Economics of Pre-Combustion Sulfur and Ash Rejection of High-Sulfur Coals by Column Flotation and Enhanced Gravity Separation

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ABSTRACT

Development of an efficient, economic and environment-friendly technology is essential for the utilization of high-sulfur coals. There are three different desulfurization methods, i.e. Post-Combustion Flue Gas Desulfurization (FGD), In-Combustion Gas-Absorption Desulfurization (ICGAD) and Pre-Combustion Inorganic Pyrite Desulfurization (PCD). Among these PCD is the only process that is capable of eliminating inorganic pyritic sulfur effectively at the very source of SOx pollution in the utilization of high-sulfur coals. Although Korea meets most of its coal needs by importing low-sulfur coals, the current 4-year project was initiated in 1994 in preparation of the proper utilization of high-sulfur coals in the future. In a pilot plant of a microcel type flotation column employing a static-mixer-bubbler, the liberated pyritic sulfur was removed along with ash minerals from the finely ground -100 mesh coals. The process was followed by an enhanced gravity separation using Falcon Concentrator for the removal of the pyrite-coal middlings, leaving the cleaned coal free from the contamination of pyritic inorganic sulfur.

The results show that the high-sulfur coal (25% ash, 4.0% total sulfur, 3.2% pyritic sulfur) can be cleaned, yielding the clean coal (10% ash, 1.25% total sulfur, 0.5% pyritic sulfur) at the thermal recovery of 80%, the pyrite rejection of 90%, total S rejection of 80% and ash rejection of 75%. For the desulfurization system of a 500MW Korean Standard Coal Power Plant, an economics of the PCD process was compared with that of the FGD process, the most common desulfurization technology being used. Under the Korean SOx standard of 1999, i.e. 0.6 1b SO_2 per 10^6 Btu, equivalent to 270 ppm SO_2 at 3% vol. O_2, the annual operation cost indicates that the hybrid desulfurization process(PC-FGD) of FGD with the pre-combustion cleaning of pyrite from the high-sulfur coal is more economical than the FGD-Only process as the pyritic sulfur content of the raw coal goes over 1.2%. In the detailed economic evaluation on the high-sulfur coal containing 3.2% pyritic sulfur, the total construction, operation and maintenance cost of the PC-FGD process is reduced by 10,570,000 $/yr (22%) from 48,470,000 $/yr of the FGD only process,.

I. Introduction

Traditionally coal cleaning has been done to increase thermal content by removing ash minerals from the raw coals. In recent years, however, various unit processes are being developed for the removal of pyrite (FeS_2) from the coals. This pre-combustion desulfurization of inorganic pyritic sulfur can be a strong alternate to the conventional post-combustion flue gas desulfurization (FGD) in controlling the acidic SOx gas during the thermal utilization of certain high-sulfur coals.

In addition to the research on SOx control, various research organizations around the world are developing many different schemes for controlling acidic gases such as SOx and NOx, green house gas such as CO_2 and other hazardous air pollutants (HAPs) such as arsenic and mercury.

In the present study, an advanced pre-combustion desulfurization of pyritic sulfur from high-sulfur coals was studied, using the combined process of Microcel column flotation for the removal of ash minerals and Falcon enhanced gravity separator for the removal of pyrite (FeS_2) and coal-pyrite middlings.

The present process is designed for the removal of ash minerals and pyrite from the high-sulfur coals. Removal of ash reduces the volume of cleaned coals, resulting in the savings of various costs of transportation and handling. Reduction in the contents of abrasive silicate ash minerals in the coal contributes to the increase in the operation efficiency of a power plant. The less wear and tear of the plant equipment will reduce the down time of the plant. Burning the cleaned coals with high thermal contents increases the boiler efficiency by lowering slagging and fouling in thermal utilization of coals. All of those factors would make the coal power generation less costly.

Removal of pyrite from high-sulfur coals for the pre-combustion desulfurization would help controlling SOx pollution in the air, resulting in the cost reduction of SOx control. The flue gas containing lower SOx concentration would increase the life time of equipments due to less maintenance requirement related to the acidic corrosion failure, resulting in the savings of operational and maintenance costs. At the same time, the improvement in the operation hours of power plants means that the number of new power plants that has to be constructed would be reduced.

In addition to the removal of pyrite and ash, the present process would also reduce the concern on HAPs, but the exact economic effect was not quantified. Sometimes the super-cleaned coal containing less than 1% ash and 0.1% sulfur can be used as the fuel for an internal combustion engine.

The economic evaluation of the coal cleaning technology should include not only the costs for removing ash, pyrite and HAPs from the coals, but also the benefits of the cost savings in down stream pollution control. In the present study, the economy of advanced clean coal technology, including column flotation and enhanced gravity separation is compared with that of the conventional flue gas desulfurization technology.

II. Pre-Combustion Desulfurization and Deashing of High-Sulfur Coals.

1. Column Flotation and Enhanced Gravity Separation.

Various investigators studied different unit processes such as flotation, gravity separation, heavy medium cyclone, and selective spherical oil agglomeration for the pre-combustion removal of pyritic sulfur from high-sulfur coals. In flotation, column flotation has many advantages, comparing with conventional mechanical flotation (1).

One of the most promising column flotation technology was the Microcell™ developed by R. H. Yoon(2) at VPISU in the United States. The process includes Microcell™ column flotation used mainly for the removal of ash minerals and some of the liberated pyrite from coals, and the enhanced gravity separation for the final removal of coal/pyrite middlings. In Figure 2, the basic design of the Microcell™ type flotation column can be seen. Comparing with the conventional mechanical flotation cells, the flotation column was found to have much merit for cleaning fine coal particles. Among many types of different flotation columns, the Microcel flotation column is unique in many aspects. It solved the ever present problem of fine air bubble generator by recirculating flotation pulp through a static mixer where flotation air was supplied. Recirculation of the flotation pulp under pressure through the static mixer air bubble generator produces better opportunity for the coal particles to meet with air bubbles, improving the efficiency of flotation.

Column flotation can be very effective in removing liberated ash minerals and pyrite. The process, however, can not reject fine pyrite particles that are included in the coal/pyrite middlings. On the other hand, it is fortunate that the big difference in the specific gravity of coal (S.G.-1.2) and pyrite (S.G.-5.0) can make it possible to remove the middlings containing pyrite from the pure coal. Small inclusion of heavy pyrite in coal/pyrite middlings can make the apparent specific gravity of middlings heavy enough to be separated through enhanced gravity separator. An enhanced gravity separator usually utilizes extra centripetal force in addition to the conventional gravity force, making it more effective. The Falcon enhanced gravity separator that was used in the present study for the removal of coal/pyrite middlings can be seen in Figure 1.

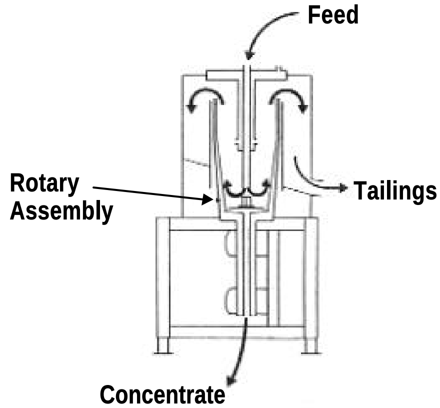

Figure 1. Falcon Enhanced Gravity Separator

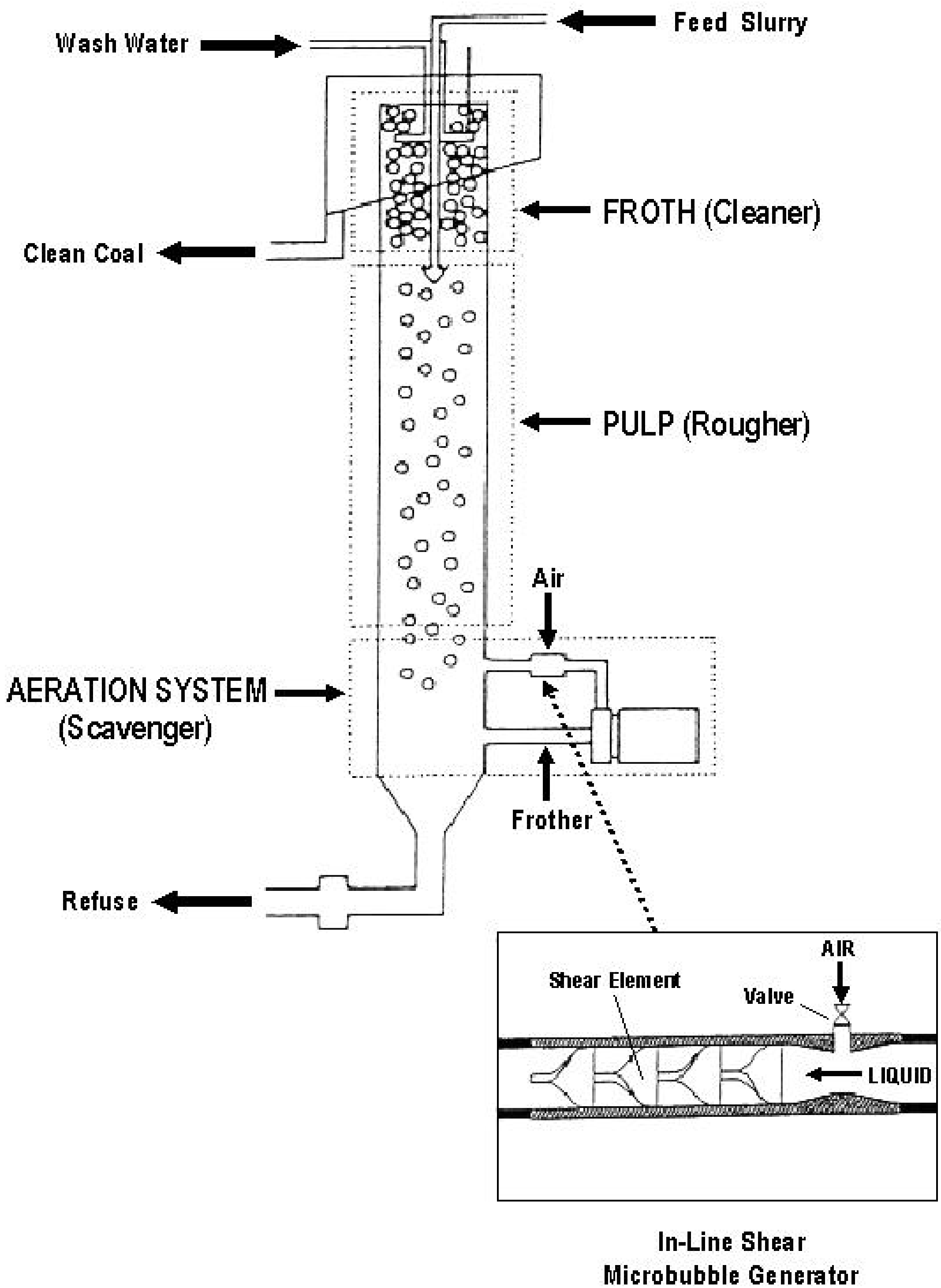

Figure 2. Microcell™ Type Flotation Column with Microbubble Generator

2. The Schematics of the Present Process

In Figure 3, the schematics of the present process is described. It includes comminution, screening, magnetic separation, column flotation, enhanced gravity separation, filtration and thickener dewatering(4). As discussed in the previous section, the merits of the Yoon's process are fully utilized in the column flotation immediately followed by an enhanced gravity separation that can lower the pyritic sulfur content in the final cleaned coal.

A typical result of the present study is summarized in Table 1 and Figure 4. One of the high-sulfur coal studied was from Hubei, China. The raw coal contained 25% ash, 4.0% total sulfur, and 3.2% pyritic sulfur. During the cleaning, 75% of ash and 90% of pyrite was rejected, resulting in 80% of total sulfur rejection at the thermal recovery of 80%. The clean coal contained 10% ash, 0.5% pyritic sulfur and 1.25% total sulfur. Due to the nature of pyrite dissemination in the coal samples used in the present study, the raw coal containing 4.0% total sulfur yielded the cleaned coal containing 1.25% total sulfur at the pyritic sulfur rejection of 90%.

Table 1.
Ash and Sulfur Contents in Raw Coal and Clean Coal
and Their Recovery and Rejection

Raw Coal			Clean Coal			% Recovery, % Rejection			
Ash	Total Sulfur	Pyritic Sulfur	Ash	Total Sulfur	Pyritic Sulfur	Thermal Recovery	Ash Rejection	Total Sulfur Rejection	Pyritic Sulfur Rejection
25%	4%	3.2%	10%	1.25%	0.5%	80%	75%	80%	90%

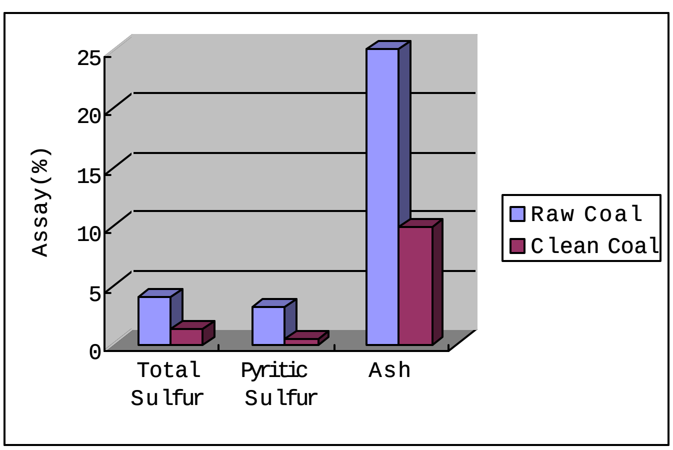

Figure 4. % Assay of Raw Coal and Clean Coal

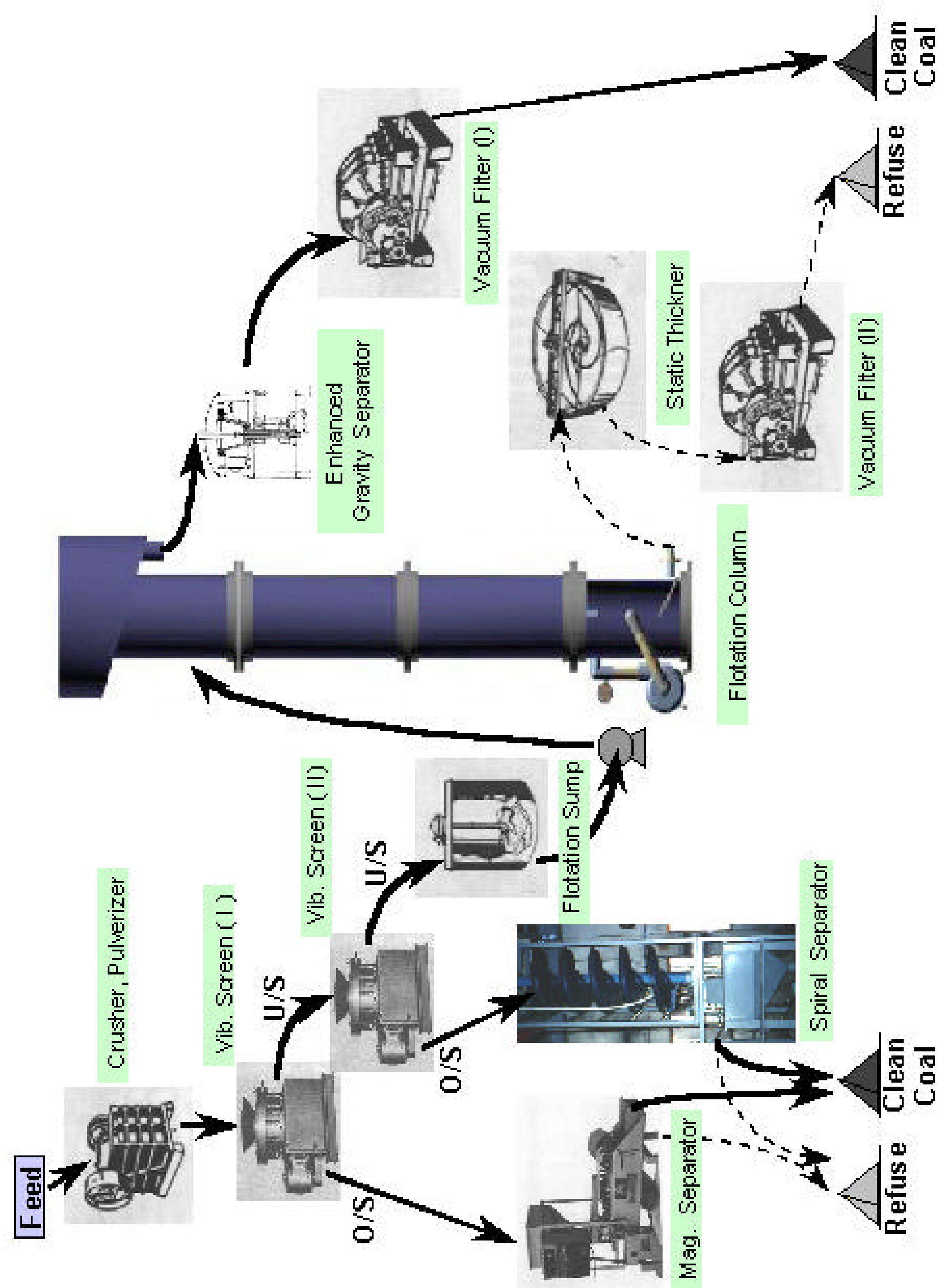

Figure 3. Schematic Diagram of PDU

III. Economic Evaluation of the Pre-combustion Desulfurization and Deashing

1. Background

The sulfur in coal can be found in two different forms, i.e. organic sulfur and inorganic sulfur. Various types of organic sulfur buried under the molecular structure of coal can not be separated from the coal by any physical means. They can be removed only by expensive chemical means. On the other hand, the inorganic sulfur, mainly pyrite, sometimes can easily be separated from the coal, making the physical separation process highly economical whenever applicable.

Due to the urgent need for controlling the SOx pollution, however, the original U.S. Clean Air Act encouraged the power industry to utilize the "Best Available Proven Technology", and not to wait until a new effective technology is developed. Consequently, flue gas desulfurization (FGD) was adopted for the simple neutralization of the acidic flue gas. This FGD is the only effective desulfurization technology in the thermal utilization of low-sulfur coal of which sulfur is mainly organic in nature. The FGD process, by its design, becomes an integrated part of the operation and maintenance system of a power plant.

Although various modification of FGD has become virtually the industry standards around the world, the post-combustion FGD desulfurization process has the limitation by nature, i.e. it tries to find the solution for the consequence of pollution(3). It is a well-known fact that any environment control technology becomes more economical and effective, when it deals with the source rather than the consequence of the pollution. This means that, in thermal utilization of coals, the desulfurization process could become more effective and economical as it moves from the conventional post-combustion FGD wet scrubbing to the in-combustion solid/gas neutralization, and to the pre-combustion desulfurization of inorganic pyritic sulfur. The pre-combustion desulfurization has built-in advantages, since it removes the source of SOx pollution at the origin, i.e. coal, prior to the thermal utilization(4). This pre-combustion desulfurization, however, is effective only for some high-sulfur coals that contains enough pyritic inorganic sulfur that can be removed effectively by means of economic physical separation. The process is ineffective in removing organic sulfur embedded in the molecule of coals. However, the pre-combustion desulfurization process could remove enough pyritic sulfur from some high-sulfur coals to make the process a stand alone process, or a hybrid process in combination with a scaled-down FGD process, all depends on the economy of the complete package. In the present study, the hybrid process of pre-combustion desulfurization and FGD was found to be more economical than the conventional FGD alone.

2. Merits of Pre-combustion Desulfurization of High-Sulfur coals.

Pre-combustion desulfurization of high-sulfur coals can save not only the direct cost of desulfurization, but also various constructions, operation and maintenance costs of an existing or an operational power plant.

In a detailed pilot plant investigation of pre-combustion coal cleaning, combustion, and power plant operation, US EPRI(8) studied various merits of ash-cleaning and pyrite-cleaning. The EPRI report found that boiler efficiency was increased from 88.4% for raw coal (23.4% ash, 4.0 S) to 89.2% for the ash-cleaned coal (6.5% ash, 3.8% S), and to 90.1% for the S-cleaned coal (2.1% ash, 1.8% S). The capital cost estimates for a new 500 MW power plant is indicated in Table 2. Various power plant systems studied includes pulverizer/firing system, air preheater system, steam generator, ash handling system, ESP system, and FGD and Waste Treatment System. In the study, three different coals were used, with ash-cleaning, with pyrite-cleaning, and without any coal-cleaning. The study found that using the cleaned coal is more economic in construction of a new power plant. The required capital costs was lowered from 123 million dollars for the uncleaned raw coal (23.4% ash, 4.0% S), to 113 million dollars for the ash-cleaned coal (6.5% ash, 3.8% S), and to 99 million dollars for the Pyrite-cleaned coal (2.1% ash, 1.8% S).

Table 2.
Capital Cost Estimation for a 500MW Power Plant,
Using Coals with and Without Pre-Combustion Cleaning

(In 1985 U.S. $1,000)

Power Plant Systems	Capital Costs for Different Coals		
	Raw (23.4% Ash, 4.0% S)	Ash-Cleaned (6.5% Ash, 3.8%S)	Pyrite-Cleaned (2.1% Ash, 1.8%S)
Pulverizer/Firing System	12,224	11,259	8,797
Air Preheater System	4,640	4,640	5,672
Steam Generator	56,996	54,967	51,003
Ash Handling System	6,750	2,880	2,880
ESP System	6,600	6,000	5,200
FGD and Waste Treatment System	36,000	33,500	25,600
Total	$123,210	$113,246	$99,152

In Table. 3, the annual operating cost estimates was summarized for a 500MW power plant, using different coals with and without pre-combustion cleaning. Coal-cleaning removes most of the voluminous and abrasive ash minerals as well as corrosion-causing pyrite. Using the cleaned coal saves the annual auxiliary power costs from 5.5 million dollars for the raw coal (23.4% ash, 4.0% S), to 5.2 million dollars for the ash-cleaned coal (6.5% ash, 3.8%S) and to 4.7 million dollars for the Pyrite-cleaned coal (2.1% ash, 1.8%S). The annual operating costs for the FGD and waste disposal system can also be saved by using the cleaned coal, i.e. 7.5 million dollars for the raw coal, 6.0 million dollars for the ash-cleaned coal and 1.5 million dollars for the Pyrite-cleaned coal. The annual maintenance costs was also reduced by using cleaned coal, i.e. 9.0 million dollars for the raw coal, 8.1 million dollars for the ash-cleaned coal and 7.0

million dollars for the Pyrite-cleaned coal. In using the Pyrite-cleaned coal, the biggest savings occurred in the annual operating costs of FGD consumable/waste disposal system by 6.0 million dollars. It was followed by 2.0 million dollars saving of the maintenance cost and 0.8 million dollars saving of the auxiliary power consumption cost. By using the Pyrite-cleaned coal instead of the raw coal, the total savings in the annual operating costs of the above three systems amounted to 8.8 million dollars, a 40% saving.

Table. 4 is the summary of the break ever coal cost analysis for a 500 MW power plant, using coals with and without pre-combustion cleaning. The US EPRI study indicated, using the pyrite-cleaned coal, that the capital investment cost was reduced by 24 million dollars (20%) from 123 million dollars to 99 million dollars, and the annual operating maintenance costs was reduced by 8.8 million dollars (40%) from 22.0 million dollars to 13.2 million dollars. As a results of the all those savings, the break-even coal costs was increased, i.e. 1.486 $/MBtu and 30.0 $/t for the uncleaned raw coal, to 1.680 $/MBtu and 42.1 $/t for the ash-cleaned coal, and to 1.915 $/MBtu and 50.4 $/t for the Pyrite-cleaned coal. The costs indicate an allowable coal cost increase of 13% for the ash-cleaned coal and 29% for the Pyrite-cleaned coal on a Btu basis for the equivalent steam generating costs. By adopting various economic factors used by Kee H. Rhee, et al(3), J. K. Min, et al (5), Jiang Zhesheng (6), Charles C. Johnson (7) and US EPRI Report (8) similar economic analysis was done in the present study as in the following sections.

2.1. Low Desulfurization Costs in Thermal Utilization of Some High-Sulfur Coals

The present process is designed to remove the majority of pyritic sulfur from the source before the thermal utilization. Using the economic physical separation technologies to remove pyrite from the high-sulfur coals makes the desulfurization process economical whenever the process is applicable.

2.2 Low Auxiliary Power Consumption in a Power Plant

A power plant usually consumes about 2-5% of its own electricity generated to run the plant. As in the present study, if the cleaned coal (8% ash) rather than the raw coal (24% ash) is used for the coal power generation, the ash volume per unit thermal content in the coal become about 1/4. As a consequence, the power requirement for running various equipments in a power plant is lowered by about 10%.

2.3 Less Needs in New Power Plants

Utilization of high quality cleaned coal could improve the operational efficiency of a power plant, including boiler efficiency, by about 8-12%. For example, 10% improvement in operational efficiency of 150 GW can save the construction cost of six billion dollars for 15,000 MW new power plants at the unit construction cost of 400 $/kW.

2.4. Lower Fuel Cost by Using Low Ash Cleaned Coal

Table 3.
Annual Operating Cost Estimates for a 500MW Power Plant,
Using Coals with and without Pre-Combustion Cleaning

(In 1985 U.S. $1,000)

Power Plant Systems	Capital Costs for Different Coals		
	Raw (23.4% Ash, 4.0% S)	Ash-Cleaned (6.5% Ash, 3.8%S)	Pyrite-Cleaned (2.1% Ash, 1.8%S)
AUXILIARY POWER CONSUMPTION			
Forced Draft Fans	586	615	604
Primary Air Fans	549	438	447
Boiler Circulating Pumps	100	100	100
Air Heater System	11	11	13
Pulverizer System	581	446	420
Ash Handling System	34	23	23
ESP System	296	290	310
FGD and Waste Treatment System	1,424	1,224	626
Induced Draft Fans	1,939	2,064	2,138
Subtotal	5,520	5,211	4,681
FGD CONSUMABLES/WASTE DISPOSAL			
Limestone Additive	2,887	2,195	735
Lime Sludge Fixative	529	396	133
Off-site sludge Disposal	2,443	1,833	616
In-line Reheater Stream	1,690	1,599	--
Subtotal	7,549	6,023	1,484
MAINTENANCE			
Pulverizer System	733	676	528
Air Preheater System	278	278	340
Steam Generator	3,420	3,298	3,060
Ash Handling System	675	288	288
ESP System	264	240	208
FGD and Waste Treatment System	3,600	3,350	2,560
Subtotal	8,970	8,129	6,984

Table 4.
Summary of Break-Even Coal Cost Analysis for a 500 MW Power Plant,
Using Coals with and without Pre-Combustion Cleaning

(In 1985 U.S. Dollars)

Cost Factors	Capital Costs for Different Coals		
	Raw (23.4% Ash, 4.0% S)	Ash-Cleaned (6.5% Ash, 3.8%S)	Pyrite-Cleaned (2.1% Ash, 1.8%S)
Annual energy Supplied (GWh/y)*	3132	3132	3132
Net Plant Heat Rate (Btu/kWh)	9706	9643	9525
Capital Investment ($\$\times10^6$)	123.210	113.246	99.152
Annual Coal Cost ($\$\times10^6$)	45.17	-	-
Annual Limestone & Waste Disposal Cost ($\$\times10^6$)	7.549	6.023	1.484
Annual Operating & Maintenance Cost ($\$\times10^6$)	8.970	8.129	6.984
Break-Even Annual Coal Cost (Present Value) ($\$\times10^6$)	(45.17)	50.61	57.83
Break-Even Coal Cost ($/kWh)	(0.0144)	0.0162	0.0185
Break-Even Coal Cost ($/MBtu)	(1.486)	1.680	1.915
Break-Even Coal Cost ($/t)	(30.00)	42.08	50.37

Notes: The numbers in parenthesis are the costs for raw coal. They are tabulated for comparison only.

Using low ash cleaned coal reduces thermal loss through useless heating of large quantity of ash minerals. The increase in the thermal efficiency could reach 1.5% by using 8% ash cleaned coal in place of 24% ash raw coal. In such a case, the savings in fuel cost only could be about 135 million dollars for 1.5% of 450 million tons of coal being used for power plants every year at 20 $ per ton of coal.

2.5. Savings in the Maintenance Costs

Handling of low volume cleaned-coal and removal of abrasive silicate ash minerals and corrosion-causing pyrite after pre-combustion desulfurization can save the maintenance costs. In the present study, by using the cleaned-coal (10% ash, 1.25% S) instead of the raw coal (24% ash, 4.0% S), a 500 MW coal power plant can save 5 million dollars annually in maintenance cost alone.

2.6. The Increase in the Power Plant Availability

By using the cleaned coal, the down time of a power plant can be reduced, resulting in an increase in the availability of a power plant by about 5%. If a nations coal power generation capacity is 150 GW, this 5% more availability translates into 3 billion dollars worth of new power plants.

2.7. Savings in Transportation Cost

The run-of-mine raw coal contains usually about 20-30% ash minerals, sometimes much higher. It also contains 10-20% moisture. Removal of ash during the pre-combustion coal-cleaning also removes that much water along with the ash. Such reduction in the cleaned-coal weight reduces transportation cost. In addition, it can help freeing the national transportation system from congestion, which is an ever present problem in many coal producing countries. At the same time, the silicate ash minerals in coal are the main cause of the air pollution by suspended solid particles, making the pre-combustion coal-cleaning process that removes ash minerals more attractive.

3. Economic Evaluation of the Present Pre-Combustion Desulfurization of a High-Sulfur Coal

In the present study, economic evaluation was carried out on the post-combustion flue gas desulfurization (FGD) of the raw coal and on the scaled-down FGD of the cleaned-coal after pre-combustion desulfurization for the high-sulfur coal. The raw coal from Hubei, China contained 25% ash, 4.0% total sulfur, 3.2% pyritic sulfur and 5,600 kcal/kg thermal value. After pre-combustion desulfurization of the raw coal, the clean coal contained 10% ash, 1.25% total sulfur, 0.5% pyritic sulfur, and 6,800 kcal/kg thermal value. The process development unit(PDU) used for the present advanced pre-combustion desulfurization study was able to recover 80% of the thermal value at 75% ash rejection, 90% pyritic sulfur rejection, and 80% total sulfur rejection.

A computer program has been developed to include various factors on the coal specification, construction schedule of the power plant, FGD, and coal cleaning plant for the present economic evaluation. The specification of a Korean Standard 500MW coal power plant and the Korean SOx standard of 1999, i.e. 0.6 1b SO_2 per 10^6 Btu, equivalent to 270 ppm SO_2 at 3% vol. O_2, were used in the present study. The annual operation cost of the FGD-Only process on the raw coal and the hybrid process(PC-FGD) of pre-combustion coal cleaning and FGD are shown in Figure 5. Two annual operation costs are crossed at the 1.2% pyritic sulfur content. Comparing with the FGD-Only process, the PC-FGD process show the lower annual operation cost as the pyritic sulfur content of the raw coal went over the cross point, 1.2%.

The detailed economic evaluation was performed for the desulfurization system of the 500MW power plant, which uses the raw coal from Hubei, China, described above. The results are summarized in Table 5. The annual investment cost was reduced from 26,600,000 \$/yr (9.33×10^{-3} \$/kWh) for the FGD-Only process to 24,190,000 \$/yr (8.49×10^{-3} \$/kWh) for the PC-FGD process. For the similar comparison, the fixed operation and maintenance costs was reduced from 11,450,000 \$/yr (4.02×10^{-3} \$/kWh) to 9,110,000 \$/yr (3.20×10^{-3} \$/kWh). The variable operation and maintenance costs was also reduced from 10,420,000 \$/yr (3.66×10^{-3} \$/kWh) to 4,590,000 \$/yr (1.61×10^{-3} \$/kWh), resulting in the reduction of total costs from 48,470,000 \$/yr (17.01×10^{-3} \$/kWh) to \$37,890,000/yr (13.32×10^{-3} \$/kWh). It indicates that, by adopting a hybrid desulfurization system after the pre-combustion of high-sulfur coal, the 500 MW power plant would save 21.8% (10,570,000 \$/yr) of the total costs of 48,470,000 \$/yr, including annual investment cost, variable operation and maintenance cost, and fixed operation and maintenance cost.

. Concluding Remarks

1. In a Process Development Unit (PDU) study of Microcell^{TM} type column flotation followed by Falcon enhanced gravity separation, a high-sulfur raw coal (4.0% total sulfur, 3.2% pyritic sulfur, 25% ash) was cleaned, resulting in a clean coal (1.25% total sulfur, 0.5% pyritic sulfur, 10% ash) at 80% thermal recovery, 90% pyritic sulfur rejection, 80% total sulfur rejection, and 75% ash rejection.

2. The annual operation costs of the FGD-Only and PC-FGD processes for the desulfurization system for a 500MW Korean Standard Coal Power Plant was evaluated using a computer program developed for the purpose. It indicates that the PC-FGD process is more economical than the FGD-Only process as the pyritic sulfur content of raw coal is greater than 1.2%.

3. The detailed economic evaluation for the 500MW power plant using the high-sulfur raw coal above shows that the construction cost for the desulfurization system can be reduced by \$25,000,000 (11%) from \$229,000,000 for the FGD-Only process to \$204,000,000 for the hybrid desulfurization process (PC-FGD), including pre-combustion pyrite cleaning (\$37,000,000) and scaled- down FGD (\$167,000,000).

4. The variable operation and maintenance costs mainly depend on the total sulfur contents of the thermal coal. Since the pre-combustion coal cleaning rejected 80% of total sulfur (90% of pyritic sulfur), the variable operation and maintenance costs (mainly for FGD consumable and waste handling) of the FGD process were reduced by 7,740,000 \$/yr (74%), resulting in the major cost reduction of the hybrid desulfurization system to be 4,830,000 \$/yr (46%).

5. The fixed operation and maintenance costs are also reduced from 11,450,000 \$/yr to 9,110,000 \$/yr by about 2,340,000 \$/yr (20%) when the hybrid system of FGD and pre- combustion desulfurization is applied.

6. It was found that, for some high-sulfur coals containing large amount of organic sulfur, removing pyritic sulfur during pre-combustion coal cleaning is not enough to make a stand alone desulfurization process. However, even in such a case, pre-combustion desulfurization can be a very strong option that should be considered in designing a hybrid desulfurization system along with FGD. That way a substantial saving in the total construction, and operation and maintenance costs can be realized for the PC-FGD desulfurization system of a new coal power plant.

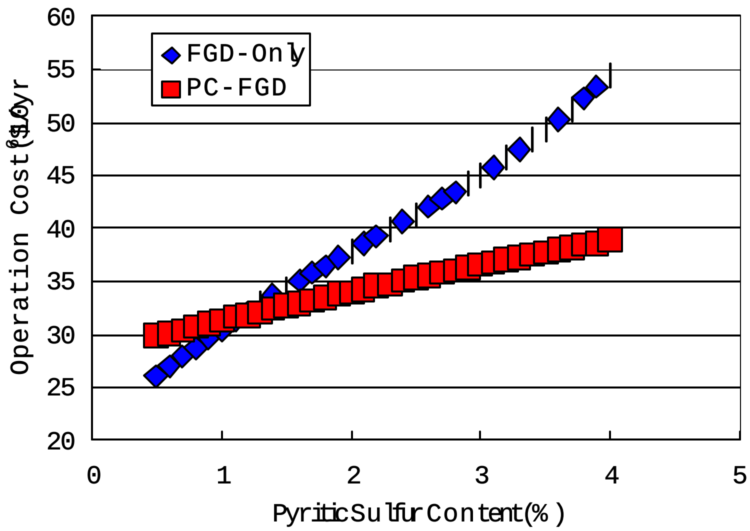

Figure 5. Annual Operation Costs of the Desulfurization Systems of a 500MW Power Plant with FGD-Only and PC-FGD

Table 5.
Economic Evaluation of the Desulfurization System of a 500MW Power Plant with and without Pre-Combustion Coal Cleaning

	FGD-Only		Hybrid Desulfurization (PC-FGD)					
			PCD		FGD		Total	
	10^6 \$/yr	10^{-3} \$/kWh	10^6 \$/yr	10^{-3} \$/kWh	10^6 \$/yr	10^{-3} \$/kWh	10^6 \$/yr	10^{-3} \$/kWh
Annual Investment Cost	26.60	9.33	4.79	1.68	19.40	6.81	24.19	8.49
Fixed O&M	11.45	4.02	0.76	0.26	8.35	2.93	9.11	3.20
Variable O&M	10.42	3.66	1.91	0.67	2.68	0.94	4.59	1.61
Total	48.47	17.01	7.46	2.62	30.43	10.68	37.89	13.30
Construction Cost	$229,052,218		$36,952,003		$167,043,438		$203,995,441	

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