The Co-Benefits of Pre-Combustion Separation of Mercury at Coal-Fired Power Plants

Paper Number: 990

Prepared by Robin R. Oder

EXPORTech Company, Inc., P.O. Box 588, New Kensington, PA 15068-0588

ABSTRACT

Coal has traditionally been cleaned at the mine to remove rock and other coarse mineral contaminants. These contaminants increase transportation costs and, when burned, cause power plant operational problems such as boiler slagging and down-stream fouling. Tightening environmental emissions controls have now caused conventional mine-mouth coal cleaning technology to be extended to wet cleaning of sub-millimeter coal fractions which were previously discarded. However, for most coals, effective mineral liberation for separation by physical means requires grinding to substantially below 74 microns.[1] This is not economically feasible at the mine.

This paper presents results obtained in pilot scale cleaning of Upper Freeport seam coal from north central Pennsylvania employing a unique dry processing technology, the MagMill™ which combines the operation of the pulverizer and a dry electric/magnetic separator at the front end of the coal-fired power plant. Based on extrapolation of results achieved in the pilot scale testing, we will illustrate the estimated value of co-benefits of pre-combustion MagMill™ cleaning for a 500 MW unit at bituminous-coal fired power plants with and without flue gas scrubbers to meet the Clean Air Mercury rule issued in March, 2005.

INTRODUCTION

Statistical analyses of the Tennessee Valley Authority (TVA) coal-fired power generation system in the mid 1970's quantified the cost of operational problems associated with burning raw coals with ash and sulfur levels in excess of design limits.[2] These costs, recently reviewed in the Journal of the Coal Preparation Society of America,[3] are significant. For example, plants burning coals with ash and sulfur levels ranging from 10% to 16% over design values can expect to incur extra operational costs ranging from \$1.4 to \$2.0 per ton coal burned [equivalent to \$0.6 to \$0.8 per Megawatt Hour generated (in 1978 dollars)] for problems associated with ash disposal, transportation, maintenance, loss of peaking capacity, loss of plant rating, and losses associated with decreased availability, all adding to the cost of generating power. These costs grow as the ash and sulfur levels in the feed coal increase from design values. The analysis, however, was carried out prior to wide scale use of post-combustion emissions controls for sulfur and nitrogen oxides which also bring additional costs. The cost to control mercury emissions has recently been added to this list.[4]

The cost of controlling emissions can be very large compared to the cost of operational problems. For example, purchase of emission allowances at $710[5] per ton of SO_2 can add $14 to the cost of burning a ton of 1% sulfur coal. Additionally, the cost of post-combustion removal of 90% of mercury from a coal with 0.1 ppm mercury, now estimated to be up to $70,000 per pound of mercury,[6] can be expected to add an additional $13 per ton of coal burned. Sulfur, ash, and trace metals are all introduced into the system through minerals inherent in the coal burned and, as can be seen, their levels need not be as high as levels suggested in earlier work to cause significant escalations in the cost of burning coal.

Coal/mineral-caused interactions between emissions control technologies and plant operations can also bring additional costs comparable to, if not greater, than those identified in the earlier work at TVA. An example lies in those minerals in coal which cause operational problems such as slagging and fouling while also contributing pollutants, i.e., sulfur, and hazardous trace metals. The chalcophile elements,[7] especially Zn, Cd, Hg, Cu, Pb, As, Sb, and Se, commonly form sulfide minerals and trace amounts of these elements are expected to be found in association with sulfide minerals. The importance of this lies in the fact that the sulfide mineral, FeS_2, iron pyrite and marcasite, is the major source of mineral sulfur in eastern US bituminous coals, contributing about 50% of the total sulfur. As can be expected, hazardous trace metals of importance such as mercury and arsenic can be closely associated with this mineral.[8] Additionally, sulfides and carbonates are major sources of slagging problems in boilers. Iron acts as a fluxing agent lowering the fusion temperature. Additionally, iron pyrite in coal can cause water-wall wastage in boilers fitted with low NO_X burners while the arsenic in coal poisons catalysts employed in catalytic NO_X control devices. Each million dollars spent on mineral related problems can be viewed as adding about $0.4 to the cost of burning a ton of coal at a 1,000 MW plant which is equivalent to increasing the cost of generation by about $0.2 per MW-Hr.

Pre-combustion coal cleaning is a practical way to limit the concentration of inorganic contaminants in coal and thus improve the reliability of electricity supply while lowering emissions.[9] Indeed, environmental regulations of the 1970's led more coal cleaning at the mine to improve coal quality to lessen sulfur emissions in lieu of installing flue gas desulfurization systems. As a result, the use of pre-combustion coal cleaning grew in the 1970-1980 decade. Coal cleaning at the mine was originally developed to remove the non-carbonaceous overburden and seam floor taken to assure efficient recovery of the carbon component. This material is denser than coal and is of a relatively coarse size, making its removal at the mine by wet means simple and inexpensive. Separation of in-seam minerals such as iron pyrite for sulfur reduction, however, presents a challenge because of the wide size distribution[10] and particle associations in which these contaminants occur in the coal seam. It is ironic that conventional water-based physical coal cleaning at the mine has arguably reached a point of diminishing returns at a time when flue gas scrubbers for sulfur and nitrogen emissions controls are in wider use. Indeed, the cost of grinding to liberation to separate mineral contaminants using water based technology, the cost of dewatering, and technical problems associated with transportation of fine coal outweigh the benefits of advancing this level of cleaning at the mine. This plus the increased emphasis on reducing fuel procurement costs provide a justification to revert to coals of higher ash and sulfur levels, thus removing the emphasis on further development of advanced pre-combustion coal cleaning. Combined physical and chemical methods offer great potential for preparing clean burning coal but in the mid 1970's they were judged to be too expensive for the utility market.[11] This may be changing with today's high cost of emissions control.

The MagMill™ technology to be discussed below [U.S. Patent 6,820,829 (November 23, 2004)] combines a pulverizer and continuously operating dry magnetic separator working together at the power plant in a novel manner to remove the in-seam minerals before combustion. By combining physical separation with the pre-combustion pulverization already practiced at the generating station, the cost of grinding to liberate the in-seam minerals does not pose an economic obstacle. Further, this is a dry operation so dewatering is eliminated. The product is blown directly into the burner, removing transportation and storage considerations.

It must be noted that the MagMill™ does not work for all coals. The coals must respond to magnetic forces, i.e., they are made weakly paramagnetic because of mineral inclusions,[12] and the mineral inclusions must liberate at sizes coarser than 200 mesh. In the U.S. market, Eastern bituminous coals are the best candidates, but it has been shown that lignites and some sub-bituminous coals can be processed magnetically as well.[13] For those coals which do respond to magnetic forces, this novel concept offers a practical opportunity to prepare clean burning coal in a mode of operation which can lower the cost of controlling emissions while also improving plant efficiency and reliability by pre-combustion separation of mineral contaminants not removed at the mine. Enumerating some of the "co-benefits" accruing to this technology is the purpose of this paper.

DRY COAL CLEANING AT PULVERIZED-COAL FIRED POWER PLANTS

Efficient pre-combustion separation of mineral contaminants, especially minerals such as hard and abrasive iron pyrite which carry mineral sulfur and trace metals, can have dramatic effects on reducing parasitic power draw, reducing abrasive wear, improving plant heat rate and on-line availability. A logical way to remove these minerals is by taking advantage of the mineral liberation which occurs in the grinding operation in the pulverizer. This can be accomplished by retrofitting a dry magnetic separator to the existing pulverizer at the front end of the coal fired power plant. This is called a MagMill™.

Fig. 1. MagMill™ Concept

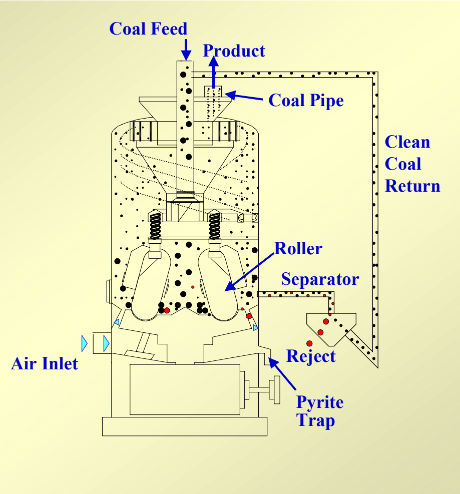


Figure 1 illustrates the MagMill™ concept. It sketches a vertical section through a B&W MPS pulverizer. Feed coal falls onto the grinding table from above. The coal is slung outward as the table rotates beneath the large metal tires which crush the coal as they roll over it. Hot air swirls upward around the outer circumference of the table and carries the fine coal released in the pulverization upward to the classifier at the top of the mill. Oversize coal is returned to the grinding table while the finest particles are blown to the burner.

Hard and abrasive minerals which grind slowly remain in the lower portions of the mill because of their densities.

They make many passes through the grinding zone before reaching the specified particle size for exiting the mill. Since the hard minerals remain inside the mill longer than the soft hydrocarbon, the concentration of these minerals builds up and can reach levels which are many times greater than those in the coal fed to the mill.

The MagMill™ withdraws a portion of the concentrated minerals (the Mill Concentrated Stream, MCS) from the lower portion of the mill through the mill wall and passes it to a dry magnetic separator outside the pulverizer. The separator recovers the carbon and sends it back to the mill for grinding to specification and rejects minerals that otherwise would have gone to the burner. The MCS can be a significant portion of the feed to the mill.

The MagMill™ is different from tramp iron chutes, now called pyrite traps. The objective of the MagMill™ is to improve the quality of coal to the burner. The objective of the pyrite trap is to protect the mill by removing a small amount of hard material such as metal wear from upstream machinery.

Table I illustrates measurements made when extracting mill concentrated stream (MCS) samples at low rates from the inside of operating pulverizers for subsequent processing in the laboratory through a dry magnetic separator. The withdrawal rate was a few percent of the rate of feed to the pulverizer. Two types of pulverizers at three power plants each using different sources of coal were sampled. The CE Raymond mill was in a plant in north central Pennsylvania and operates at nominally 15-20 tons per hour (tph). One 45 tph MPS mill was in an Ohio plant and was grinding Pittsburgh seam coal which had been wet cleaned at a mine in southwestern Pennsylvania. The last mill, located in northern West Virginia, was grinding a blend of 80% washed Pittsburgh seam coal from southwestern Pennsylvania and 20% raw coal from surrounding environs in West Virginia. The sources of the Pittsburgh seam coals are different for the two plants.

Table I. Mineral Concentrations in Feed, Mill Concentrated Stream and Magnetic Separator Reject Withdrawn from Pulverizers.

	Ash	**Sulfur**	**Pyritic Sulfur**		**Hg**	**As**	**Se**
	——— wt.% ———				**—— (ppm) ——**		
CE Raymond 633, Lower Kittanning							
Feed	14	2	1		0.1	27	4
MCS	32	11	9		4	142	13
MS Reject	56	19	17		8	169	18
B&W MPS 89K, Cleaned Pittsburgh Seam							
Feed	8	2	1		0.1	3	1
MCS	21	11	9		2	27	10
MS Reject	53	40	29		7	58	23
B&W MPS 89K, Blend of Raw & Cleaned Pittsburgh							
Feed	8	2	1		<0.1	3	1
MCS	28	10	8		2	29	15
MS Reject	62	20	17		3	58	29

In the table MCS is the sample withdrawn from the inside of the mill and MS Reject is the magnetic separator reject. The quality of minerals and associated trace metals withdrawn from the inside of the pulverizers and rejected by the dry magnetic separator are obvious. The rejected material does not go to the burner – this can have a marked effect on pulverizer and boiler operations! The MS reject is non-hazardous because the minerals are in the stable state in which they occurred in the ground. If the MS reject is disposed, neutralization of the sulfur will be required. Bottom and fly ash from the plant will serve as neutralizers.

In addition to operating alpha and beta prototypes, most major types of pulverizer used in coal-fired power plants in the US have been sampled to study the response of different coals and different pulverizers to the MagMill™ concept. The feed rates of the pulverizers sampled ranged from 15 to 55 tph. Over 70 coals have been processed to determine their response to dry magnetic separation. Additionally, knowledge has been gained in extracting refuse particles from the pulverizers internal circulating stream.

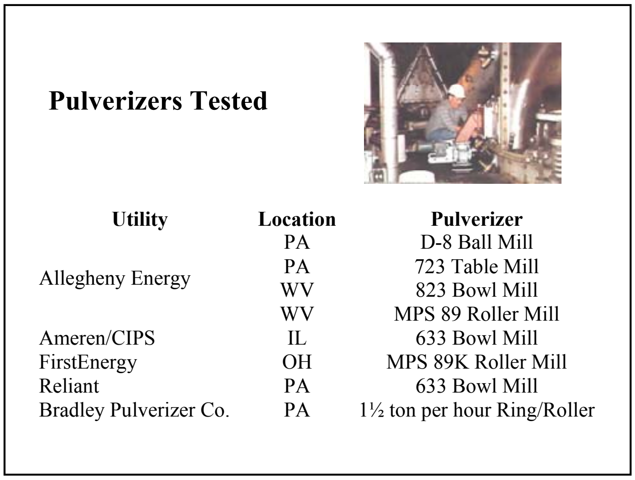


Fig. 2. Pulverizers Tested

Pulverizers Tested

Utility	Location	Pulverizer
Allegheny Energy	PA	D-8 Ball Mill
	PA	723 Table Mill
	WV	823 Bowl Mill
	WV	MPS 89 Roller Mill
Ameren/CIPS	IL	633 Bowl Mill
FirstEnergy	OH	MPS 89K Roller Mill
Reliant	PA	633 Bowl Mill
Bradley Pulverizer Co.	PA	1½ ton per hour Ring/Roller

The US Department of Energy, a group of electric utilities represented by EPRI, and the state of Pennsylvania funded an engineering evaluation, carried out by the Bechtel Corporation, of the cost and feasibility to retrofit a MagMill™ in two generating stations, one in Illinois and one in West Virginia.[14] We have used this evaluation and the results of sampling operating pulverizers to estimate the capital and operating costs of MagMill™ retrofit installations.

RESULTS OF BETA PROTOTYPE TESTING

This presentation illustrates the benefits associated with sulfur and mercury reductions achieved with the beta prototype MagMill™ and, using those results, will estimate cost savings for a hypothetical 500 MW coal-fired plant. A summary of beta-prototype testing is given below; details can be found elsewhere.[15]

Beta Prototype MagMill™

In 1999 a beta prototype MagMill™ was installed and operated at the Bradley Pulverizer Company pilot test facility in Allentown, PA. The prototype consisted of a 3000 lb/hr Hercules air swept ring/roller pulverizer with static classifier attached to a one ton per hour ParaMag™ magnetic separator [U.S. Patents 5,017,283 (May 21, 1991); 5,127,586 (July 7, 1992); 5,176,260 (January 5, 1993)]. 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 were made of mill power consumption and throughput to produce products in the 70 to 80% finer than 200 mesh. Although the 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 Run #6 for the Upper Freeport coal are summarized below.

Figure 3 is a photograph of the prototype. The structure in the background is the 3,000 lb/hr Hercules air-wept ring/roller pilot mill. It is instrumented for automated process control. Feed, air and product rates were continuously measured and controlled. The product particle size was continuously monitored with an on-line laser particle size analyzer. The structure on the skid-mount is EXPORTech's dry magnetic separator (including the power supply and chiller for cooling the electromagnet). Coal is withdrawn from more than one location in the mill and is shipped to the separator via the inclined conveyor. The cleaned product returns to the mill feed via another conveyor and reject is collected underneath the separator.

Fig. 3. Beta Prototype MagMill™

Run #6 for the Upper Freeport coal had a 91% Btu recovery This is neither the best nor the worst but the recoveries and the ash and sulfur reductions are comparable to or better than Level IV coal cleaning.[16] Coal cleaning results achieved in this run are used as the basis for the cost comparison to be made in the section **Co-Benefits**.

Ash and Sulfur Reductions

Table II summarizes results of Run #6. In the table, Product is the MagMill™ product and Reject is discarded. In all tables to follow, the Feed is calculated by mass-balance using the Product and the Reject. All measurements are on a dry basis.

Table II. Summary of Results for Ash and Sulfur Concentrations, Upper Freeport Run #6

	Feed	**Product**	**Reject**
Weight Recovery	100.00	81.72	18.28
Btu Recovery	100.00	91.10	8.90
	(wt.% in Coal)		
Ash	19.78	11.90	55.04
Sulfur, Total	2.68	1.43	8.29
Pyritic Sulfur	1.43	0.39	6.09
Sulfate Sulfur	0.00	0.00	0.02
Organic Sulfur	1.25	1.04	2.18
LbSO_2/MBtu	4.4	2.1	28.1
	Btu/Lb		
Heat Content	12,135	13,528	5,908

Table III presents the above results expressed on a pounds per million Btu basis. It is apparent that the MagMill™ product contains only 44% of the ash, 39% of the total sulfur, and 20% of the iron pyrites of the feed coal on a pounds per million Btu basis. The MagMill™ reduces ash and sulfur, especially pyrites, to the burner.

Table III. Summary of Results Expressed on Lb/MBtu Basis, Upper Freeport Run #6, Beta Prototype MagMill™

	Concentration (Lb/MBtu)			**Recovery (Lb/MBtu)**
	Feed	**Product**	**Reject**	**Product**
Ash	16.3	7.2	17.0	44.1
Sulfur, Total	2.2	0.9	2.6	39.1
Pyritic Sulfur	1.2	0.2	1.9	20.0
Sulfate Sulfur	0.0	0.0	0.0	
Organic Sulfur	1.0	0.6	0.7	61.1

Trace Metals in MagMill Products

Table IV shows results of measurements of the reductions of trace metals achieved in MagMill™ processing for the Upper Freeport coal.

Table IV. Trace Metal Measurements, Upper Freeport Run #6, Beta Prototype MagMill™

Trace Element	**Concentration (Lb/TeraBtu**			**Reduction (%)**
	Feed	**Product**	**Reject**	**Product**
Thallium	117	35	965	73
Arsenic	**4070**	**1330**	**32200**	**70**
Lead	912	340	6770	66
Mercury	**33**	**13**	**237**	**63**
Nickel	1390	687	8630	55
Selenium	**191**	**96**	**1168**	**54**
Manganese	2430	1260	14400	53
Copper	1320	710	7620	51
Cobalt	347	200	1860	48
Molybdenum	203	133	914	40
Chromium	1720	1330	5760	30
Zinc	1810	1400	5920	29
Vanadium	1970	1700	4740	21
Beryllium	99	89	203	18
Cadmium	16	16	25	14
Antimony	18	17	27	13

On an equal Btu basis, the MagMill™ product sends only 32.7 % of the mercury in the feed coal to the burner for the Upper Freeport coal.

CO-BENEFITS

Five different configurations representing combinations of MagMill™ pre-combustion coal cleaning, limestone-forced-oxidation (LSFO) flue gas scrubbing, and pulverized activated carbon (PAC)[17] post-combustion mercury separation are employed to illustrate co-benefits to the upstream technologies of the cost of mercury separation. These configurations are described in detail in the **Results** section below. Measured results obtained in the unoptimized beta prototype MagMill™ testing made using the Upper Freeport raw coal and given in section **Beta Prototype Results** above are used in the analysis. Cost estimates for MagMill™ retrofits are based on the engineering evaluation of the cost to retrofit commercial demonstration units at plants in Illinois and West Virginia. Cost estimates for LSFO are taken from a study by Sargent & Lundy, LLC.[18]

Ash, sulfur, and mercury reductions obtained by the MagMill™ are given above in Tables II-IV. It is assumed that the LSFO unit removes 70% of the mercury and that catalytic NO_X controls are not used.

The costs to operate the MagMill™ and the LSFO scrubber are given as levelized costs. The levelizing factors used in making the capital and operating costs are given in Table V.

Table V. Levelizing Factors

	New Unit	**Retrofit**
Plant Life, years	30	20
Capital cost levelizing factor, %/year	14.5	15.43
Discount rate, %	8.75	8.75
Inflation rate, %	2.5	2.5
Operating cost levelization factor	1.3	1.22

These numbers, developed by Sargent & Lundy, based on utility cost factors for a 500 MW pulverized-coal fired generating station burning Appalachian bituminous coal, have been used to put MagMill™ capital and operating costs, supplying enough coal to generate 500 MW, on a levelized basis, also. The costs for the LSFO are for 2.95% and 1.59% sulfur bituminous coals (see Section on **Results**). The values have been obtained by interpolation and extrapolation from the Sargent & Lundy costs which were for 3% and 1.5% sulfur coals. The values of 2.95 and 1.59 are taken from Federal Energy Regulatory Commission data for November, 2004,[19] and are near matches for values observed in the beta prototype MagMill™ testing with the Upper Freeport coal.

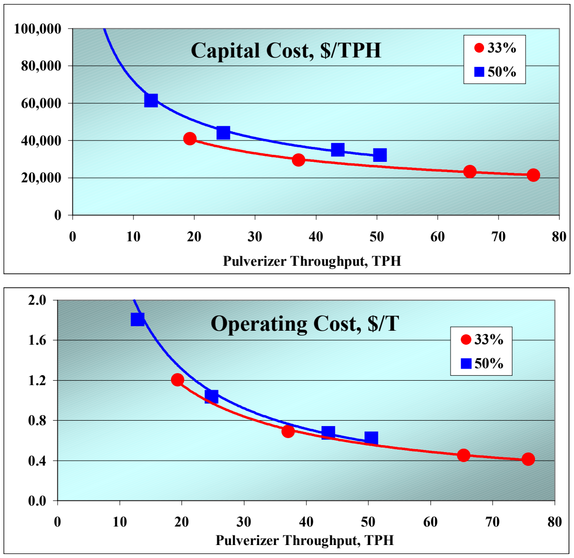
Levelized costs for the MagMill™ and LSFO are given in Table VI for the various options considered.

Table VI. Levelized Costs for the MagMill™ and LSFO

Option 1. No MagMill™, No Scrubber, purchase 1.59 % sulfur coal					
Option 2. MagMill™, No Scrubber, purchase 2.95 % sulfur coal					
Option 3. No MagMill™, New Plant with scrubber, purchase 2.95 % sulfur coal					
Option 4. MagMill™, New Plant with scrubber, purchase 2.95% sulfur coal, scrub 1.59 % sulfur					
Option 5. MagMill™, Existing Plant, retrofit scrubber, purchase 2.95% sulfur coal, scrub 1.59% sulfur					
Option	**1**	**2**	**3**	**4**	**5**
Feed Coal, Tons per year	1,349,697	1,538,529	1,401,600	1,538,529	1,538,529
Sulfur (wt.%)	1.59	2.95	2.95	2.95	2.95
#SO_2/MBtu	2.58	4.96	4.96	4.96	4.96
Hg (ppm)	0.15	0.15	0.15	0.15	0.15
Cost, $/Ton	38.72	29	29	29	29
Capital Costs, $ Million					
MagMill™	0	9.37	0	9.37	9.37
Scrubber	0	0	62.19	53.85	76.69
Total Capital	0	9.37	62.19	63.22	86.07
Levelized Capital Costs, $ Million					
MagMill™	0	1.36	0	1.36	1.36
Scrubber	0	0	9.02	7.81	11.83
Total Levelized Capital Costs	0	1.36	9.02	9.17	13.19
Levelized Operating Costs, $ Million					
MagMill™	0	1.36	0	1.36	1.36
Scrubber	0	0	10.69	7.93	8.10
Total Levelized Operating Costs	0	1.36	10.69	9.29	9.46
Total Levelized Costs, $ Million	0	2.72	19.70	18.46	22.65

The capital and operating cost estimates for the MagMill™ technology shown in Figure 4 were developed from the alpha and beta prototype tests. The two curves, 33% and 50%, show the effect on capital and operating costs of treating differing amounts of material withdrawn from the pulverizer, expressed as a percentage of the rate of the pulverizer feed rate. The technology has not been tested at the commercial level. Accordingly, the cost estimates are of a conceptual nature.

Fig. 4. Estimated Capital and Operating Costs, MagMill



Cost estimates for 90% post-combustion mercury removal, ranging from $50,000 to $70,000 per pound of mercury removed, are taken from the literature.[20]

The cost of coal is included in the total cost estimate to reflect the weight recovery and Btu recovery measured in the Beta Prototype tests using the Upper Freeport coal.

The system costs include cost of coal, levelized costs for the MagMill™, LSFO, and mercury removal. Effects on power plant operational performance are based on the TVA results and reflect improved plant operation with the clean MagMill™ product. These costs are reckoned directly from the earlier results and are thus given in 1978 dollars. The basis for the calculation is given in Reference 3. Table VII shows typical economic penalties attributable to ash and sulfur content expressed as $/Ton in 1978 dollars as developed by the TVA.

Table VII. Typical Economic Penalties, $/Ton, Attributable to Ash and Sulfur Content As Determined by TVA (1978$).

Ash, %	**Sulfur %**	**A+S %**	**Disposal Costs, $/T**	**Transportation Costs, $/T**	**Maintenance Cost, $/T**	**Peaking Capacity Loss, $/T**	**Rated Capacity Loss, $/T**	**Availability Loss, $/T**	**Total Costs $/T**
10.5	2.0	12.5	0.26	0.63					0.89
12.5	2.5	15.0	0.31	0.75	0.38				1.44
14.5	3.0	17.5	0.36	0.88	0.75				1.99
16.5	3.5	20.0	0.41	1.00	1.13	0.19	1.08	0.47	4.28
20.5	4.5	25.0	0.51	1.25	1.88	0.27	3.08	1.35	8.34
22.5	5.0	27.5	0.56	1.38	2.26	.031	4.08	1.79	10.38
25.0	5.5	30.5	0.61	1.51	2.64	0.35	5.08	2.23	12.42

RESULTS

Five different cases have been chosen to illustrate the effects of MagMill™ coal cleaning on the cost of mercury emissions. The five comparison cases are described in Table VIII. Total sulfur scrubbing is considered for all cases for simplicity. It is further assumed that 90% removal of post-combustion mercury is required for all cases.

Table VIII. Comparison Cases. Appalachian Coals

Option	
1	No MagMill™, No Scrubber, purchase 1.59 % sulfur coal
2	MagMill™, No Scrubber, purchase 2.95 % sulfur coal
3	No MagMill™, New Plant with scrubber, purchase 2.95 % sulfur coal
4	MagMill™, New Plant with scrubber, purchase 2.95% sulfur coal, scrub 1.59 % sulfur
5	MagMill™, Existing Plant, retrofit scrubber, purchase 2.95% sulfur coal, scrub 1.59% sulfur

- Option 1 is the base case where no cleaning is carried out at the power plant. The costs are for sulfur emissions at the current rate of \$710 per ton SO_2 and mercury removal at \$70,000 per pound of mercury removed. A low sulfur coal is procured. This is the only option for which a low sulfur coal is chosen as feed to the power generating station. The price of the coal is high, reflecting low sulfur, but the cost of sulfur emissions allowances should be low. For this and all of the options to follow, both 80% and 95% sulfur oxide removal are considered. It is assumed that this does not affect mercury removal by the wet method.

- Option 2 employs only the MagMill™ technology. There is no flue gas scrubber. A high sulfur coal is chosen for this option, and it is assumed that the MagMill™ will produce a coal for feed to the burner which is comparable in sulfur to the low sulfur coal chosen in Option 1. There will be pre-combustion removal of mercury in Option 2 which is not observed in Option 1.

- Option 3 illustrates the cost and technical effectiveness of a wet sulfur oxide scrubber where a high sulfur coal is procured. No MagMill™ is employed.

- Options 4 and 5 show the effects of combined front end coal cleaning and flue gas scrubbing in a new plant and in an existing plant retrofitted with a MagMill™ and a scrubber. In both options high sulfur coals are procured and cleaned by the MagMill™ so that the level of sulfur going to the scrubber is comparable to the low sulfur in Option 1.

The Sargent & Lundy flue gas scrubbing cost analysis was carried out for Appalachian coals with sulfur levels of 3% and 1.5%. The beta prototype tests were carried out with a North Central Pennsylvania Upper Freeport Seam raw coal with 2.68% sulfur. The MagMill™ product had 1.43% sulfur. It is assumed that these values are close enough to those employed in the Sargent & Lundy evaluation to justify their application. It was not possible, however, to match the raw coal characteristics with those of commercial coals in the market today because virtually all commercial coals are now cleaned at least to some extent. Because of this we obtained coal characteristics, i.e., average ash, sulfur, pounds SO_2 per Million Btu, and delivered price for a nominal 3% sulfur Appalachian coal, matching the upper sulfur level from the Sargent & Lundy study. Then we obtained similar information for a nominal 1.59% sulfur coal, corresponding to the sulfur reduction observed in the beta prototype testing. We then interpolate the Sargent & Lundy cost data to obtain costs for the scrubber processing the 2.95 and 1.59 % sulfur coals.

The purchase prices and coal qualities of a range of Appalachian coals with ash and sulfur values near 3% (high sulfur coal) and 1.59% (low sulfur coal) as reported by the Federal Energy Regulatory Commission (FERC) in November, 2004 are given in Table IX. It is assumed that each of the high and low sulfur coals has similar levels of mercury, i.e., 0.15 ppm.

Table IX. Quality and Costs for Comparison Coals (FERC, November 2004)

	Low	**High**
Sulfur Range	1.54 - 1.68	2.90 - 3.11
Average Sulfur	1.59	2.95
Average Ash	11.10	8.73
Average Btu Content	12,341	11,884
Average LbSO_2/MBtu	2.58	5.0
MBtu/Ton	24.68	23.8
A+S	12.69	11.68
Contract Market:		
Average Price, $/Ton	38.72	29
$/MBtu	1.57	1.23

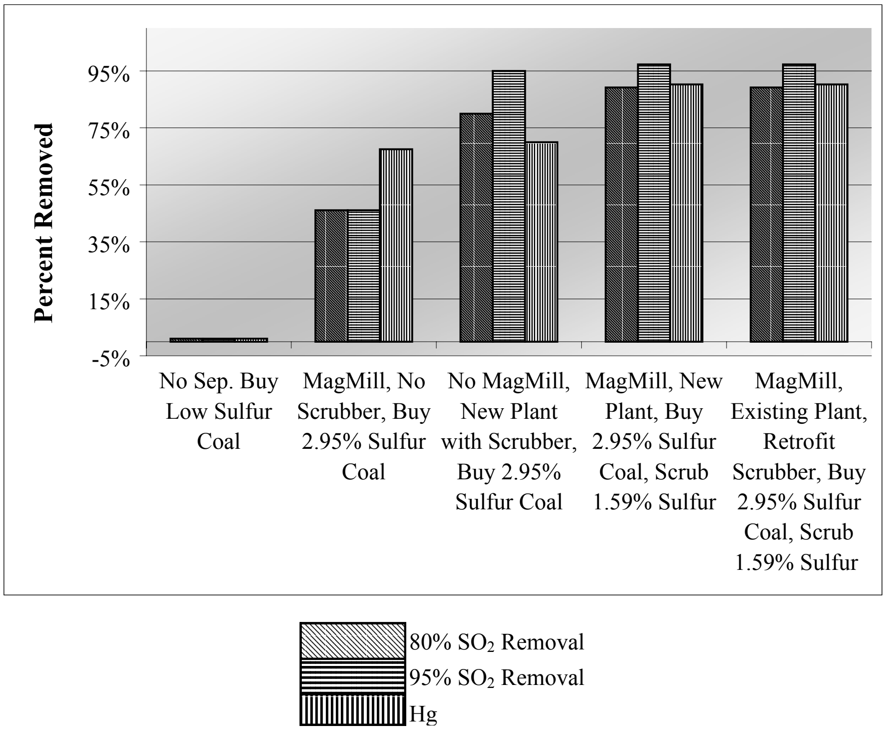
All averages are determined on a weight-averaged basis, i.e., each sulfur value in the range is weighted by the percentage of all shipments characterized by this value. The prices are delivered costs, and include the cost of the coal and transportation.

In the analysis to follow it is assumed that the MagMill™ achieves the same levels of sulfur and mercury reductions and Btu recovery that were measured in the beta prototype testing employing the raw coal, i.e., 47% reduction in sulfur concentration and 63% reduction in mercury at 91.1% Btu recovery. It is further assumed that the LSFO flue gas scrubber removes either 80% or 95% of the sulfur dioxide and 70% of the mercury in the flue gas fed to the scrubber. It is assumed that enough mercury in the flue gas is removed post-scrubbing at a cost of $70,000 per pound of mercury to bring the overall post-combustion mercury removal to 90%.

Sulfur and Mercury Emissions

Emissions of SO_2 and mercury for each of the options are shown in Figure 5, expressed as percentages of the potential emissions in the plant feed coal which has been removed. No sulfur oxide or mercury has been removed from the off-gasses of Option 1 since no coal treatment or scrubbing was employed. Option 2 is fueled by a high sulfur coal which is cleaned by the MagMill™. For Option 2, however, both mercury and sulfur oxides have been removed by front-end coal cleaning. Option 3, a scrubbed plant burning high sulfur coal but with no MagMill™, achieves better sulfur oxide removal at both levels of performance but is similar to the MagMill™ in mercury separation, i.e., 63% for the MagMill™ and 70% for LSFO scrubbing. The best removals of mercury and sulfur oxides are for combined pre-combustion coal cleaning with the MagMill™ and post-combustion sulfur oxide scrubbing as shown in Options 4 and 5. This is true for either 80% or 95% scrubber efficiency. The efficiency of separation of mercury is assumed to be the same for both options.

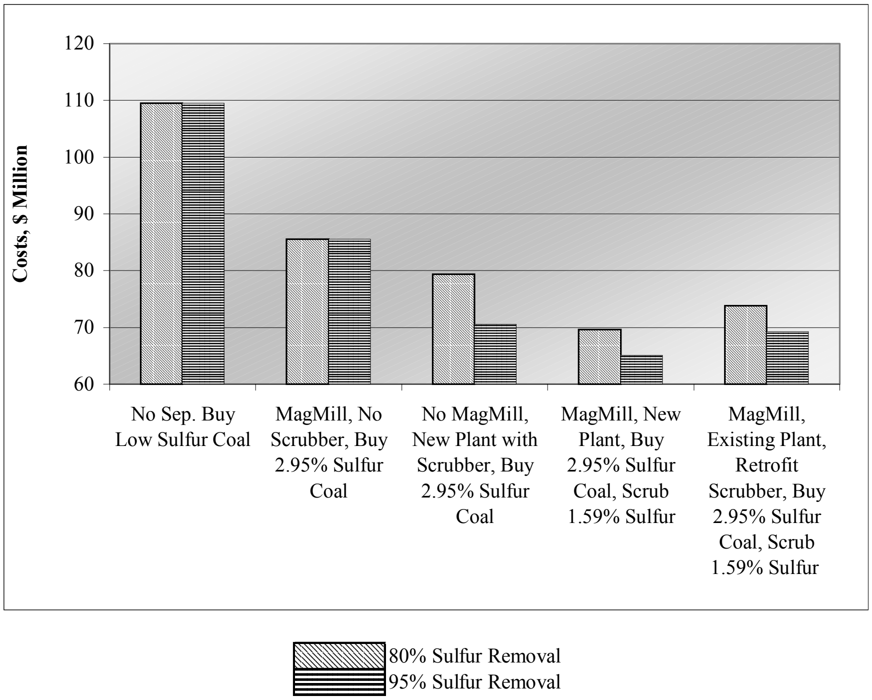
Fig. 5. Percent of SO_2 and Hg Removed from Feed Coal



Cost Estimates

Estimates of the total cost for sulfur and 90% mercury removal are given in Figure 6 for the five options.

Fig. 6. Costs for Sulfur and Mercury Removal
90% Mercury Removal



For Option 1, where a low sulfur coal is purchased and no coal cleaning at the plant is employed, a penalty of $0.93 per ton of coal or $1.26 million is assessed for transportation, disposal, and maintenance associated with the 12.7% ash + sulfur in the feed coal. An added cost of $0.71 per ton or $0.99 million is assessed to Option 3 where the ash + sulfur level is 11.7%.

For Option 2, there is a $25 million saving per year realized by installing the MagMill™ technology for mercury and sulfur separation over the base case where purchased allowances are used. With the levelized cost for a MagMill™ of about $2.9 million, this technology will pay out in less than 2 months! The savings alone is equivalent to about $17 per ton of coal burned!

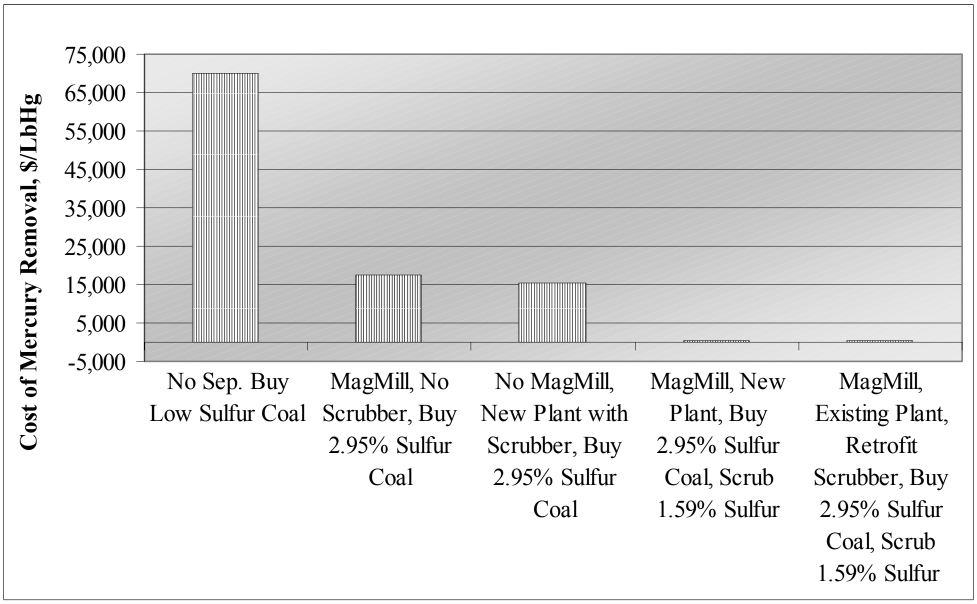
Nonetheless, Option 3 is equally attractive. With a savings compared to the base case of $30 million per year and a levelized cost of $19 million, the pay-back is about 8 months! Sulfur oxide separation is better, but mercury separation is about the same.

Option 4, combined pre-combustion coal cleaning and flue gas scrubbing for a new plant, is the least-cost combination for 90% mercury separation. Option 5, combined MagMill™ coal cleaning and retrofit flue gas scrubbing at an existing plant, is close behind. With a total cost savings ranging from $40 million to $45 million and levelized costs ranging from $18 million to $22 million, the payout for these two technologies range from five to seven months for new vs. retrofit installations. Pre-combustion cleaning with a MagMill™ results in less mercury to be removed post-combustion to meet the overall 90% removal requirement.

Co-Benefit to Cost of Mercury Removal

The cost of mercury removal expressed as dollars per pound of mercury removed is shown in Figure 7 for each of the options. Where no mercury is removed either by the MagMill™ or by scrubbing, the cost of $70,000 per pound of mercury is assumed. Use of the MagMill™ drops the cost to less than $20,000 per pound of mercury and the scrubber reduces the cost further to about $15,000 per pound of mercury. Recalling Figure 5, Options 4, and 5 achieve 90% removal and as such have no costs associated with separation of mercury. The desired level is achieved by use of the combined pre-combustion MagMill™ cleaning and post-combustion wet scrubbing.

Fig. 7. Cost of Mercury Separation, $/LbHg



CONCLUSIONS

Pre-combustion MagMill™ cleaning can have a significant positive effect on the cost and efficiency of mercury removal from coal-fired power plant off-gases. Combined MagMill™ cleaning and flue gas scrubbing is the most cost effective of the five technology combinations explored. In this conceptual evaluation, costs for mercury separation at the 90% level are lowered from $70,000 per pound removed to substantially $0 for the combined MagMill™ and the limestone forced oxidation scrubber.

Another significant co-benefit of pre-combustion MagMill™ coal cleaning is lowering economic penalties associated with burning coals with ash and sulfur levels above design limits, which have been generally determined by TVA to be 12.5 % ash plus sulfur.

A renewed emphasis on coal cleaning is gaining momentum, at least in part, because of the rapid escalation of the cost of sulfur oxide emissions allowances and impending control of mercury emissions. In less than a year, the price of sulfur emissions allowances has escalated from $200 per ton of SO_2 to over $700. The benefits to be gained by developing dry coal cleaning technology for use at the power plant are great. Here the coal is ground to a size which promotes mineral liberation to improve combustion characteristics, no water is involved, and since the fine coal is blown directly to combustion, there are no storage or transportation problems! The opportunity is now.

ACKNOWLEDGEMENTS

EXPORTech Company has carried out work sponsored by the U.S. Department of Energy (Contract DE-AC26-99FT40156) and the Electric Power Research Institute (EPRI Agreement WO-3852-13) to test the MagMill™ concept for the pre-combustion removal of hazardous air pollutant precursors from coal. A portion of this program, which was also sponsored by Bradford Coal Company, included sampling a pulverizer at the Shawville Generating Station and subjecting the samples to subsequent magnetic separation at ETCi's facilities in New Kensington. We would also like to acknowledge funding for the MagMill™ prototype demonstration from the Pennsylvania Ben Franklin Challenge Grant program, Grant 98W.CR00303R-3.

It is a pleasure to acknowledge assistance from Russell Jamison, Greg Crusan, Dr. Yuru Feng, and Dr. Edward Brandner.

REFERENCES

[1] Finkelman, Robert B., *Journal of Coal Quality,* 1993, 12:4, 132-143.

[2] Barrett, R. E.; Mack, G.A; Holt E.C.; Frank, R.L., *Examining Relationships Between Coal Characteristics and the Performance of TVA Power Plants,* 1982, Report No. TVA/OP/EDT-83-12.

[3] Cole, Randy; Frank, Rob, *Coal Preparation Society of America Journal*, 2004, 3:2, 10-15.

[4] US Environmental Protection Agency, Clean Air Mercury Rule, issued March 15, 2005. www.epa.gov.

[5] $711 per ton of SO_2, www.emissionstrading.com, January 3, 2005.

[6] *Mercury Study Report to Congress*, EPA Office of Air Quality Planning & Standards, Office of Research and Development, *EPA-452/R97-003*, 1997; *DOE Announces Further Field Testing Of Advanced Mercury Control Technologies*, U.S. Department of Energy, National Energy Technology Laboratory TechNews, November 5, 2004.

[7] Goldschmidt, V.M. in *Geochemistry,* A. Muir, Ed., 730, Clarendon, Oxford, 1954.

[8] Gluskoter, Harold J., *Mineral Matter and Trace Elements in Coal*, Advances in Chemistry Series No. 141, *Trace Elements in Fuel,* American Chemical Society, 1-22, 1975.

[9] *Coal Preparation,* Editor Joseph W. Leonard, III, Associate Editor, Byron C. Harding; Society of Mining, Metallurgy and Exploration, 1991.

[10] McCartney, J. T.; O'Donnell, H. J.; and Ergun, S., *Pyrite Size Distribution and Coal-Pyrite Particle Association in Steam Coals, Correlation With Pyrite Removal by Float-Sink Methods,*

Report of Investigations 7231, United States Department Of Interior, Bureau of Mines. See also: Gluskoter, H. J., *Energy Sources*, 3:2, Crane, Russak & Company, Inc., 1977.

[11] Oder, R.R.; Kulapadithoram L.;. Lee, A.K and. Ekholm, E.L., *American Mining Congress Journal*, 1977, 63:8, 42-49.

[12] Honda, H. and K. Ouchi; *Fuel,* 1975, 36, 159-175.

[13] R. R. Oder, *Dry Magnetic Separation Of Ash, Sulfur, And Mercury From A Southwestern Wyoming Coal*, 18th International Low Rank Fuels Symposium*,* June 24-26, 2003, Billings, Montana.

[14] Oder, R.R.; Feng, Y.; and Jamison, R.E., *Pulverizer Modification for Pyrite Separation at the Power Plant*, Final Report, Phase II, U.S. Dept. of Energy Small Business Innovation Research Grant DE-FG05-94ER81764, 1997.

[15] Oder, R.R.; Jamison, R.E.; and Brandner, E.D., *Mining Engineering*, 2001, 53:11, 47-51.

[16] Ibid.

[17] *Performance and Cost of Mercury Emission Control Technology Applications in Electric Utility Boilers,* EPA-600/R-00-083, September, 2000.

[18] DePriest, William; Gaikwad Fajendra P., *Economics of Lime and Limestone for Control of Sulfur Dioxide* Paper #169, http://www.lime.org/Wet_FGD.pdf; *Wet Flue Gas Desulfurization Technology Evaluation,* Project Number 11311-000, Prepared for National Lime Association, January 2003, by Sargent & Lundy, LLC.

[19] http://www.ferc.gov/docs-filing/eforms/form-423/data.asp.

[20] See Reference 6.