

DESULFURIZATION OF COALS BY HIGH-INTENSITY HIGH-GRADIENT
MAGNETIC SEPARATION: CONCEPTUAL PROCESS DESIGN AND COST ESTIMATION

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BACKGROUND

It is well-known that the main difficulty in increasing the utilization of coal in the United States lies in the pollution problem, as the emission level of sulfur oxides and ash particles from coal burning facilities are being regulated by stringent environmental standards. Although the particulate emission standard can generally be met by using electrostatic precipitators, there apparently exists no accepted technology for controlling the sulfur oxide emissions from the flue gases (28). Thus, there has been a growing effort recently in developing effective and economical alternatives to flue gas desulfurization, and one of the most attractive alternatives is the pre-combustion cleaning of coal. Several new physical and chemical methods for removing sulfur and ash from coal prior to its combustion have already been proposed and are currently under intensive further developments (4). An important physical method for cleaning coal that appears to hold much promise is the well-established magnetic separation technique. Previous experimental investigations have clearly indicated that most of the mineral impurities in coal which contribute to the pyritic sulfur, the sulfate sulfur and the ash content are all paramagnetic. These sulfur-bearing and ash-forming minerals, if sufficiently liberated as discrete particles, can normally be separated from the pulverized diamagnetic coal by magnetic means (14, 16, 17, 31). Indeed, the technical feasibility of the magnetic cleaning of coal has been demonstrated in a number of previous studies, with substantial amounts of sulfur and ash removal reported (18, 19).

During the past few years, the magnetic cleaning of coal has been given new impetus with the introduction of a new level of magnetic separation technology, the high-intensity high-gradient magnetic separation (HGMS). The HGMS technology was developed around 1969 for the wet cleaning of feebly magnetic contaminants from kaolin clay (9,10,22,23 25). A typical HGMS unit in this wet application is shown schematically as Figure 1(a). The electromagnet structure consists of the energizing coils and the surrounding iron enclosure. The coils in turn enclose a cylindrical, highly magnetized working volume packed with fine strands of strongly ferromagnetic packing materials such as ferritic stainless steel wools. With this design, an intense field intensity up to 20 kilo-gauss can be generated and uniformly distributed throughout the working volume. Furthermore, because of the placement in the uniform field the ferromagnetic packing materials which increase and distort the field in their vicinity, large field gradients of the order of kilo-gauss/micron can be produced. In the wet beneficiation of kaolin clay, the HGMS unit is employed in a batch or cyclically operated process like a filter. The kaolin feed containing the low-concentration feebly magnetic contaminants is pumped through the stainless steel wool packing or matrix of the separator from the bottom while the magnet is on. The magnetic materials (mags) are captured and retained inside the separator matrix; and the nonmagnetic components (tails) pass through the separator matrix and are collected as the beneficiated products from the top of the magnet. After some time period of operation, the separator matrix is filled to its loading capacity. The feed is then stopped and the separator matrix is rinsed with water. Finally, the magnet is turned off, and the mags retained inside the separator matrix are backwashed with water and collected. The whole procedure is repeated in a cyclic

fashion. In general, if this batch process is employed in other wet applications where the magnetic materials occupy a large fraction of the feed stream, the down time for backwashing will be considerable, possibly necessitating the use of one or more back-up separators. To overcome this problem which is inherent to batch operations, a continuous process employing a moving matrix HGMS unit, called the Carousel separator, has been proposed (10, 22, 23, 25) as shown schematically in Figure 1(b). A number of pilot-scale studies of the wet beneficiation of kaolin clay and iron ores using the Carousel separator have been reported (23).

Because of the very low costs and the outstanding technical performance of the HGMS demonstrated in the kaolin application, the HGMS was recently adapted to the removal of sulfur and ash from a finely pulverized Brazilian Coal suspended in water in a bench-scale exploratory study (31). Other investigators later utilized pilot-scale HGMS units for the desulfurization and deashing of water slurries of some Eastern U.S. Coals. For instance, results from pilot-scale studies that demonstrated the technical feasibility of the magnetic separation of sulfur and ash from water slurries of pulverized Illinois No. 6, Indiana No. 5 and No. 6, and Kentucky No. 9/14 coals have been published (16, 17, 21). In particular, the quantitative effects of residence time, field intensity, packing material and density, slurry concentration and recycle on the grade and recovery of the magnetic separation of sulfur and ash from water slurry of pulverized Illinois No. 6 coal have been established experimentally and can be predicted reasonably by an available magnetic filtration model (16, 17). Depending upon the types of coals used and the separation conditions employed, the existing bench-scale and pilot scale results have already shown that the use of single-pass HGMS was effective in reducing the total sulfur by 40-55%, the ash by 35-45%, and the pyritic sulfur by 80-90%; while achieving a maximum recovery of about 95% (19). These available results have also indicated that both the grade and recovery of the separation can be generally enhanced with the use of larger separator matrix or by the recycle of the tail products. Further detailed review of the reported results on the magnetic cleaning of pulverized coals in water slurries can be found in the literature (18,19). An important point to be made here is that these published data and other recent analyses (3,4,7,19,24,29,30) have indicated that a significant portion of the United States coal reserve, low enough in organic sulfur, can be magnetically cleaned for use as an environmentally acceptable, low sulfur fuel. It has been estimated that a total of 100 million short tons of U.S. coals per year may be magnetically cleaned. This amounts to over 17% of the total U.S. production per year (19). Although the existing data have not yet established the total deashing by magnetic means, there are some indications that by optimizing the separation conditions, and enhancing the magnetism of ash-forming minerals, etc., further improvement in the effectiveness of magnetic separation of ash from coal can be made (19).

Recent studies (8,16-19, 26) have also suggested that coal cleaning by the HGMS technique could serve as a significant adjunct to coal liquefaction processes. In particular, the technical feasibility of adapting the HGMS as an alternative, effective mineral residue separation method as compared to the conventional precoat filtration in the solvent refined coal (SRC) process has already been demonstrated in the bench-scale, exploratory study done at Hydrocarbon Research, Inc. (HRI). The HGMS was effective in removing up to 90% of the inorganic sulfur from the liquefied SRC filterfeed slurry of Illinois No. 6 coal, and about half of the experimental runs conducted by HRI indicated over 87% inorganic sulfur removal (8,19,26). In general, the work done by HRI showed that the HGMS was less effective in ash removal, but did remove 25 to 35% of the ash. Quite recently, a pilot-scale HGMS system for the removal of mineral residue from the liquefied coal has been designed and constructed by the authors (17). Typical results from experiments conducted with the liquefied SRC filter feed slurry of Kentucky No. 9/14 coal have been quite encouraging.

indicating that the HGMS could reduce the total sulfur, ash and pyritic sulfur contents by as high as 70, 76 and 95%, respectively. Available data from the above bench scale and pilot-scale investigations have also showed that an even greater deashing of the liquefied SRC filter feed can be achieved by improved separation conditions. A detailed discussion of these results along with their technical implications can be found in the literature (19,26). Furthermore, a close examination of the inherent physical and chemical characteristics of the hydrogenated product prior to the filtration step in the SRC and other related liquefaction processes will indicate that the HGMS may be developed as a practically applicable mineral residue separation method. It is known that the hydrogenation reaction will generally reduce a major portion of the pyritic sulfur to the highly magnetic pyrrhotite; and the sulfur-bearing and ash-forming minerals tend to be more easily liberated from the dissolved organic components in the filter feed slurry when compared to the case of pulverized coal suspended in water. Furthermore, the typical mean particle size of the SRC filter feed sample is often less than 5 microns, which dictates the use of methods capable of handling micron-size materials like the HGMS. All of these factors seem to suggest that the significant potential of utilizing the HGMS for removing the mineral residues from liquefied coal. For certain types of coals, it has been pointed out that even without further enhancement of the magnetic removal of ash, the magnetically cleaned SRC would be acceptable for use as a feed to boilers which already have electrostatic precipitators (34). This follows because the cost of solid-liquid separation in coal liquefaction is generally substantial, and the moderately low-ash SRC should be less expensive (2,26, 34). Indeed, a preliminary cost estimation of the magnetic desulfurization of liquefied coal based on the laboratory data obtained by HRI seems to support this observation (26).

The preceding discussion has indicated that the scientific and technical feasibility of the magnetic desulfurization of both wet and liquefied coals has been well established. Recently, there have been several estimates of the costs of magnetic desulfurization reported in the literature (9,20,21,24,26,31). Because of the simplifying assumptions involved as well as the technical performance specified and the estimation methods used in these analyses, however, most of them seem to be somewhat approximate in nature. In this paper, the latest data from pilot-scale studies of sulfur and ash removal from both wet and liquefied coals by the HGMS are used to design conceptual processes for magnetic desulfurization of coals. Estimates of magnetic desulfurization characteristics and conceptual process requirements, as well as installation and processing costs are determined. In particular, the extents to which the processing conditions can affect the magnetic desulfurization costs are to be examined. The latter will provide some indications on the possible impact of future process improvements. Finally, the results are compared with other approaches to the desulfurization of coals (2,4,15,27,33).

MAGNETIC DESULFURIZATION OF COAL/WATER SLURRY: PROCESS AND COSTS

A conceptual process for the magnetic desulfurization of pulverized coal suspended in water by the HGMS is shown schematically in Figure 2. A coal slurry of a fixed concentration is prepared first by mixing known amounts of pulverized coal, water and a dispersant (wetting agent) like Alconox. The HGMS unit employed here is the largest commercial unit now in use for producing high quality paper coating clays. It is operated at a fixed field intensity of 20 kilo-gauss generated in an open volume of 7-foot in diameter and 20-inch in length. A stainless steel wool separator matrix of 94% void is placed in the open volume. The coal slurry is pumped through the energized separator matrix at a fixed residence time (flow velocity) until the matrix reaches its loading capacity. After rinse with water, the maqs are sent to a settling pond or a classifier for recovering water for re-use. The tails are collected, dewatered and dried.

By removing 80 to 90% of the pyritic sulfur magnetically and achieving a recovery of 85 to 90% as was demonstrated from the results of reported studies of magnetic desulfurization of pulverized coals in water slurries (16-19,21,31), the process can be used for the cleaning of about one-fifth of the recoverable U.S. coals with a low organic sulfur content of 0.7 to 0.9 Wt% as an environmentally acceptable fuel. A detailed documentation of the reserve and production of U.S. coals which may be magnetically cleanable to 1 Wt% total sulfur according to the Seam, district and county in each state, along with the total and organic sulfur contents can be found in the literature (7). Here, a reasonable range of add-on costs (excluding those for grinding, dewatering and drying) can be estimated for the wet magnetic cleaning of coal slurries designed to achieve the similar desulfurization characteristics as reported in the recent studies (16-19,21,31). The method used for estimating the costs of magnetic desulfurization was based on the technique employed by the Federal Power Commission Synthetic Gas-Coal Task Force in their report on synthetic gas (2,5). The investor capitalization method used in this approach was the discount cash flow (DCF) financing method with assumed DCF rates of return such as 15% after tax. This method essentially determines the annual revenue during the plant life which will generate a DCF equal to the total capital investment for the plant. Several major assumptions were included in the method (2,5): (a) The plant life was assumed to be 20 years with no cash value at the end of life. (b) A straight-line method was used to calculate the annual depreciation. (c) Operating costs and working capital requirements were assumed to be constant during the plant life. (d) The current value of the investment included the cost of capital during the construction period and 100% equity capital was assumed. (e) Total plant investment, return on investment during the plant life and working capital were treated as capital costs in year zero (the year ending with the completion of start-up operations). (f) Start-up costs were treated as an expense in year zero. (g) 48% federal income tax was assumed. Based on these assumptions, equations for calculating the unit costs (\$ per ton coal processed annually) can be suggested from the referenced documents (2,5). They are summarized in Table 1, in which some further cost information used in the present estimation is given. Note that the costs of major installed equipments and the unit costs listed in Table 1 were based on the values of June 1976. For instance, the costs of pump and tank used were estimated first according to reference 6 and then brought them up to date by multiplying a CE plant cost index ratio of (205/113.6); while the cost of the installed HGMS unit with a separator matrix of 7-foot diameter and 20-inch length was estimated to be 1.936 million (11).

The estimated capital investments and unit costs for four typical cases, designed as A-D, are summarized in Table 2. Slurry velocities of 2.61 and 4.0 cm/sec, slurry concentrations of 15,25 and 35Wt%, as well as separation duty cycles from 59.0 to 77.9% have been considered. These separation conditions are similar to those used in the latest pilot-scale investigations reported (16-19,21,31). The results shown in this table clearly illustrate the effects of slurry velocity and concentration, as well as separation duty cycle. For instance, the comparison of cases A-C shows that at the same slurry velocity and similar magnetic desulfurization characteristics, the higher the slurry concentration, the cheaper will be the investment and unit costs. While this observation is to be expected, it is worthwhile to mention that there have been pilot-scale testing data which indicate the fact that increasing the slurry concentration of pulverized Illinois No. 6 coal from 2.57 to 28.4 Wt% did not appreciably change the grade and recovery of the separation. Further effects of processing conditions, as well as operating and cost factors, etc. on the unit costs are illustrated in Table 3. It is seen from the table that by doubling the amount of coal processed per cycle relative to a fixed amount of stainless steel wools packed in the separator matrix, a reduction of the unit cost by about 15% can be achieved. This result shows the importance of the separator matrix loading characteristics on the costs of magnetic desulfurization. Another factor which affects the unit costs considerably is the washing time required in a complete separation cycle. This can be illustrated by comparing items 4 and 6 in Table 3. In particular, the computed results indicate

that doubling the amount of washing water required only leads to a negligible increase (0.27 to 0.60 %) in unit costs. However, if both the amounts of washing water and the washing time are doubled, the unit costs are increased by about 15%. The above observations clearly suggest the important economic incentive for further pilot-scale investigations of the separator matrix loading and washing characteristics in the magnetic desulfurization of coal/water slurry. Finally, item 7 of Table 3 shows that labor cost seems to be a significant fraction of the unit cost. Fortunately, it is not expected that the labor requirement is to be doubled in actual commercial practice from the nominal case in Table 2. This follows because the existing experience in the commercial cleaning of kaolin clays by the HGMS indicate that the labor requirements in both operation and maintenance are minimum (9,23).

In Table 4, the estimated costs of magnetic desulfurization are expressed in terms of the capital and unit costs per ton coal processed annually, and compared with the results of this study. The costs given by Murray (21) were based on the existing cost estimates for kaolin beneficiation by the HGMS given in reference 9. At a residence time of 0.5 minute, the coal feed rate to a commercial HGMS unit of a separator matrix of 7-foot diameter and 20-inch length was set at 100 tons per hour by Murray. This rate appears to be higher than that expected in the commercial practice. In addition, the costs of labor and maintenance per HGMS unit were estimated by Murray to be 1 and 2 \$ per hour, respectively. These costs also appear to be lower than those reported in reference 9. Consequently, the costs estimated by Murray shown in Table 4, especially the unit cost U_0 (0.37\$ per ton processed annually), are believed to be lower than the actual costs. Next, while the costs estimated by Oder (24) seem to be relatively comparable to those obtained in this study, it appears to be difficult to identify clearly the differences in both estimates. This follows because the specific details regarding the costs of major installed equipments, cycle time, and washing time, etc. were not reported in reference 24. Finally, the costs estimated by Trindade (31) are also believed to be lower than the actual costs. Note that in the cost estimation by Trindade, the Carousel separator was taken as the desired HGMS unit, although there have not yet been any testing data reported on the magnetic desulfurization of coal/water slurry using the Carousel separator. Only the separator cost was included as the capital cost in the analysis by Trindade, and it was about one-half of the cost of installing an equivalent cyclic HGMS unit. This led to the relatively low capital investment per ton coal processed, 0.82 to 1.64 \$, estimated by Trindade as shown in Table 4. It may also be noted that the cost estimation method used by Trindade will generally lead to lower unit costs. For instance, by using Trindade's method, the unit cost U_0 obtained in this work at a slurry velocity of 2.61 cm/sec shown in Table 4 will be decreased from 1.06 to 0.85 \$ per ton coal processed annually.

An approximate comparison of estimated capital and unit costs of different pyritic sulfur removal processes currently under active developments (1,4,15,33) is given in Table 5. With the exception of the MAGNEX process (15), all the approaches listed in Table 2 are wet processes, thus requiring relatively comparable dewatering and drying costs. This table indicates that the costs of wet magnetic desulfurization by the HGMS apparently appear to be attractive when compared to those of other approaches, even after adding the necessary costs of grinding, dewatering and drying. However, it should be emphasized that the above comparison is only an approximate one, because of the difference in the methods used in estimating the costs and in the desulfurization characteristics reported, etc. Based on the available cost information on these pyritic sulfur removal processes (1,4,15,33), it is not yet possible to carry out a rigorous comparison.

MAGNETIC DESULFURIZATION OF LIQUEFIED COAL: PROCESS AND COSTS

A flow diagram for the conceptual process for removing the mineral residue from the liquefied SRC by the HGMS is shown in Figure 3. The HGMS unit used here is the same commercial separator employed in the desulfurization of coal/water slurry. The magnetic desulfurization of the liquefied SRC is to be conducted at elevated temperature to reduce the viscosity of the coal slurry. Furthermore, the packed stainless steel

wool matrix is also to be heated up to the desired separation temperature during operation. The elevated temperature in the matrix will prevent the coal slurry from congealing and plugging the matrix. It is also necessary to insulate the heated portion of the matrix from the magnet windings. The insulated matrix is further surrounded by a water jacket. These provisions for heating, insulating and cooling the separator matrix slightly reduce the actual working volume of separator matrix from 7-foot to 6'10" in diameter. In actual separation runs, the unfiltered liquefied SRC is pumped through the energized separator at a constant flow rate until the separator matrix reaches its loading limit. After rinse with a process generated solvent, the matrix is backwashed with the same solvent with the magnet de-energized. The mags are sent to a hydroclone separator. The overflow from the hydroclone is recycled back to the wash solvent tank for re-use; while the underflow is sent to an evaporator to recover the solvent, and the residual solids are packed for other uses. The tails from the separator are sent to a vacuum column to recover the solvent for process recycle and the vacuum bottom is sent to a product cooler to produce the solidified SRC.

The conceptual process is designed to achieve the same extents of inorganic sulfur and matrix loading observed by HRI for slurry velocities varied from 0.25 to 14.0 cm/sec (8). The specific magnetic desulfurization characteristics corresponding to those slurry velocities are summarized as the first three rows of Table 6. Note that according to the survey of the sulfur reduction potential of 455 U.S. coal samples conducted by the Bureau of Mines, the average total and inorganic sulfur contents are 3.02 and 1.91 Wt%, respectively (3). Thus, if the hydrogenation step in the SRC and other related liquefaction processes can remove 70% of the organic sulfur, a reduction of the inorganic sulfur content by about 67% after the hydrogenation will be sufficient for producing a SRC with an emission level smaller than 1.20 lb SO₂/million Btu, assuming that the SRC has a heating value of 16,000 Btu/lb. By using the same method for cost estimation summarized in Table 1 with the exception of replacing the dispersant by steam with a nominal cost of 2\$/1000 lb, the estimated capital investments and unit costs for the conceptual process are presented in Table 6. Here, the costs of majored installed equipments have included those of the HGMS unit, wash solvent tank, feed surge tank, feed pump, flush pump and evaporator, etc. In Table 7, the effect of steam price on the unit cost U₀ of magnetic desulfurization of liquefied coal is illustrated. It is seen that doubling the steam price will increase the unit cost U₀ by 3 to 32% in the range of slurry velocities considered. As steam is mainly used in the process in conjunction with the evaporator for recovering the wash solvent, this comparison also implies that the higher the process throughput, the more expensive will be the operating cost for solvent recovery. Finally, an approximate comparison of the capital investments and unit costs of several solid-liquid separation methods, including precoat filtration, centrifugation, solvent precipitation and HGMS, is given in Table 8 (2). This table shows that although the precoat filtration and the solvent precipitation can generally meet the stringent environmental standards for both sulfur and ash, the costs of these methods are more expensive than those for the HGMS. Thus, there seems to be some economic incentive for using the magnetically cleaned SRC as a feed to boilers which already have electrostatic precipitators. Obviously, additional development work is needed to firmly support this observation.

CONCLUSIONS

In this paper, the latest data from pilot-scale studies of sulfur and ash removal from both pulverized coals suspended in water slurries and liquefied SRC coal by the HGMS have been used to design conceptual processes for the desulfurization. Estimates of magnetic desulfurization characteristics and conceptual process requirements, as well as installation and processing costs have been determined. The results indicate that the magnetic desulfurization appears to be attractive when compared to other approaches for the desulfurization, in terms of costs and performance.

ACKNOWLEDGMENTS

The financial supports provided by the Auburn University Board of Trustees 1975-1976 Special Research Award, the National Science Foundation (Grant Nos. GI-38701 and AER 76-09300), the Gulf Oil Foundation and the Engineering Experiment Station of Auburn University are gratefully acknowledged. The authors also wish to thank Professor Leo Hirth and Mr. M. J. Oak for their assistance in this work.

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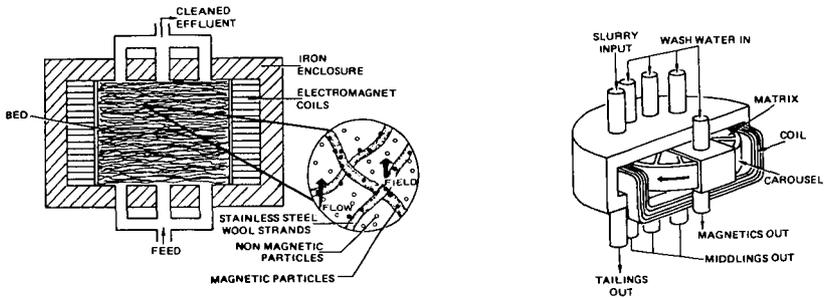


Figure 1 (a) Cyclic High Gradient Magnetic Separator (Left)
 (b) Carousel High Gradient Magnetic Separator (Right)
 (Taken from Reference 25)

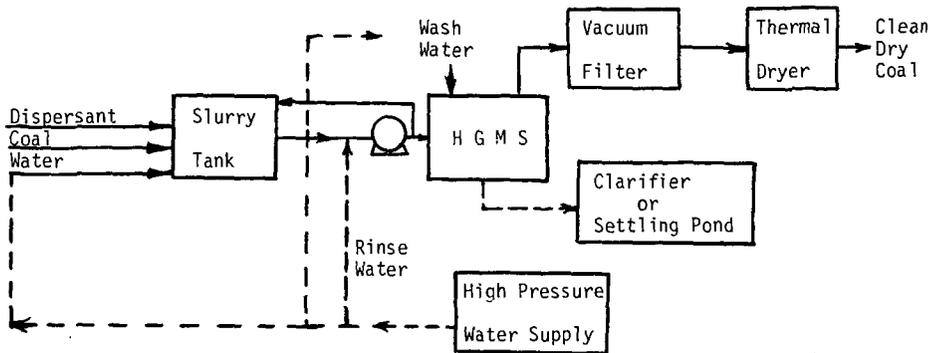


Figure 2. Desulfurization of Coal/Water Slurry by H G M S.

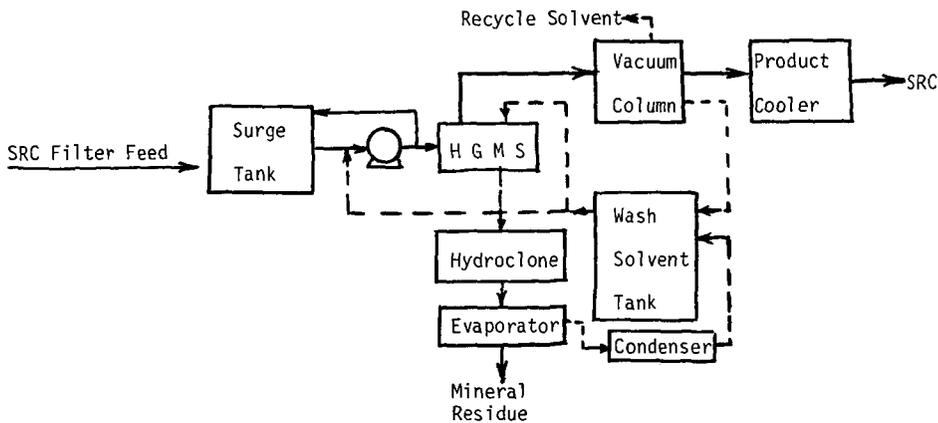


Figure 3. Desulfurization of Liquefied Coal by H G M S.

Table 1
 Basis for Estimating the Unit Costs of
Magnetic Desulfurization of Coal/Water Slurry (2,5,6,11)

A. Investment Costs:

1. Costs of Major Installed Equipments:
 HGMS unit, pump, tank, etc.

2. Add 20% Contingency
 Total Investment, I \$

B. Operating Costs:

1. Dispersant (57¢/lb)
 2. Electric Power (2¢/KWH)
 3. Water (3¢/1000gal)
 4. Operating Labor (men/shift x 8304 man-hours/year x 6.5\$/man-hour)
 5. Maintenance Labor (1.5% of investment cost)
 6. Supervision (15% of operating and maintenance labor costs)
 7. Operating Supplies (30% of operating labor cost)
 8. Maintenance Supplies (1.5% of investment cost)
 9. Local Taxes and Insurance (2.7% of investment cost)
- Annual Net Operating Cost, N \$
 Coal Processed Annually, G tons

C. Unit Costs (\$/ton coal processed annually):

1. Based on 0% DCF Rate of Return, $U_0 = (N+0.05I)/G$
2. Based on 15% DCF Rate of Return, $U_{15} = (N+0.34749I)/G$
3. Based on Capital Amortization over
 20 Years at 10% Interest Rate, $U = (N+0.11746I)/G$

Table 2

Cost of Desulfurization of Coal/Water Slurry by HGMS
Using Separator Matrix of 7-Foot Diameter and 20-Inch Length

	<u>Case A</u>	<u>Case B</u>	<u>Case C</u>	<u>Case D</u>
1. Slurry Velocity, cm/sec	2.61	2.61	2.61	4.0
2. Slurry Concentration, Wt%	15	25	35	25
3. Coal Feed Rate, ton/hr	44.77	66.13	83.07	89.61
4. Cycle Time, minute	9.00	6.10	4.85	4.50
5. Duty Cycle, %	77.9	67.4	59.0	59.6
6. Tons of Coal Processed Per Cycle	403	403	403	403
7. Unit Costs, \$ Per Ton Coal Processed Annually				
U	2.083	1.401	1.109	1.067
U ₀	1.802	1.063	0.858	0.829
U ₁₅	3.676	2.479	1.967	1.880
8. Capital Investment Per Ton Coal Processed Annually, \$	6.93	4.69	3.73	3.53

Basis:

- (1) Amount of coal processed per cycle=7 times weight of stainless steel wool
- (2) Amount of rinse water required per cycle=1.5 times volume of separator matrix
- (3) Amount of wash water required per cycle=7 times volume of separator matrix
- (4) Velocity of rinse water=velocity of coal slurry
- (5) Washing time=1 minute
- (6) Time for energizing the magnet=0.5 minute
- (7) Labor required=2 men per shift
- (8) Amount of dispersant required=10 ppm

Table 3

Sensitivity Analysis of Unit Costs (\$ Per Ton Coal Processed Annually)
of Desulfurization of Coal/Water Slurry by HGMS

	U_0		U_{15}	
	\$	%Change	\$	% Change
1. Basis: 2.61 cm/sec, 25 Wt% slurry, and other conditions in Tables 1-2.	1.0628	0.00	2.4117	0.00
2. Amount of Coal Processed Per Cycle Doubled	0.9004	-15.28	2.0341	-15.66
3. 25% Reduction in Capital Investment	0.9389	-11.66	1.9506	-19.12
4. Amount of Washing Water Required Doubled (Washing Time Unchanged)	1.0691	+0.60	2.4181	+0.27
5. Cost of Water Increased 5/3 Times (5¢/1000gal)	1.0835	+1.95	2.4324	+0.86
6. Both Amounts of Washing Water and Washing Time Doubled	1.2256	+15.32	2.7883	+15.62
7. Labor Requirement Doubled	1.3587	+27.82	2.7077	+19.12

Table 4

Comparison of Estimated Costs of Desulfurization
of Coal/Water Slurry by HGMS*

	<u>Murry (21)</u>	<u>Oder (24)</u>	<u>Trindade (31)</u>	<u>This Work</u>
1. Slurry Velocity, cm/sec	1.7-3.4	2	4	2.61 4.0
2. Slurry Concentration, wt%	30			25
3. Unit Costs, \$ Per Ton Coal Processed Annually				
U_0	0.37	0.70-0.25	0.39-0.84	0.22-0.45
U_{15}		2.47-0.93		1.06
4. Capital Investment Per Ton Coal Processed Annually, \$	2.02	5.95-2.28	1.64	0.82
				2.48
				4.69
				3.53

*Note: See text of the paper for further discussion.

Table 5

Approximate Comparison of Estimated Capital and
Unit Costs (\$ Per Ton Coal Processed Annually)
of Different Pyritic Sulfur Removal Processes

<u>Process</u>	(\$ Per Ton Coal Processed Annually)		
	<u>U₀</u>	<u>U₁₅</u>	<u>Capital Investment</u>
1. MAGNEX-Hazen Reserach, Inc. (15)	5.83	7.05	4.17
2. Froth Flotation- Bureau of Mines (15)	2.77	4.47	5.71
3. Meyers- TRW Systems and Energy (33)	6.00-14.00		13.80 (leaching only)
4. Ledgemont Oxygen Leaching- Kennecott Copper Corporation (1)	Comparable to Meyers		11.30 (leaching only)
5. HGMS-This Work, See Table 2	0.83-1.06	1.88-2.48	3.53-4.69

Table 6

Costs of Desulfurization of Liquefied Coal by HGMS
Using Separator Matrix of 6'10"-Diameter and 20"-Length

1. Slurry Velocity, cm/sec	0.25	1.60	2.71	2.71	5.42	14.0
2. Apparent % Pyritic Sulfur Removal	90	87	78	74	67.7	66.4
3. Cycle Time, Minute	45.86	9.15	5.84	11.33	4.32	2.39
4. Duty Cycle, %	85.8	74.9	66.3	82.6	59.8	33.5
5. Tons of Liquefied Coal Processed Per Cycle	22.52	24.71	23.63	57.21	31.48	25.25
6. Filtration Rate Based on Actual Filtering Time, GPM/ft ²	3.74	23.56	39.91	39.91	79.82	206.2
7. Unit Costs, \$ Per Ton Coal Processed Annually						
U ₀	6.58	1.45	1.10	0.76	0.67	0.61
U ₁₅	15.65	3.31	2.53	1.80	1.54	1.37
U	8.64	1.87	1.42	1.00	0.87	0.79
8. Capital Investment Per Ton Coal Processed Annually, \$	30.5	6.26	4.79	3.49	2.89	2.53

Table 7

Effect of Steam Price on the Unit Cost for Desulfurization of Liquefied Coal by HGMS

<u>Slurry Velocity, cm/sec</u>	<u>Unit Cost U₀, \$ Per Ton Liquefied Coal Processed Annually</u>		<u>% Increase from Case A to Case B</u>
	<u>Case A</u>	<u>Case B</u>	
0.254	6.580	6.600	3.0
2.71*	1.100	1.311	30.0
2.71**	0.763	0.850	11.0
5.42	0.670	0.836	25.0
14.00	0.614	0.811	32.0

Case A: Steam Price = 2 \$/1000 lb.

Case B: Steam Price = 4 \$/1000 lb.

* Amount of Liquefied Coal Processed Per Cycle = 23.63 Tons
=25.83 Times of Stainless Steel Wool Weight.

** Amount of Liquefied Coal Processed Per Cycle=57.21 Tons
=62.53 Times of Stainless Steel Wool Weight.

Table 8

Approximate Comparison of Capital and Unit Costs
(\$ Per Ton Liquefied Coal Processed Annually) of
Different Solid-Liquid Separation Methods (2)

<u>Method</u>	(\$ Per Ton Liquefied Coal Processed Annually)		
	<u>U₀</u>	<u>U₁₅</u>	<u>Capital Investment</u>
1. Rotary Drum Filtration (SRC)	2.77	8.10	17.89
2. Pressure Leaf Filtration (SRC)	7.03	9.87	9.52
3. Two-Stage Centrifugation* (H-Coal)	2.57	7.57	15.38
4. Solvent Precipitation (H-Coal)	1.82	3.98	6.70
5. HGMS*			
5.4 cm/sec	0.68	1.54	2.89
2.7 cm/sec	1.10	2.53	4.79

* The ash content of separated product may not satisfy EPA specification, and the use of electrostatic precipitators may be needed.