# THE USE OF MAGNETIC FORCES TO UPGRADE LOW RANK COALS

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## ABSTRACT

This talk will present the basis for magnetic upgrading of low rank coals at the power plant using the MagMill™. The MagMill™ is a pulverizer and a dry magnetic separator operating together as a unit and has been shown to be effective in separation of minerals and trace metals from coal. This presentation will address the requirements for application of magnetic forces and the nature of and the reasons for the two stage separator employed in the MagMill™ and will draw upon examples of dry magnetic separation of low rank coals from the US and Thailand.

## INTRODUCTION

Application of magnetic methods to coal cleaning has been of interest for many years because of the association of iron with ash and sulfur in coal. However, in the pre-1970's it was felt that magnetism would never play a role in desulfurizing coals because of the weak magnetism of iron pyrite.[1] Nonetheless, the use of magnetic methods received renewed interest in coal cleaning in the late 1970's because of the development of High Gradient Magnetic Separation (HGMS) technology for commercial beneficiation of kaolin clay.[2] The novel wet technology demonstrated that feebly magnetic impurities such as iron pyrite could be removed from a mineral slurry but that the cost, including grinding to liberation and slurry dispersion, was too great for coal cleaning at the time. In that same time frame, novel "open gradient" methods were tested for application to dry processing of minerals and coal.[3] The technologies were based on the use of superconducting magnet technology to achieve the magnetic forces necessary for separation of weakly magnetic materials such as iron pyrite. The applications did not go forward for a variety of technical and economic reasons primarily associated with the cost and complexity of superconducting magnet technology at the time.

Today, the prospects for application of magnetic methods for cleaning coal are changing both because of the advent of new technology and because of the evolving high cost of environmental compliance in generating electricity by burning coal. With sulfur emissions allowances now selling for over $700 per ton of $SO_2$, it costs $14 more to burn a ton of coal containing 1% sulfur than it did in the 1970's. Similarly, with the cost of mercury separation estimated at $70,000 per pound of mercury, burning a coal with 0.1 ppm mercury could soon also cost an additional $14 more than in the earlier time frame. Environmental issues such as these and the advent of new technology are changing the outlook for using magnetic forces in pre-combustion cleaning of coal.[4]

The focus of this paper is on application of dry magnetic separation technology to coal cleaning and specifically to coal cleaning at the power generating station. Unlike more conventional applications – such as combining dry magnetic separation and air jig cleaning at the mine[5,6] – dry cleaning at the power station encompasses all of the criteria for successful application in a novel way. The market for this technology originated in the US where environmental constraints now place severe penalties on burning coals containing even modest amounts of sulfur and hazardous trace metals. The power plant is the logical place to prepare clean burning coal because the pulverizer for grinding to liberation is in place, the coals are dried in the pulverizer, no additives of any type are employed, and the clean product is blown directly to the burner with no fine coal transportation or storage.

One interesting aspect to this idea is that it is a ideal way for a coal company to extend its range of business. No one knows better than the coal company about the business of coal cleaning. It would be natural for the coal company to operate the cleaning unit at the front end of the generating station under contract for the power generator. This assures the coal sales contract for the coal company and leaves the power generator to the business of operating the balance of plant. There is a precedent for this type of operation in the petroleum industry where independent parties contract to do major unit operations at the refinery in order to gain access to specialty feedstocks for their products.[7]

## THE MagMill™

The MagMill™ [U.S. Patent No. 6,820,829 (November 23, 2004) South Africa 2002/6310 (October, 2003) and other foreign patents pending] is a novel combination of a pulverizer and a dry electric/magnetic separator working together at the front end of a coal-fired power plant or any other facility needing a special clean coal feed such as a coal gasifier. The MagMill™ and its applications have been described extensively in the literature.[8] The examples presented here are intended to support understanding of the concept. The method of operation is suggested in the schematic of Figure 1 which is a vertical section through a B&W MPS mill.

Feed coal falls onto the grinding table inside the pulverizer 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 and 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

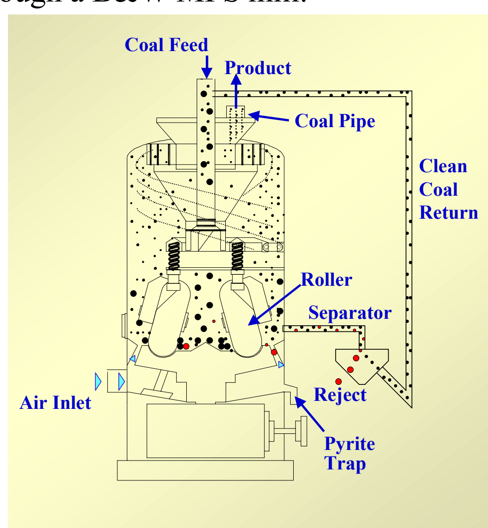


Figure 1. Vertical Section Through a MagMill™

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™ technology withdraws a portion of this concentrated stream of minerals from the mill through the mill wall and passes it to a dry magnetic separator outside the pulverizer. The separator recovers a middling product and sends it back to the mill for additional grinding and rejects concentrated mineral streams that otherwise would have gone to the burner.

By way of example,
Table I shows the levels of minerals and trace metals that have been withdrawn from operating pulverizers at three power stations and processed through a dry magnetic separator. The rates of withdrawal are small compared to the rates of feed to each of the pulverizers. The CE Raymond mill is located at a power station in North Central Pennsylvania which was burning a raw Lower Kittanning seam coal. The middle plant is an Ohio plant which was burning a cleaned Pittsburgh seam coal from Southwestern Pennsylvania. The bottom plant is in Northern West Virginia and is burning a blend of 80% washed Pittsburgh seam coal from a wash plant in Southwestern Pennsylvania and 20% raw Pittsburgh seam coal from upper West Virginia.

Table I. Mineral Concentrations in Feed, Mill Concentrated Stream (MCS) and Magnetic Separator Reject for Samples Obtained at Three Different Power Plants

| | **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 |

The rows labeled **Feed** are the quality of the coal entering the pulverizer. The material which has been withdrawn through the pulverizer wall is labeled **MCS** (mill concentrated stream). Note the increase in the concentrations of ash, sulfur, trace metals, etc. The material labeled **MS Reject** is the reject stream from the magnetic separator. Note the elevated concentrations of the streams of ash, sulfur, pyritic sulfur, mercury, and arsenic. The reject stream from the Pennsylvania plant was determined to be non-hazardous. The minerals are in the stable forms in which they occur in the ground. The stream requires neutralization before disposal. This can be done with post-combustion ash resources available at the power plant.

Figure 2 illustrates the arrangement employed in the 3000 pound coal per hour beta prototype. That test work, carried out at the Bradley Pulverizer Company in Allentown, PA, employed ten tons each of two raw coals from North Central PA. The results have been published elsewhere.[9]

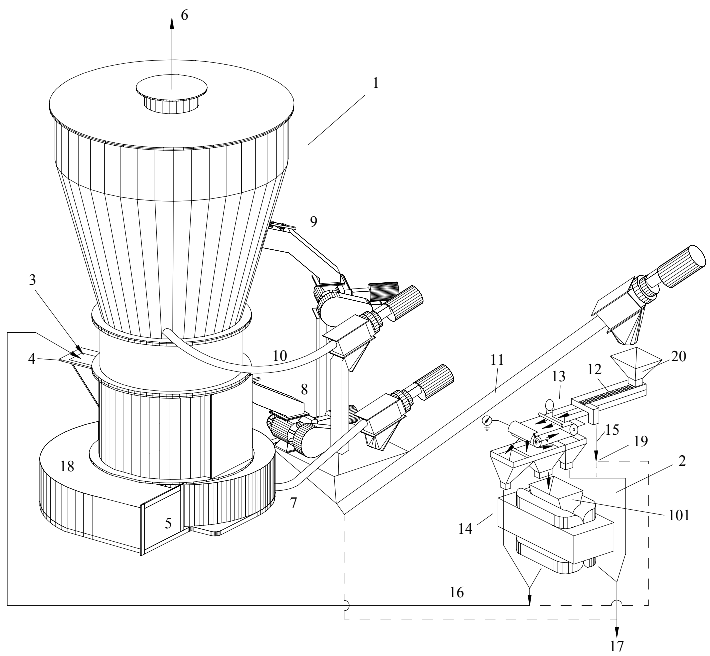


Figure 2. 3000 Pound Coal Per Hour Hercules Air Swept Ring/Roller Pulverizer with Two Stage ParaMag™ Magnetic Separator Attached

The material withdrawn from the mill is fed to a screen at the input to the magnetic separator where oversize material can be separated for returned to the mill or discarded depending on quality. The underflow from the screen is fed to a vibratory feeder and then onto a belt separator for separation of strongly magnetic particles which otherwise would plug the flow path of the second stage electromagnet separator [US Patents 5,017,283 (May 21, 1991), 5,127,586 (July 7, 1992), 5,176,260 (January 1, 1993)] employed to separate pyrite and other weakly magnetic particles. Modifications of the belt separator have been made to introduce electric forces [the ElectriMag™ Separator, US 6,540,088 (April 1, 2003)] and other forces (the VacuMag™ Separator, patent pending) to enhance the primary separation.

## CRITERIA FOR APPLICATION OF MAGNETIC METHODS TO DRY CLEANING OF COALS OF ANY RANK

Just as any physical or chemical method, magnetic methods are not suitable for cleaning all coals. In addition to being economical and to having a market, magnetic methods must have the following five attributes.

1. The mineral inclusions or elements to be removed must have a magnetic signature sufficiently different from that of the hydrocarbon component of the coal to permit separation

on a practical basis. The hydrocarbon components of the greatest number of coals are diamagnetic,[10] that is, they are very weakly repelled by magnetic fields. The materials to be separated must be at least paramagnetic, i.e., weakly attracted to magnetic fields. This difference in magnetism is the fundamental basis of any magnetic method. The source of the paramagnetism in the inorganic fraction of coal is association with magnetic elements such as iron. There are many ways in which this association can happen and only small amounts of the magnetic element, measured in atomic percent, are necessary. These possibilities are cataloged and values of magnetic properties are presented elsewhere.[11]

The unit of magnetism used here is specific magnetic susceptibility per gram, $\chi$, measured in units of $10^{-6}$ emu/g-Oer. The emu is the electromagnetic unit of magnetic moment, g is grams, and Oer is the electromagnetic unit of magnetic field intensity, H. emu/g-Oer is equivalent to cc/g and the units for susceptibility are expressed as micro cc/g, or μcc/g.

For example, some values of concentrations and magnetic susceptibilities of a variety of mineral forms separated from Lower Kittanning seam coal by dry magnetic separation are given in Table II. The basic mineral form need not be paramagnetic to be separated. Its association with other more magnetic elements and minerals dictates separability., e.g., see quartz and massive quartz in Table II.

Table II. Composition and Magnetic Susceptibility (μcc/g) of Products of Magnetic Separation of Lower Kittanning Seam Coal (concentrations in volume percent)[12]

| **Magnetic Fraction** | **Coal** | **Clay** | **Massive Clay** | **Quartz** | **Massive Quartz** | **Calcite** | **Pyrite** | **Other** |
|---|---|---|---|---|---|---|---|---|
| Feed | 86.4 | 2.6 | 3.0 | 1.8 | 0.0 | 0.6 | 2.6 | 3.0 |
| Clean | 93.7 | 1.6 | 0.2 | 1.2 | 0.0 | 0.0 | 0.8 | 2.5 |
| First Refuse | 18.0 | 3.4 | 16.8 | 8.9 | 42.2 | 2.8 | 5.9 | 2.0 |
| Second Refuse | 33.6 | 5.6 | 26.0 | 6.6 | 0.0 | 6.6 | 17.2 | 4.4 |
| Magnetic Susceptibility (μcc/g) | -.68 | -0.5 | 7.5 | -0.5 | 95 | 1 | 0.3 | 9.5 |

Not all coals which exhibit significant paramagnetism separate well. An example can be found in lignite from Thailand. Several samples of lignite from various locations in Thailand were supplied by the Mine Evaluation and Development Division of the Electric Generating Authority of Thailand.[13] These materials were subjected to dry magnetic separation for evaluation of the potential for separation of sulfur and ash. Gross characteristics of one sample is given in Table III.

Table III. Gross Characteristics of Samples from MAE MOH #3 Mine. All Values on a Dry Basis

| | | | **Forms of Sulfur** | | | |
|---|---|---|---|---|---|---|
| **MAE MOH #3** | **Ash** | **Sulfur** | **Pyrite** | **Sulfate** | **Organic** | **Susceptibility** |
| | **(wt.%)** | | | | | **(μcc/g)** |
| | 37.44 | 4.89 | 1.34 | 1.38 | 2.17 | 2.17 |

The coal has high levels of ash and sulfur with large amounts of iron pyrite and sulfate sulfur which is consistent with the rather high value of the paramagnetic susceptibility for the whole coal sample. The coal as received was about 5000 Btu/Lb. Analysis of screen fractions is given in Table IV.

Table IV. Size Fractions of MAE MOH #3 Coal Sample

| **MAE MOH #3** | | | | **Forms of Sulfur** | | | |
|---|---|---|---|---|---|---|---|
| | **Recovery** | **Ash** | **Sulfur** | **Pyrite** | **Sulfate** | **Organic** | **Susceptibility** |
| | **(wt.%)** | | | | | | **(μcc/g)** |
| 8×16 | 34.66 | 32.84 | 4.18 | 1.43 | 0.40 | 2.35 | 2.27 |
| 16×30 | 23.01 | 34.44 | 4.07 | 1.27 | 0.48 | 2.32 | 2.26 |
| 30×50 | 15.32 | 36.55 | 4.12 | 1.2 | 0.63 | 2.29 | 2.38 |
| 50×100 | 9.21 | 38.90 | 4.59 | 1.17 | 1.17 | 2.25 | 2.94 |
| 100×200 | 6.62 | 42.94 | 5.58 | 1.13 | 2.31 | 2.14 | 2.19 |
| 200×325 | 3.22 | 46.62 | 7.14 | 1.19 | 4.03 | 1.92 | 2.36 |
| -325 | 7.96 | 60.24 | 12.63 | 1.68 | 9.31 | 1.64 | 2.91 |
| Cumulative | 100.00 | 37.63 | 5.04 | 1.33 | 1.48 | 2.24 | 2.39 |

It is apparent that discarding the minus 100 mesh fraction of this coal, about 18% of the weight, would result in a reduction in the sulfur and ash of about 17% and 8% respectively because ash, sulfur, and mineral forms of sulfur increase in the smaller particle sizes. In order to see effects on a coarser size, a 30×50 mesh size fraction of sample J(4,5) +Q#3, a blend with MAE MHO #3, was magnetically separated into 9 fractions of differing magnetic susceptibility. The results are shown in Table V.

Table V. Results of Dry Magnetic Separation of Sample, J(4,5) + Q #3, sorted on Ash

| | **Weight %** | **Ash wt.%** | **Sulfur wt.%** | **Susceptibility μ cc/g** |
|---|---|---|---|---|
| | 0.26 | 22.94 | 1.95 | 1.98 |
| | 0.68 | 20.62 | 2.28 | 0.67 |
| | 2.24 | 18.92 | 3.11 | 0.47 |
| | 6.07 | 24.43 | 3.83 | 0.95 |
| | 59.34 | 42.8 | 4.03 | 2.53 |
| | 27.95 | 30.35 | 4.26 | 1.55 |
| | 2.4 | 41.49 | 4.52 | 3.42 |
| | 0.53 | 34.59 | 5.68 | 2.59 |
| | 0.53 | 61.98 | 11.56 | 40.1 |
| Composite | 100.00 | 37.49 | 4.10 | 2.32 |

If all points are used, the ash and sulfur of the magnetic isolates are correlated as shown in Equation (1).

$S = -1.45 + 0.18 * Ash$, $RSq = 0.784$ Eq. (1)

Excluding the point of highest ash and susceptibility, ash and magnetic susceptibility are correlated for the magnetic isolates as shown in Equation (2),

$A = 15.57 + 7.88 * Susceptibility$, $RSq = .782$. Eq. (2)

These equations are solved for Ash = 8.06 wt.% and $\chi = -0.95$ @ S = 0. This indicates that about 79%, 100*(1-7.97/37.49), of the ash in this screen fraction is paramagnetic and in principle could be removed by magnetic methods. Further, the magnetic susceptibility at S=0, ie.-0.96 μcc/g, is a reasonable number. The overall relationship between ash, sulfur, and magnetic susceptibility is similar to that observed in numerous measurements of bituminous coals of Northern Appalachia in the US.

Magnetic separation could produce a low sulfur coal from this material but, without additional size reduction, the recovery will be low. The magnetic minerals are probably disseminated in sizes smaller than 50 mesh in this lignite.

2. The application can be either wet or dry. This paper focuses on dry applications. For dry methods, it is necessary that the surface moisture be generally below 6%. The drying operation can be supplied by a variety of means such as an associated cleaning operation, e.g., an air jig, a fluidized bed drier, or a pulverizer.

3. The contaminants must be physically separated from the carbon matrix for particle sizes smaller than nominally 8 mesh for the method to achieve high values of recovery. See discussion of magnetic separation of lignite samples from the MAE MHO #3 mine above. The magnetic method presently employed in the MagMill™ is capable of efficient separation of iron pyrite down to nominally 200 mesh (74 microns) where the particles are liberated. This is illustrated for Lower Kittanning Seam raw coal in Table VI.

Table VI. Effects of Particle Size on Separation of Iron Pyrite Particles from Lower Kittanning Raw Coal

| | **Reduction In Pyritic Sulfur, wt.%** | | |
|---|---|---|---|
| **Screen Fraction** | **Btu Recovery, %** | | |
| **Mesh** | **80** | **85** | **90** |
| 30×50 | 79.8 | 77.0 | 71.9 |
| 50×100 | 78.6 | 77.2 | 75.9 |
| 100×200 | 74.0 | 70.2 | 61.8 |
| 200×325 | 51.8 | 49.2 | 45.7 |
| -325 | 0.5 | 0.5 | 0.4 |

It is important to note two things in the data for Table VI. First, in the MagMill™ configuration, all the coal is size-reduced to pass 200 mesh whereas in conventional coal cleaning, the fine coal cleaned is restricted to that part of the nominal 1 or 2 inch topsize coal which passes typically 30 mesh. Minerals in the coarser size fractions are not liberated as they are with the MagMill™. Secondly, it is to be noted that the results shown in Table VI are for direct magnetic separation of the raw coal and not for a concentrated coal fraction withdrawn from a pulverizer as is the practice with the MagMill™. The two samples are different since the pulverizer acts as a first stage concentrator based on differences in hardness and density. The overall effect for the MagMill™ can be better as is shown by the results obtained in the 3000 pound per hour beta prototype testing which were comparable or better than that expected for Level IV coal cleaning.

4. For the MagMill™ technology, it is ideally preferred that the minerals liberate in the 8 mesh by 200 mesh size range. This distinguishes the magnetic method from conventional air cleaning processes which are applicable to coals finer than nominally 60 mm topsize but coarser than approximately ¼ inch.[14]

   By way of example, the North Dakota lignites studied by Falkirk Mining Company are low rank coals which liberate paramagnetic minerals in the appropriate size range, as evidenced by the beneficial effect of adding the dry magnetic separator to cleaning of the minus ¼ inch size fraction discarded by an air jig (patent pending).[15] Further, results of cleaning an Adaville series coal from the Kemmerer Mine[16] which is neither bituminous nor sub-bituminous illustrates that better separation results could be obtained with modest additional grinding as compared to the work involving the air jig and the dry magnetic separator.

5. Lastly, for the MagMill™ application, it is desirable that the minerals be harder and denser than the coal.

## CONCLUSIONS

Magnetism has a role to play in cleaning coals of all ranks. Magnetic forces are intense and can be made very specific. Magnetic separators are compact in size and are well suited to retrofitting inside power plants where a whole new opportunity for coal cleaning is opening. Developments in modern magnet technology are reducing costs and improving efficiency of separation. The technology is applicable to all coals for which there is sufficient iron or other magnetic elements associated with the mineral matter in the coal. At present, dry methods are generally restricted to separation of particles coarser than 200 mesh. Combining triboelectric and magnetic separators and magnetism with other force fields offers the possibility of extending the size range to even smaller particles.

## ACKNOWLEDGEMENTS

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