad (17)$$

The resulting regression coefficients are given in Table V.

Btu Yield of Washing Process

The Btu yield of the washing process is estimated in a manner similar to that for ash reduction. Three separate analyses are carried out for Levels 2, 3 and 4 washing. The equation fitted is:

$$\log(1 - Y')$$

$$= a_5 + b_5 \log\left(\frac{\Delta S'}{p - \Delta S'}\right) + c_5 \log S'_r + d_5 \log A'_R + e_5 \log H'_R \qquad (18)$$

This equation is the most important in determining the ultimate cost of the washed coal. Results for each region are shown in Table VI.

Washing Costs

Elements of coal washing cost, expressed in current 1984 dollars per dry ton of raw coal, were obtained from the coal preparation plant model assuming a 500 tph plant size. Several of these elements were combined or simplified to yield three cost components: (1) plant labor cost; (2) non-labor operating and maintenance cost; and (3) plant capital cost. Each cost element, i, was regressed against washing mass yield for each washing level producing equations of the form:

$$C_i = a_{6i} Y^{-b_{6i}} (i = 1, \ldots 3) \qquad (19)$$

Table VIII. Financial assumptions for annualized capital costs.[a]

Parameter	Value
Inflation rate	6%/yr
Real escalation rate, capital cost	0%/yr
Real escalation rate, labor cost	1%/yr
Real escalation rate, non-labor cost	0%/yr
Real after-tax return on equity	6.1%
Real rate of debt cost	1.5%
Debt fraction	30%
Corporate tax rate	50%
Depletion allowance (% of gross profits)	50%
Plant life	20 yrs

[a] These assumptions give a nominal after-tax discount rate of 10.4% and a capital recovery factor of 12.1%. To express costs in real terms, or to substitute other assumptions, appropriate ratios can be applied to cost factor C_3 in Table VII.

Supply Region 1 Penna. (E) — Bituminous coal

Washed coal categories (lb SO_2/MMBtu)

Raw coal categories	>8.0	6.0–8.0	4.0–6.0	3.0–4.0	2.5–3.0	2.0–2.5	1.5–2.0	1.2–1.5	0.8–1.2	0.6–0.8	<0.6	No. levels
>8.0	X	X	X	X	X							5
6.0–8.0		X	X	X	X	X						5
4.0–6.0			X	X	X	X						4
3.0–4.0				X	X	X	X					4
2.5–3.0					X	X	X					3
2.0–2.5						X	X	X				3
1.5–2.0							X	X				2
1.2–1.5								X				1
0.8–1.2									X			1
0.6–0.8										X		1
<0.6												0
No. coals	1	2	3	4	5	5	4	3	1	1	0	29

Figure 1. Matrix formulation showing feasible coal washing levels. X in a diagonal element means a raw coal exists. X in an off-diagonal means a washed coal is physically possible.

where the weight yield is determined from the Btu yield by the identity:

$$Y = Y'(H_R/H_W). \tag{20}$$

The regression coefficients are shown in Table VII. The values of cost parameters assumed for annualizing the capital costs are summarized in Table VIII. The total cost of washing per ton of raw coal is then given by:

$$C_C = C_1 + C_2 + C_3 \tag{21}$$

Finally, to determine the total cost of washed coal for a specified degree of sulfur removal the following equation is used:

$$C_W = \frac{C_R + C_C}{Y} \tag{22}$$

Note that this cost is expressed on a dry basis. To obtain results on a moist (as delivered) basis, Equation 22 must be multiplied by one minus the washed coal moisture content.

Implementing the Methodology

The general framework within which the coal washing models are used to identify cost-effective emission reduction strategies is shown in Figure 1. The diagram takes the form of a triangular matrix defined by the eleven sulfur categories for raw and washed coals used in the AUSM. As noted earlier, coal washing is viewed as a means by which a coal may be upgraded from one sulfur category to another at an increase in cost, and with an adjustment to other physical properties. Characteristic coals for a particular supply region before washing are represented by points on the diagonal of the matrix. The physical sulfur removal limit, approximated by Equation 11, determines the number of lower sulfur categories to which a particular characteristic coal may be washed. The feasible washing levels for one Pennsylvania coal supply region are indicated by the crosses in Figure 1. Associated with each of these levels are data on washing costs, washing yields and washed coal properties. Within each sulfur category, washed coals thus compete with unwashed coals as the least cost alternative for each utility demand region. For example, in the range of 1.2–1.5 lb $SO_2/10^6$ Btu, there are three coals potentially available from the Pennsylvania supply region, two that have been washed from higher sulfur levels, and one that occurs naturally. For each utility demand region, an efficient algorithm developed for the AUSM allows the coal with the lowest delivered cost in a given sulfur category to be identified after additional transportation costs from each of 35 supply regions are considered.[11] The final selection of a coal then considers total power plant capital and operating costs for all feasible emission reduction strategies to identify the most economic alternative.[11,12] In this way, washed coals also can be blended or selected in conjunction with FGD systems to minimize the total compliance cost for a particular plant or region.

Ideally, the characteristic coals on the diagonal of the washing matrix of Figure 1 should be run-of-mine coal without any degree of preparation, i.e., have a yield of 100 per-

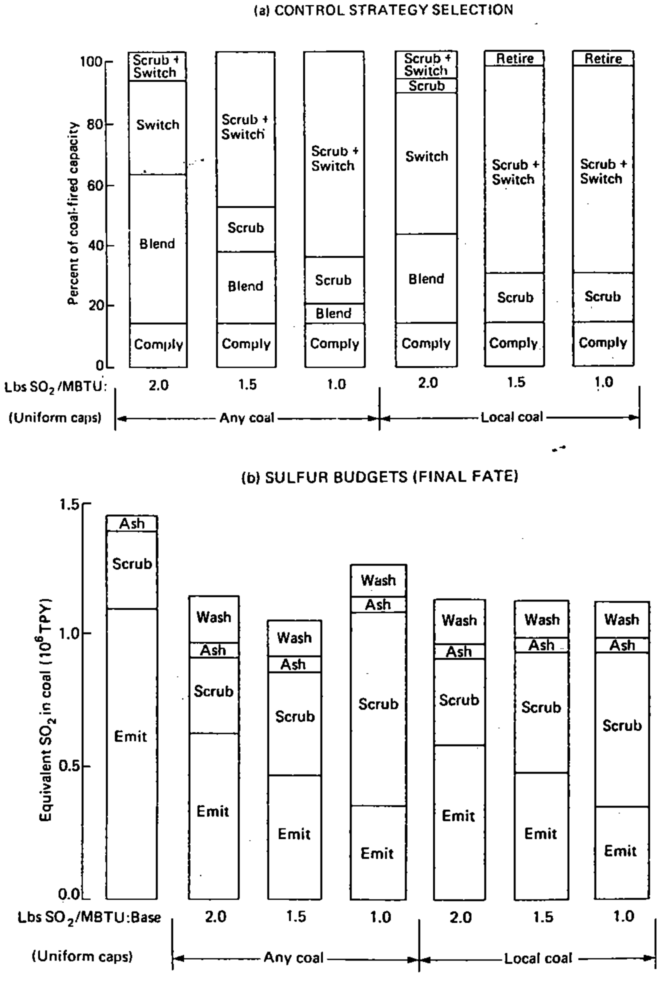

Figure 2. Modeling results for emission reduction scenarios in Pennsylvania.

Table IX. "Basic preparation" assumptions.

State	Plant level[a]	Basic yield (Y_B)[b]
Alabama	3	70
Arizona	1	98
Arkansas	1	98
Colorado (N)	2	90
Colorado (S)	1	98
Illinois	2	85
Indiana	2	85
Iowa	1	98
Kansas	2	85
Kentucky (E)	3	80
Kentucky (W)	2	85
Maryland	3	70
Missouri	1	98
Montana	1	98
New Mexico	1	98
North Dakota	1	98
Ohio	2	85
Oklahoma	1	98
Pennsylvania	3	80
Tennessee	3	70
Texas	1	98
Utah	2	90
Virginia	3	70
Washington	2	80
West Virginia	3	75
Wyoming	1	98

[a] Level 1 = crushing and breaking.
Level 2 = specific gravity separation of top sizes.
Level 3 = specific gravity separation of top and mid sizes.
[b] Tons out as percentage of tons in.

cent and zero washing costs. Such data, however, are not normally available. In the AUSM, characteristic coals were defined from the U.S. Department of Energy Demonstrated Reserve Base (DRB), which generally reflects seam quality properties. The USBM washability data base also refers to seam quality coal. This, however, is generally of higher quality than run-of-mine coal, which usually includes considerable quantities of noncombustible material picked up during the mining process. Furthermore, typical utility coal, particularly in the eastern U.S., usually has been subjected to some degree of preparation prior to delivery. It is this level of preparation which should be the baseline measure assumed for purposes of modeling.

For the AUSM the following approach was adopted. The characteristic coals from the DRB were assumed to have been subjected to some degree of "basic preparation," characteristic of the producing region. This is assumed to have involved removal of ash and extraneous material sufficiently to enable the coal to compete in the market. Because sulfur removal has not been an objective to date, coals in different sulfur categories within the same supply region are assumed to be subject the same degree of basic preparation. The consequence of this will have been to restore, approximately, the qualities of the coal in the seam. This enables the DRB coals, the coals actually sold on the market, and the coals in the USBM washability data base to be seen as part of a coherent framework. The washing equations which have been derived may then be applied when characteristic coals are washed to further improve their seam properties.

This approach does require the definition of basic preparation characteristics in each coal supply region. Estimates were made using data on current preparation practices published by the U.S. Energy Information Agency.[13] Results are shown in Table IV. These assumptions, plus the cost algorithms defined by Equation 19, are applied to the characteristic coals on the diagonal of the triangular matrix to estimate the run-of-mine coal volume and cost. Raw coal costs are then used as the starting point for estimating the cost of coal preparation beyond the "basic" level assumed for each supply region. To obtain a realistic yield for deeper cleaning, the yield from Equation 18 is multiplied by the yield associated with basic preparation. Thus:

$$Y_T = Y \times Y_B \qquad (23)$$

This allows for the difference between DRB and run-of-mine coal qualities, and effectively assumes that the deeper cleaning (linked to the USBM washability data base) occurs subsequent to basic preparation. The revised cleaning yield, Y_T, is then used in Equations 20 and 22 to obtain an estimate of the final washed coal cost.

Coal Washing in a Simulation Model Framework

Among states relying extensively on coal for electric power production, Pennsylvania also ranks high as a major producer of coal, with significant interest in the potential for increased coal washing. To illustrate the use of the coal cleaning model, we look at the role of coal cleaning for six hypothetical scenarios requiring increasing levels of SO_2 reduction from Pennsylvania utilities by 1995. These scenarios require individual plants to meet increasingly tighter emission caps of 2.0, 1.5, and 1.0 lb $SO_2/10^6$ Btu, or current state standards (whichever are more stringent), thus reducing overall SO_2 emissions by 10 percent to 40 percent below 1980 levels. The first three cases allow utilities to have an unconstrained choice of U.S. coals, while three additional scenarios restrict the coal choice to only "local coals" produced with the state.

The analysis was carried out using the Utility Control Strategy Model (UCSM),[12,14] which is similar in nature to the AUSM and uses the identical coal washing algorithms. For plants subject to individual SO_2 emission standards, the model examines alternative strategies at the plant or unit level and selects the one with the lowest levelized cost over the remaining life of the facility. For cases involving regional emission reductions, the site-specific analysis is used to construct a marginal cost curve which determines the least cost strategy for a collection of plants. The strategies available at the unit level include no action (for plants that already comply), coal-switching, coal blending, retrofitting an FGD system with the current coal, scrubbing an alternative coal (scrub/switch), or retiring the plant ahead of schedule.

Figure 2(a) summarizes the abatement strategies chosen for each of the six uniform emission cap scenarios. Note that the total capacity shown for plants choosing FGD includes many cases where only partial scrubbing is employed to meet the standard. As the emission cap becomes tighter there is an increasing move toward scrubbing, often in combination with coal switching (to coals of either higher or lower sulfur content). The switching, blending and scrub/switch options all may involve the use of washed coal. For the scenarios with an unconstrained coal choice, two-thirds of the coals selected were washed for sulfur removal for the 2.0 lb cap, falling to one-third for the 1.0 lb cap. For the "local coal" scenarios, the contribution of washed coals was higher, never falling below 65 percent at any level of abatement. In all cases, coal washing had the lowest average cost of sulfur abatement per ton of SO_2 removed.[15] The average sulfur reduction of the washed coals selected by various plants was on the order of 10 percent.

The role of coal cleaning in reducing atmospheric emissions is illustrated in Figure 2(b). The final fate of all sulfur mined with the coal is shown as reporting either to the atmosphere (emit), the scrubber solid waste (scrub), the boiler bottom ash (ash), or the coal cleaning plant waste (wash). In the 1995 base case, nearly 80 percent of the sulfur mined is emitted to the atmosphere as SO_2. For the emission reduction scenarios, coal washing contributes 28 percent of the SO_2 reduction for the 2.0 lb cap and 11 percent for the 1.0 lb cap. Note that in the 1.0 lb cap scenario with free coal choice more total sulfur is mined than in the less stringent scenarios. This is because many of the plants unable to comply by coal switching or blending select FGD systems together with inexpensive high sulfur coals to minimize the overall cost in that scenario. In the local coal scenarios the total sulfur mined remains relatively constant, with emissions reduced through increased use of scrubbing.

The feasibility of a mandatory coal cleaning requirement also has been examined using the coal cleaning model to test the effects of a hypothetical regulation requiring a minimum level of sulfur reduction, with allowances for coals not readily amenable to washing. Details of the analysis are presented elsewhere.[15] The conclusion, however, is that such a requirement would be ineffective, serving only to raise coal cleaning costs while providing no significant benefits in terms of additional emissions reduction.

Conclusion

This paper has presented results of multivariate regression models developed to estimate the properties and cost of U.S. coals washed for varying degrees of sulfur removal using commercially available physical coal preparation processes. The models are intended for use in cases where detailed coal washability data and preparation plant performance models are unavailable, or where the computational burden of "processing" individual coals through a detailed plant model is prohibitive. Within this context, the methodology developed here is believed to incorporate several important improvements over past methods for estimating coal washing potential by using more realistic models of preparation plant performance, in conjunction with a comprehensive data base of coal washability characteristics. Use of the regional regression equations within the framework of more comprehensive utility and coal market models then allows the economic potential of coal cleaning to be assessed relative to other means of reducing sulfur emissions from coal combustion, without the need for *ad hoc* assumptions regarding preparation plant performance. Case studies show that in conjunction with other methods of sulfur control, coal cleaning frequently may contribute to the most cost-effective means of achieving emission reductions from coal-fired power plants.

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