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PRE-COMBUSTION REMOVAL OF ASH-FORMING MINERALS FROM COAL AT PULVERIZED COAL FIRED POWER PLANTS©

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Abstract

This paper presents results of in-plant measurements of mineral fractions circulating inside operating pulverizers. We will also present results obtained in operation of a 3000 Lbm/Hr beta prototype MagMill™ (patent pending). The MagMill™, a pulverizer that has been retrofitted with a magnetic separator, is a dry method for pre-combustion removal of hard and abrasive inorganic impurities from coal. A concentrated stream of the inorganic minerals is withdrawn from the pulverizer and processed by the magnetic separator. Cleaned coal is recovered and returned to the pulverizer for grinding to specification; concentrated minerals are rejected. The method is specific to iron pyrite which is one of the hardest and most abrasive minerals in coal. The MagMill™ is capable of efficient removal of all minerals from coal which liberate in sizes coarser than 200 mesh; measurements will be presented showing removal of minerals from an operating pulverizer which were not removed in deep cleaning at the mine.

Introduction

Minerals in coal have an adverse effect on plant performance. They can control energy consumption and limit throughput of the pulverizer; they cause slagging and fouling problems along the combustion train and are responsible for some of the hazardous emissions from the plant. The hard minerals in coal cause abrasive wear[1] in the pulverizer and in all downstream equipment touched by the coal. These minerals include iron sulfides which lead to approximately half of the sulfur emissions from eastern U.S. power plants. These sulfides cause burner problems and aggravate water wall wastage in plants equipped with low NO_x burners. Trace metals such as mercury, arsenic and selenium, which are carried with the inorganic component of the coal, create problems for the utility in managing its toxic release inventory. Additionally, arsenic poisons SCR catalysts used to remove NO_x from the flue gases.

The result of burning coals with included minerals is an increased bus-bar cost of electricity. Figure 1 shows the relationship between ash content and forced outage ratio (F.O.R.) for the TVA system from 1963 –1977.[2] The detrimental effect of burning coals with high ash levels is apparent.

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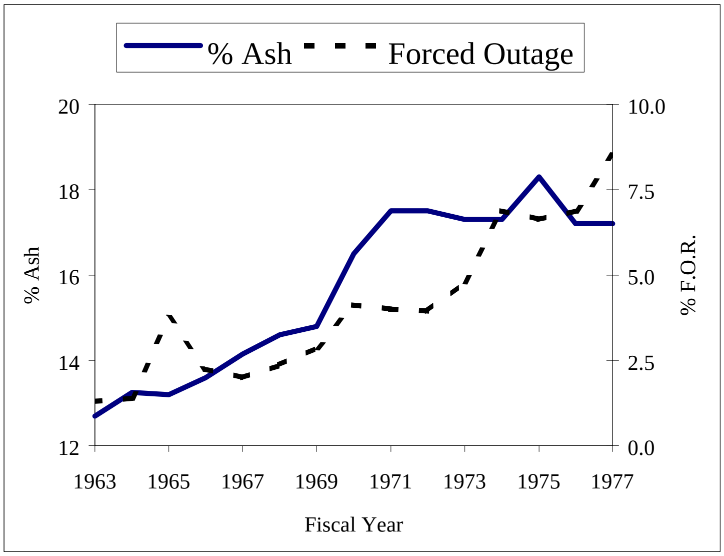


Figure 1. Relationship between Ash Content and Forced Outage Ratio at TVA, 1963-1977

Philips and Cole[3] published a methodology for estimating the cost of burning coals with ash-plus-sulfur contents greater than 12.5% . While this method is an underestimate by current standards and ignores the effects of different mineral types, it does serve to focus the relationship between minerals in coal and important factors such as plant availability, forced outage ratio, maintenance, etc. Now we must add the cost of sulfur emissions, water wall wastage in plants with low NO_x burners, toxic release inventory, SCR catalyst poisoning, etc. Further, there is mounting evidence that the hard and abrasive minerals which concentrate inside the pulverizer are especially problematical.

Coal Cleaning

Out-of-seam rock is a source of minerals in coal that was a major concern of Philips and Cole. At the mine, this rock is normally produced along with the coal when using modern mining methods. It is removed from coal before shipment using relatively simple and inexpensive water-based operations at the preparation plant. In-seam minerals, however, are more difficult to remove using conventional coal cleaning technology because of the very broad range of particle sizes in which they occur in the coal matrix. The in-seam minerals also contribute to the loss of plant efficiency. Additionally, they also carry the bulk of trace metals in coal, especially hazardous air pollution precursors such as mercury, arsenic, and selenium. Most bituminous coal must be ground finer than 30 mesh (.069 mm) for efficient separation of in-seam minerals and their associated trace metals but this is not practical for wet cleaning at the mine mouth because of the cost of dewatering coal fines.

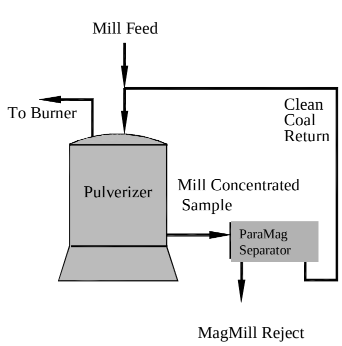
Coal is ground dry into the 200 mesh (74 micron particle diameter) size range at the pc-fired power plant to improve combustion characteristics. Pulverized coal presents an opportunity for dry separation of the inorganic minerals before combustion. While technology exists, prior attempts at dry cleaning pulverized coal have been unsuccessful largely because of cost and infrastructure problems.

The MagMill™

The MagMill™, which is a pulverizer and dry separator operating together, is a method for removing inorganic impurities from coal at the power plant. A high volume stream rich in inorganic minerals is withdrawn from the pulverizer and processed by the magnetic separator as shown in Figure 2. Clean coal is recovered by the separator and returned to the pulverizer for grinding to specification; concentrated minerals are rejected. In this fashion, inorganic minerals including sulfur and trace elements are removed from the pulverizer before they are overground; similarly, their concentration is reduced in the pulverizer output.

The advantages and benefits are summarized in Figure 2. The process improves plant performance by selectively removing hard and abrasive minerals from the pulverizer before they are overground. The energy draw is reduced and the pulverizer throughput is simultaneously increased. Abrasive wear is reduced in the pulverizer and in all downstream equipment that is touched by the coal. The magnetic separator preferentially rejects iron sulfides. Lowering levels of iron sulfides to low NO_x burners reduces burner- tip fouling and water wall wastage problems. Sulfur emissions are lowered and downstream catalyst poisoning in catalytic reactors is reduced. Entities associated with the iron sulfides, such as trace elements, are also separated.[4] Coal dependent, the net gain for the power plant can be significant. It is estimated that Eastern U.S. pulverized coal fired power plants can save between $2 and $4 per ton of coal burned and pay out the retrofit in less than two years. For a 2000 MW plant burning bituminous coal the net savings can be $15 million per year.

FEATURE **ADVANTAGES** **BENEFITS**



ADVANTAGES	BENEFITS
More effective than conventional coal cleaning	Improves Plant Performance by: Increasing pulverizer throughput Reducing: Power draw, Water wall wastage Maintenance, Plant down-time
Separation of hard & abrasive minerals	Mitigates Emissions by: Reducing: Sulfur emissions, Unburned carbon Hg, As, Se
No water	Widens choice of coals by: Lowering fuel costs
No additives	Net savings/Ton (1999$) Utility: $2-$4; Blast Furnace: $6-$8
No storage	
No transportation	

Figure 2. Feature, Advantages and Benefits of the MagMill™

MagMill™ Concept. Coal is pulverized to reduce the particle size which improves combustion characteristics. A variety of mills are employed in power plants; a Babcock & Wilcox MPS 89 shown in cut-away view in Figure 3 is used here as an example. This is an air swept mill producing coal which is 70% to 80% finer than 200 mesh or 74 microns. Coal is fed onto the surface of a rotating table in the grinding zone where it is crushed as the table rotates underneath large and heavy tires. Hot air blown into the grinding zone around the inside circumference of the pulverizer lifts the fine particles produced in the grinding and conveys them to the top of the mill which houses a static classifier. There, oversize particles are returned to the grinding zone and the fines are blown through pipes to the burners. There is a continuous stream of particles circulating inside the pulverizer which carries oversize particles back to the grinding zone. Hard minerals carrying sulfur and trace metals concentrate in this stream on the basis of hardness and density.

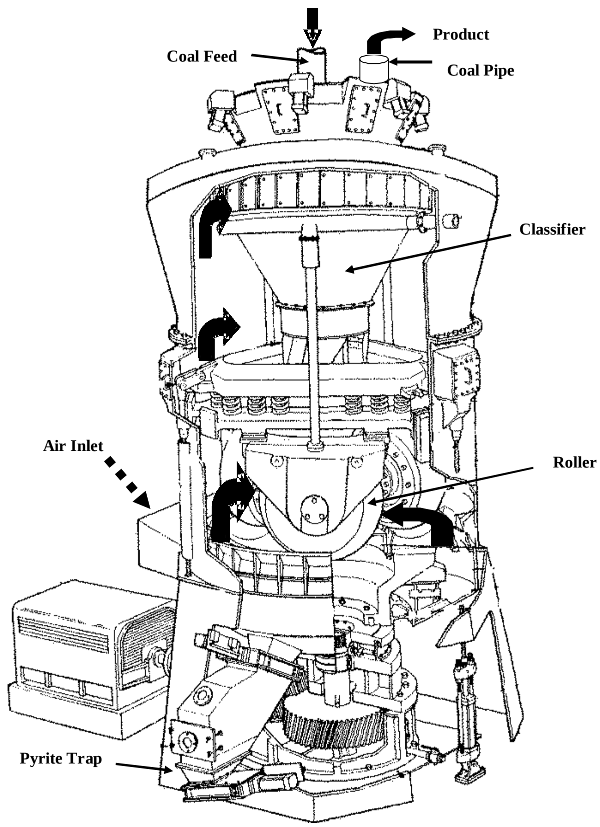


Figure 3. B&W MPS 89 Mill

Minerals, especially iron sulfides and quartz, are generally the hardest components of coal. A portion of these minerals is withdrawn from the internal circulation of a MagMill™ and is sent to a dry beneficiation stage for rejection of the minerals and recovery of the carbon for return to the mill.

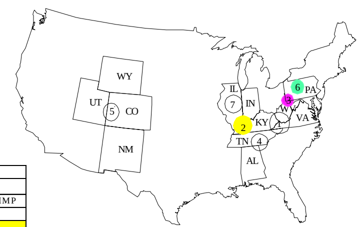
This and other air-swept mills employ pyrite traps, such as that shown in Figure 3, to protect the mill from damage. A very small amount of coarse, dense material is withdrawn through the traps, typically at a rate less than 0.1% of that of the feed to the mill. This is not enough material to improve the quality of the mill product but it does protect the mill from damage by large pieces of metal such as rail spikes and other debris coming in with the coal feed. For the MagMill™, however, high ash coal is withdrawn at rates typically 30% of that of the feed for the MagMill™. This is enough material for the magnetic separator to make a marked improvement in the quality of the product.

Coal Testing

Figure 4 shows the results of testing over 70 coals from throughout the US for response to the MagMill™. Forty-five of the coals were supplied by one utility. Approximately 58 of these coals were tested for response to dry magnetic separation alone. This is shown as survey testing, **S**, in Figure 4. These measurements were equivalent to magnetic separation of feed to the pulverizer. In this mode of testing all coals exhibited consistent and good reductions in ash, whereas many coals did not respond well to sulfur reduction. Eight coals have been sampled from inside operating pulverizers at power plants in Pennsylvania, West Virginia, Illinois, and Ohio. The pulverizer throughputs ranged from 16 to 51 TPH. The coals, identified as Mill Concentrated Samples, **MSC**, respond better to reductions in sulfur than do the survey samples because the mill is providing a sample concentrated in sulfur. Four coals have been tested in prototype MagMills, **MMP**. They generally show the best sulfur removal. Ash reductions by this method can be less than for the survey coals, however, because the MagMill™ does not separate soft and friable minerals such as clays which do not concentrate inside the mill.

Twelve of the survey measurements, three of the pulverizer samples, and 2 of the prototype samples have also been tested for trace metals. Results for mercury are shown in the table. The average reduction in mercury is 51% for the MagMill™ products. The MagMill™ product has fewer pounds of mercury per TeraBtu* than either the survey or the mill concentration samples.

* TeraBtu = 10^{12} Btu



Coals for which Btu Recovery and Ash and Sulfur Reduction Have Been Studied

	Number of Test Coals			Btu Recovery, %			Reduction, %								
							Ash			Sulfur			Lbs. SO_2/MBtu		
Region	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP
1	12			89			32			7			13		
2	21	1	1	89	87	97	32	27	41	9	37	26	16	40	
3	6	4		95	88		25	34		6	39		6	43	
4	1			82			26			5			7		
5	9	1		91	95		26	36		13	60		16	62	
6	6	2	3	88	83	93	41	29	33	26	34	29	36	44	38
7	3			85			17			9					
Number	58	8	4												
Average				89	87	94	30	32	35	11	40	28	16	45	38

Coals for which Reduction in Mercury Has Also Been Studied

	Number of Test Coals			Btu Recovery, %			Reduction, %											
							Ash			Sulfur			Lbs. SO_2/MBtu			Lbs. Hg/MMBtu		
Region	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP	S	MSC	MMP
1	1			93			33			21			25			57		
2	5			87			40			16			23			38		
3	3	1		94	94		33	24		9	36		18	41		44	42	
4	0																	
5	2			94			23			35			37			45		
6	1	2	2	94	83	92	26	29	33	31	34	32	36	44	38	35	45	51
7	0																	
Number	12	3	2															
Average				91	87	92	34	27	33	19	35	32	26	43	38	42	44	51

S = Survey Coal
MSC = Mill Concentrated Sample
MMP = MagMill Product

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Figure 4. Results of Coal Testing

Beta Prototype MagMill™

During the summer of 1999 a beta prototype MagMill™ was installed and operated at the Bradley Pulverizer Company pilot test facility in Allentown, PA. The prototype, shown in Figure 5, consisted of a skid-mounted one ton per hour ParaMag™ magnetic separator retrofitted to a 3000 Lb/hr Hercules air swept ring/roller pulverizer with static classifier attached (See Figure 5). The MagMill™ prototype was tested to demonstrate sulfur and ash removal from 10 tons each of two raw coals from North Central Pennsylvania: Upper Freeport from Clarion County and Lower Kittanning from Clearfield County. Measurements of mill power consumption and throughput to produce products of 70 – 80% finer than 200 mesh size were made. Although the prototype MagMill™ was not optimized due to limited time, several runs were made on each coal to verify results and to test mill and coal parameters. The results of one run for each coal are summarized in the following. Details are given elsewhere.[5]

Run #6 for the Upper Freeport coal had a 91% Btu recovery while Run #4 for the Lower Kittanning coal had a 94% Btu recovery. These are typical results achieved with the unoptimized prototype testing. They are neither the best nor the worst. When operating at these conditions, the MagMill™ prototype increased the throughput 9% and 12% and decreased the power draw 26% and 12% for the Upper Freeport and Lower Kittanning coals respectively.

Figure 5. Beta Prototype MagMill™

Ash and Sulfur Levels, Beta Prototype MagMill™

Table I summarizes results of runs for each of the two coals. All measurements are on a dry basis. It is apparent that the Upper Freeport MagMill™ product contains only 44% of the ash, 39% of the total sulfur, and 20% of the iron pyrites of the feed coal while producing the same number of Btu's. The MagMill™ reduces ash and sulfur, especially pyrites, to the burner.

Table I
Summary of Results Expressed on Lb/MBtu Basis
Beta Prototype MagMill™

	Upper Freeport Run #6				**Lower Kittanning Run #4**			
	Concentration			**Recovery**	**Concentration**			**Recovery**
	Product	**Reject**	**Feed**	**Product**	**Product**	**Reject**	**Feed**	**Product**
	Lb/MBtu			**%**	**Lb/MBtu**			**%**
Ash	7.2	17.0	16.3	44.1	10.4	12.9	17.3	60.2
Sulfur	0.9	2.6	2.2	39.1	2.7	3.7	4.6	58.0
Pyritic	0.2	1.9	1.2	20.0	1.8	2.7	3.2	56.3
Sulfate	0.0	0.0	0.0		0.0	0.0	0.0	57.3
Organic	0.6	0.7	1.0	61.1	0.9	1.0	1.4	61.9
HGI				68				78

Ash Chemistry, Beta Prototype MagMill™

The effects of MagMill™ treatment on the ash-fusion temperatures are shown in Table II. Selected ratios determined from ash chemistry are given in the bottom portion of the table. Measured increases in ash fusion temperatures are particularly significant for the Upper Freeport coal.

Table II
Effects of MagMill™ Processing on Ash Fusion Temperatures
Beta Prototype MagMill™

	Upper Freeport Run #6 Temperature, Deg. F			**Lower Kittanning Run #4 Temperature, Deg. F**		
	Product	**Feed**	**Reject**	**Product**	**Feed**	**Reject**
Initial Deformation	2599	2228	2092	2328	2318	2338
Softening	2692	2400	2215	2414	2476	2555
Hemispherical	2700+	2510	2376	2505	2525	2606
Fluid	2700+	2579	2489	2622	2621	2685
		Ratios			**Ratios**	
Base/Acid*	0.22	0.29	0.34	0.39	0.50	0.63
Silica/Alumina *	2.0	2.2	2.3	1.8	2.0	2.3
Iron/Calcium	2.9	5.9	14.4	14.5	20.0	68.3
Iron/Dolomite	2.2	4.2	8.3	10.3	13.6	29.4
Dolomite Percentage	26.1	16.1	9.6	8.4	6.4	3.1
Total Alkalies	3	4	3	1	2	2

Trace Metals in MagMill™ Products

Table III compares measurements of the trace metals in the MagMill™ feed and products for the two coals. The trace metals are sorted by recovery in the table. On an equal Btu basis, the MagMill™ product sends only 32.7 % and 43.8 % of the mercury in the feed coal to the burner for the Upper Freeport and Lower Kittanning coals, respectively.

Table III
Trace Metal Measurements
Beta Prototype MagMill™

	Upper Freeport Run #6				Lower Kittanning Run #4				
	Concentration			Recovery		Concentration			Recovery
	Product	Reject	Feed	Product		Product	Reject	Feed	Product
	Lb/TeraBtu*			%		Lb/TeraBtu*			%
Thallium	28.4	176.3	117.5	24.2	Thallium	27.6	90.1	72.1	38.2
Arsenic	1087.4	5877.5	4073.6	26.7	**Mercury**	14.8	38.0	33.8	43.8
Lead	277.9	1237.4	912.2	30.5	**Arsenic**	309.1	616.7	623.6	49.6
Mercury	10.9	43.3	33.2	32.7	Nickel	483.9	901.4	946.1	51.1
Nickel	561.8	1577.6	1394.4	40.3	Lead	477.1	711.6	849.8	56.1
Selenium	78.5	213.4	191.5	41.0	Manganese	806.4	1186.0	1428.5	56.5
Manganese	1027.0	2629.4	2424.9	42.4	**Selenium**	315.9	379.5	519.6	60.8
Copper	579.9	1392.0	1324.2	43.8	Zinc	1008.0	1186.0	1646.5	61.2
Cobalt	163.1	340.3	347.5	46.9	Molybdenum	134.4	123.3	203.2	66.1
Molybdenum	108.7	167.0	202.5	53.7	Cadmium	8.1	6.6	11.8	68.1
Chromium	1087.4	1051.8	1724.2	63.1	Cobalt	168.0	125.7	240.7	69.8
Zinc	1147.8	1082.7	1806.6	63.5	Chromium	1142.5	782.8	1602.6	71.3
Vanadium	1389.5	866.2	1970.6	70.5	Copper	806.4	545.6	1128.0	71.5
Beryllium	72.5	37.1	98.9	73.3	Vanadium	1142.5	640.5	1535.8	74.4
Cadmium	12.7	4.6	16.4	77.4	Beryllium	54.4	23.5	69.9	77.9
Antimony	13.9	4.9	17.9	77.6	Antimony	13.4	3.1	16.0	84.1

*One Tera = 10^{12} = one million million

MagMill™ Simulation

ETCi is developing a computational model of grinding similar to that of Austin and Luckie.[6] In the ETCi simulator, measurements of the size distribution and quality of coal emerging from the grinding zone are input to the program. Using results of laboratory measurements of magnetic separator performance on mill reject samples, the program calculates the effects of the magnetic separator loop on the quantity and quality of coal produced by the mill. Figure 6 shows the comparison of predictions and measurements of reductions in ash, sulfur, pyritic sulfur, and $LbSO_2$/MBtu for four of the beta prototype runs (represented by different symbols) employing the Upper Freeport coal. A similar comparison is shown in Figure 7 for the Lower Kittanning coal. Only runs for which the product fineness was between 67 and 75% finer than 200 mesh were considered. The runs employed a wide range of mill sampling and magnetic separator operation alternatives. Agreement is encouraging.

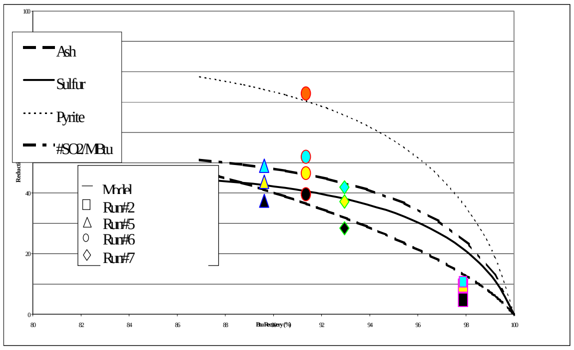


Figure 6
Comparison of Predictions and Measurements
Upper Freeport Coal

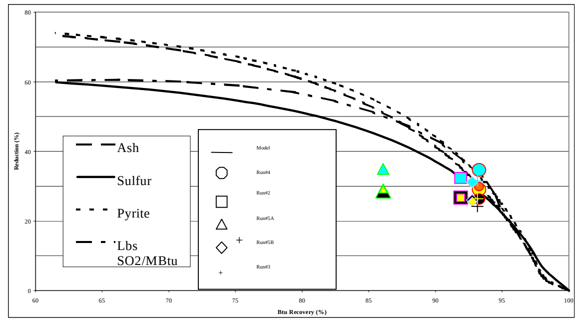


Figure 7
Comparison of Predictions and Measurements,
Lower Kittanning Coal

Pennsylvania Power Plant

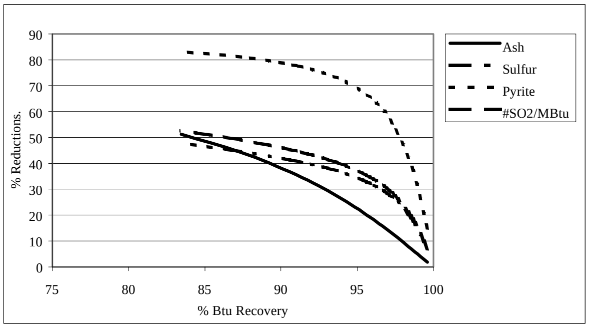
Sampling

Figure 8 shows an ABB-CE Raymond 633 pulverizer instrumented with diagnostic sampling ports. This mill is one of four installed on a nominal 190 MW Unit at a coal fired power station in Pennsylvania. It was processing approximately 13 TPH of a blend of Pennsylvania raw coals at the time of sampling. Samples collected from the mill were taken to ETCi for characterization and magnetic separation.

Figure 8. ABB-CE 633 Mill

MagMill™ Simulation

Figure 9 show the projections for ash, sulfur, and trace metals for the MagMill™ product at the power station in Pennsylvania. Table IV compares values for the case of 94% Btu recovery. The table and figure show how well the magnetic separator removes ash and especially pyritic sulfur from this coal. Only 26% of the pyritic sulfur fed to the mill is projected to enter the product pipes.



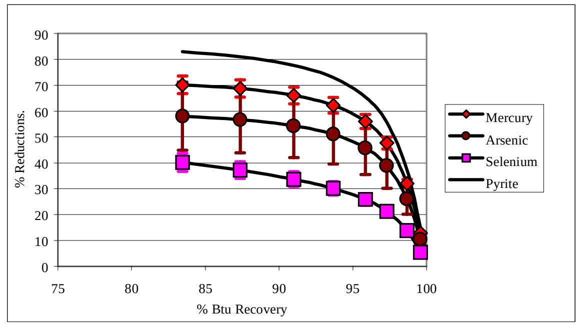


Figure 9. Effect of Btu Recovery on Calculated Product

Table IV
Projected Product, Reject, and Feed Characteristics for a MagMill™
Processing a Blend of Raw Pennsylvania Coals

94% Btu	**Concentration**			**Recovery**
Recovery	**Product**	**Reject**	**Feed**	**Product**
Quantity	**Lb/MBtu**			**%***
Ash	8.02	65.66	11.67	68.74
Sulfur	1.01	10.06	1.69	59.59
Pyritic	0.20	9.11	0.76	26.06
Sulfate	--	--	0.07	--
Organic	0.81	0.95	0.93	86.76
Trace Element	**Lb/10^{12} Btu**			
Mercury	14	349	35	40.3
Arsenic	1069	16472	2045	52.3
Selenium	219	1395	293	74.6

*Lb/MBtu Basis

The change in ash chemistry projected for the MagMill™ at 94% Btu recovery is summarized in Table V. Reductions in iron, ash, pyrites and sulfur are expected to reduce slagging in the boiler.

Table V
Projected Mineral Ash Characteristics per MBtu
for MagMill™ Processing a Blend of PA Coals (Lb/MBtu Basis)

94% Btu Recovery	Concentration			Recovery
	Product	Reject	Feed	Product
Oxide	Lb/MBtu			%*
SiO_2	3.7	27.8	5.2	70.9
Al_2O_3	2.0	13.0	2.7	74.4
TiO_2	0.1	0.8	0.2	73.2
ACID	5.9	41.6	8.1	72.1
Fe_2O_3	1.1	15.6	2.0	54.2
CaO	0.2	0.6	0.2	85.9
MgO	0.0	0.7	0.1	49.4
K_2O	0.1	1.9	0.2	51.3
Na_2O	0.0	0.2	0.0	56.9
BASE	1.4	19.0	2.6	56.4
P_2O_5	0.0	0.3	0.0	60.4
MnO_2	0.0	0.0	0.0	59.3

The simulator projects a maximum increase in throughput of 22% for the coal blend. After accounting for the 94% Btu recovery, it is estimated that 17% more Btu's will go to the boiler, offering the possibility of generating an additional 180,000 MW-Hr/year. If this power could be sold at $25/MW-Hr, then an additional $4.5 million of revenue could be generated each year by the four pulverizers on the plant unit.

Ohio Power Plant

Figure 10 illustrates measured reductions achieved for dry magnetic separation of a mill concentrated sample of deep cleaned Pittsburgh seam coal taken from an MPS 89K mill at an Ohio power plant. The sample taken from the operating pulverizer was highly concentrated in ash forming minerals. These are minerals which were not removed at the coal preparation plant. Iron pyrite was especially high in concentration. As can be seen in Figure 10, mercury appears to be more closely related to iron pyrite than are arsenic and selenium.

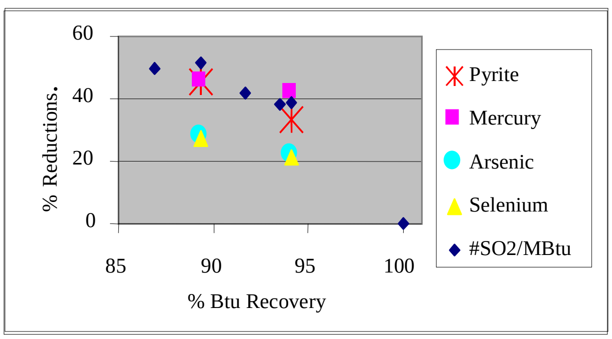


Figure 10. Magnetic Separation of Mill Concentrated Sample

Based on these measurements, reductions for a MagMill™ installation at this power plant are projected in Figure 11 where the relationship of pyrite and mercury is apparent. The projected mercury reduction is nearly 40% and the projected pyrite reduction is nearly 50% at greater than 95% Btu recovery. Arsenic and selenium are projected to associate more closely with the total ash of the coal.

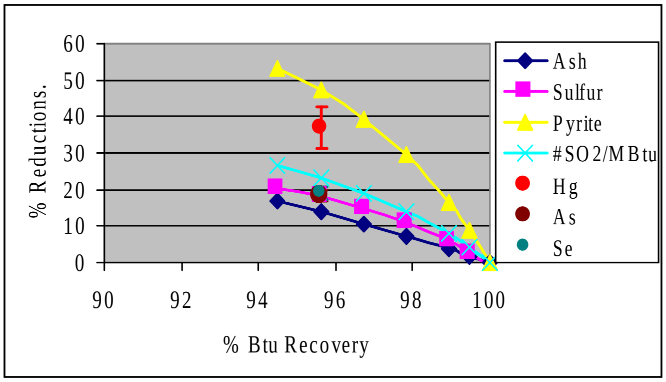


Figure 11. Ohio Plant Simulated MagMill™ Product

Table VI shows simulated MagMill™ performance for the pulverizer. The data project a 55% reduction in pyritic sulfur at the 94.5% Btu recovery level. Mercury, arsenic and selenium are reduced 42%, 38%, and 35%, respectively. Even though the heat content of the MagMill™ reject is high, there is very little of this material and it carries high concentrations of pyrites and associated trace metals.

Table VI
Simulated MagMill™ Performance for Pittsburgh Seam Coal*

	Ash	Sulfur	Pyritic Sulfur	Heat Content	**Mercury**	**Arsenic**	**Selenium**
	Lb/MBtu			Btu/Lb	Lb/TBtu		
Pulverizer Feed	5.6	1.7	0.73	13,960	19	240	100
Simulated MagMill**							
Product***	4.8	1.3	0.33	14,000	11	150	65
Reject	23	9.7	7.6	11340	160	1800	750

TBtu = TeraBtu = 10^{12} Btu
* Simulated MagMill™ numbers calculated, all other numbers measured
** Treatment Rate = 40% of Mill Feed Rate
***93.4% Weight Recovery, 94.5% Btu Recovery

Summary of Results

- Coals taken from inside pulverizers have high concentrations of:
  - Ash forming minerals, especially iron sulfides.
  - Trace metals, especially mercury, arsenic, and selenium.
- MagMill™ technology separates ash, pyritic sulfur, and trace metals from coals withdrawn from pulverizers.
- MagMill™ simulation indicates that a MagMill™ treated coal (expressed as Lb/MBtu):
  - Has 30% - 40% less SO_2
  - Has 30% - 45% less ash
  - Has 70% - 85% less pyritic, and
  - Has 40% - 60% less mercury.
- MagMill™ products have high ash fusion temperatures.
- Increases in pulverizer throughput between 10% and 25% are possible. A 1200 MW plant can generate $18 million new revenue annually.

Acknowledgements

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