FACTORS IN EVALUATION OF NEW METHODS OF LIBERATION AND SEPARATION OF PYRITE AND OTHER MINERALS FROM COAL

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Introduction

Present methods of coal cleaning are based on one or more of these common factors:

(1) appearance - as in hand cleaning

(2) shape and toughness - as in Bradford-type rotary breaker

(3) specific gravity - as in pneumatic cleaning, jigging, and heavy media separation

(4) surface phenomena - as in froth-flotation or oil agglomeration

Electrostatic separators are widely used in mineral beneficiation, especially for beach sands, but have not achieved much acceptance in the coal industry.

Before considering factors involved in new methods of liberation and separation of mineral matter from coal, the limitations of the methods already in use should be recognized. These limitations are mainly economic but some are based upon a distinct lack of appreciation for the mode of occurrence of mineral matter in coal. Large sizes of coal can be economically cleaned by simple gravity methods and suitable products are prepared for the market by crushing and screening the cleaned coal. Fine coal is either (a) cleaned separately and blended with larger sizes, (b) blended uncleaned with larger sizes, (c) rarely cleaned and sold as a separate product, or (d) discarded. With ever increasing application of mechanical mining techniques the larger proportion of fines produced now prohibits any coal to be discarded other than extreme fines, and even these fines, because of water clarification problems, are being recovered at some preparation plants.

There is no problem in beneficiation where mineral matter in the form of large pieces of roof and floor rock, thick partings, large concretions or lenses of clay, shale, and pyrite are the common impurities. Ordinary jigging or the use of a sand cone will readily remove these gross impurities from the coal. Separation and removal of large, tough, tabular pieces of rock and mineral is simply performed by the Bradford rotary breaker. The details of these devices and almost every other coal preparation apparatus are given in "Coal Preparation," edited by D. R. Mitchell.(1)

Fine coal cleaning may be considered from two different viewpoints, depending on the nature of the coal and its associated impurities and depending on the ultimate market. Where a low grade coal is being processed the fine coal may not require cleaning prior to blending with other coal unless the percentage of non-combustibles is so high as to severely affect the quality of the entire blend. For premium grade coal, especially metallurgical coal, the fines may represent an appreciable percentage of low-sulfur coal - an irreplaceable commodity.

Fine coals, down to about 48 mesh, may be cleaned on concentrating tables, or by froth flotation, a process which is restricted almost exclusively to the premium low-sulfur coals. With a sufficient number of cells it appears that there is no lower limit to the size of the coal cleaned by froth flotation. Two methods of washing fine coal that have recently been introduced from abroad are modifications and extensions of the equipment already used in coal preparation plants - the feldspar jig[2] and the Dutch State Mines heavy medium cyclone.[3]

Some concept of the magnitude of fine coal cleaning is to be gained from inspecting the data in Table I which shows the tonnages and percentages of bituminous coals and lignite mechanically cleaned in the years 1948 and 1958.

TABLE I. COMPARATIVE DATA FOR BITUMINOUS COALS AND LIGNITES MECHANICALLY CLEANED DURING 1958 AND 1948[4]

	1000's of Net Tons		Percentage of Total	
	1958	1948	1958	1948
Jigs	115,321	87,500	44.5	48.4
Concentration Tables	18,142	4,360	7.0	2.4
Classifiers	8,793	18,304	3.4	10.1
Launders	6,768	16,768	2.6	9.3
Dense Medium Processes	52,735	20,638	20.4	11.4
Jigs and Tables	10,076	5,252	3.9	2.9
Other Combinations	28,318	11,816	10.9	6.5
Pneumatic	18,882	16,216	7.3	9.0
Total	259,035	180,880	100.0	100.0
Percentage of Total Coal Production Mechanically Cleaned	63.1	30.2		
Percentage of Refuse Discarded From Raw Coal	19.3	16.0		

These figures, taken from the Bureau of Mines Yearbook for 1958[4] are the latest such complete data publicly available. The twofold increase in the percentage of coal mechanically washed from 1948 to 1958 is not at all surprising since the rate of mechanical mining and machine loading has sharply increased during the same time interval. Consequently, fine coal cleaning has become increasingly important, and statistics on fine coal cleaning facilities show an upward trend in the application of the older, established methods of fine coal cleaning. Acceptance of the newer techniques of fine coal cleaning, such as application of the feldspar jig, heavy media cyclones, and the recently repopularized froth flotation of coal fines has not yet reached the level that significant trends can be evaluated - but there can be no doubt that there will be an increase in the use of these techniques. Data from "Coal Age"[5] show that during 1959 seven froth flotation plants with a combined capacity of 313 tons per hour were contracted for by the coal industry, while "Coal Age"[6] shows that during 1958 eight froth flotation plants were contracted for, of which six had a combined capacity of 149 tons per hour with the capacities of the other 2 plants not disclosed. A capacity of 462 tons per hour may not seem impressive, but the aggregate capacity of these new plants alone, operating at two shifts a day for only 200 days, becomes more than 180,000 tons a year.

The application of these techniques to fine coal cleaning has resulted in a decrease in the waste of a valuable raw material, and with proper care, at no reduction in the quality of the coal shipped to the consumer.

New Factors

All commercial processes for cleaning coal are based upon practical application of standard washability tests. Generally these sink and float washability tests are adequate for coal preparation plants which are designed to meet specifications based on these tests. Factors that have not been considered in the design of coal cleaning plants are:

(1) Size distribution of mineral particles in the coal.

(2) Spatial arrangement of minerals through the coal substance.

(3) Differential grindability of coal and its constituents, and the influence of mineral matter composition on coal grindability.

Size of Mineral Particles

The size of mineral particles and their distribution is fundamental to the washability characteristics of any coal. In making routine washability tests at any predetermined specific gravity the sole controlling factor as to whether a free-settling particle will report to the sink or to the float fraction is the proportion of high-specific-gravity mineral matter in that particle. Where a large fragment sinks because a small single grain of mineral matter is included, it is a relatively simple matter to recycle that particle to a crusher and to make the separation on a second pass. But where a similar large particle contains an equivalent amount of mineral matter as many small disseminated grains, rather than as one large grain, simple crushing will fail to release sufficient mineral particles from the coal to permit a clean separation by gravity methods. Fortunately, this has not been the situation for many of the commercially important coals, otherwise beneficiation by the relatively simple means heretofore developed would not have been possible. The issue now is to what extent does this condition prevail in coals which cannot be beneficiated to a more desirable level of ash and sulfur content by conventional coal cleaning methods?

An estimation of the relative size of mineral grains in coal can be made from grain counts and size measurements of minerals in surface sections of coal by micrometric methods. In the example to be cited only measurements of pyrite grains were made because of the emphasis on sulfur in the project for which the research was conducted. Polished surface sections were made of samples of five test coals and of separates prepared from these coals as described here:

(1) raw run-of-mine coal crushed to 1/2" x 0"

(2) float fraction (1.58 Sp. Gr.) of 30 mesh x 0" coal

(3) sink fraction (1.58 Sp. Gr.) of 30 mesh x 0" coal

(4) float fraction (1.58 Sp. Gr.) of 1/2" x 30 mesh coal

Micrometer measurements were made on at least 500 to 1000 pyrite grains from samples prepared from each of the separates described for all five test coals. These data are summarized in Table II. While quantitative as to the size of pyrite grains relative to each other, the data do not take into account the grouping or bunching of pyrite grains at any particular locus or along a particular plane.

From the data in Table II it can be seen that a very large percentage of pyrite particles are extremely small, with from 70 to 98 percent of the measured particles smaller than 20 microns in diameter. Yet, with such a range of sizes, the relative weight percentage of these particles ranges from a low of about 1.3

TABLE II. PYRITE PARTICLE SIZE DATA FOR TEST COALS AND THEIR FLOAT-SINK FRACTIONS (Sp. Gr. 1.58)

(Data are reported as the percentage of pyrite particles within a size range and as the relative weight percent of particles as determined by computing the average volume of pyrite particles within the size range.)

Size range, microns	Average vol. of particles, cu. microns	Original Coal 1/2" x 0"		Float 30 mesh x 0"		Sink 30 mesh x 0"		Float 1/2" x 30 mesh	
		% Particles in size range	Relative wt. %	% Particles in size range	Relative wt. %	% Particles in size range	Relative wt. %	% Particles in size range	Relative wt. %
Kentucky No. 11 Coal									
< 5	15.6	40.0	0.2	66.8	0.5	58.7	--	26.8	--
5 - 20	1950	55.0	42.5	31.6	33.0	58.7	0.5	65.4	11.3
20 - 40	27 x 10^3	4.9	49.7	1.1	16.0	23.2	2.7	7.4	18.3
40 - 75	18.9 x 10^4	0.1	7.6	0.5	50.5	11.6	9.4	--	--
75 - 150	19.5 x 10^5	--	--	--	--	5.1	42.0	0.4	70.4
150 - 250	8 x 10^6	--	--	--	--	1.2	41.0	--	--
> 250	52.5 x 10^6	--	--	--	--	0.2	4.4	--	--
Pittsburgh Bed Coal (W. Va.)									
< 5	15.6	25.7	--	44.8	0.1	48.9	--	45.2	--
5 - 20	1950	44.8	1.3	44.0	13.9	48.9	0.2	37.8	3.0
20 - 40	27 x 10^3	17.3	7.0	9.8	43.0	29.2	1.5	13.0	14.6
40 - 75	18.9 x 10^4	9.8	2.8	1.4	43.0	11.5	0.4	3.3	25.8
75 - 150	19.5 x 10^5	2.2	64.7	--	--	7.5	27.7	0.7	56.6
150 - 250	8 x 10^6	0.2	24.2	--	--	2.5	30.4	--	--
> 250	52.5 x 10^6	--	--	--	--	0.4	39.8	--	--
Meigs Creek No. 9 Coal (Ohio)									
< 5	15.6	31.5	0.1	28.7	--	38.4	--	36.9	0.1
5 - 20	1950	60.5	13.3	59.4	13.0	38.4	0.3	54.5	17.8
20 - 40	27 x 10^3	6.8	20.9	8.8	27.0	30.4	3.3	7.0	31.6
40 - 75	18.9 x 10^4	1.0	21.4	3.1	60.0	15.4	11.8	1.6	50.5
75 - 150	19.5 x 10^5	0.2	44.3	--	--	4.2	33.0	--	--
150 - 250	8 x 10^6	--	--	--	--	1.6	51.6	--	--
> 250	52.5 x 10^6	--	--	--	--	--	--	--	--
Illinois No. 6 Coal									
< 5	15.6	54.2	0.2	54.6	0.1	35.7	--	52.3	0.1
5 - 20	1950	36.1	1.6	38.0	9.0	41.0	0.5	42.9	14.6
20 - 40	27 x 10^3	6.7	2.4	6.2	20.4	14.7	2.3	2.6	12.3
40 - 75	18.9 x 10^4	2.0	8.6	1.0	23.0	5.6	6.2	2.2	73.0
75 - 150	19.5 x 10^5	0.7	32.4	0.2	47.5	1.4	16.0	--	--
150 - 250	8 x 10^6	0.3	54.8	--	--	1.6	75.0	--	--
> 250	52.5 x 10^6	--	--	--	--	--	--	--	--
Tebo Coal (Missouri)									
< 5	15.6	81.5	0.1	70.0	0.2	34.2	--	63.3	0.1
5 - 20	1950	16.1	2.4	23.9	6.7	42.1	0.8	25.5	2.7
20 - 40	27 x 10^3	1.9	3.9	4.2	16.3	10.3	2.6	8.4	12.2
40 - 75	18.9 x 10^4	0.2	2.8	1.8	48.8	8.2	1.5	2.2	22.3
75 - 150	19.5 x 10^5	0.2	29.8	0.1	28.0	5.2	95.1	0.6	62.7
150 - 250	8 x 10^6	0.1	61.0	--	--	--	--	--	--
> 250	52.5 x 10^6	--	--	--	--	--	--	--	--

weight percent to a high of about 42.7 percent. This means that, except for the Kentucky No. 11 coal, the amount of pyritic sulfur in pyrite grains less than 20 microns in size is negligible. In contrast, for three of the coals, most of the pyrite is in grains larger than 75 microns (plus 200 mesh). This information can be used in two ways: to show that dissemination of fine grained minerals throughout a coal could, if no moderating factors are involved, completely abrogate established coal cleaning practice; and, to show to what extent these moderating factors have influenced coal cleaning. Knowing this, it may then become possible to apply this information to improvement of coal cleaning processes and to the beneficiation of coals, which, despite inherently desirable properties and characteristics, contain too much fine grained pyrite and other minerals to permit their utilization in the premium markets.

Arrangement of Minerals in Coal

Table III shows what might be expected from certain coal-pyrite mixtures if all the pyrite were uniformly disseminated. Such expectations would be most disheartening to any preparation plant manager. For example, with two percent by volume of pyrite, all the sample would sink at specific gravity 1.25, and all would float at specific gravity 1.30.

TABLE III. SPECIFIC GRAVITY FACTORS FOR MIXTURES OF PYRITE AND COAL

Vol. % Pyrite	Wt. % Pyrite	Wt. % Pyritic Sulfur	Calculated Specific Gravity of Mixture
1	4.04	2.16	1.238
2	7.84	4.18	1.276
4	14.8	7.9	1.352

Assume: Sp. Gr. Mineral-free Coal = 1.2, Sp. Gr. Pyrite = 5.0,
Sp. Gr. Non-Pyritic Minerals = 2.5

Table IV is a somewhat more realistic array of figures showing what coal producers would be faced with if all the mineral matter in coal was present in a highly disseminated form. The ash and pyritic sulfur figures in Table IV are equivalent to that of many fine, high grade premium coals mined today. But imagine what a dismal future any producer would have if a coal with 10 percent ash and almost two percent pyritic sulfur could not be greatly beneficiated by washing at a 1.30 specific gravity?

To know that the washability of coals is dependent upon the amount and distribution of minerals in coal is not enough. What is necessary is an understanding and appreciation of how the minerals occur in every hard-to-wash coal of potential value. Research on methods to beneficiate these coals, though not immediately successful, must result in techniques that would enhance the washability characteristics of all other coals.

Microscopic examination of polished surface sections of coal shows that the minerals in coal, and especially pyrite, are largely present in some regularized pattern. Despite the seeming randomness of occurrence of pyrite and other minerals, low power magnification shows individual pyrite grains to be concentrated in planar distributions which are roughly, and often ideally, parallel to the bedding plane of the coal. This is illustrated in Figures 1, 2 and 3. Pyrite, which is so clearly recognized in photomicrographs taken with reflected light, is representative of the occurrence of other minerals which are interbedded with the coal, but which may have a different origin.(7)

TABLE IV. SPECIFIC GRAVITY, PYRITIC SULFUR AND ASH DATA FOR MIXTURES OF MINERAL MATTER, PYRITE AND COAL

Non-Pyritic Minerals		Pyrite		Pyritic Sulfur	*Theoretical Ash	
Vol. %	Wt. %	Vol. %	Wt. %	Wt. %	Wt. %	Sp. Gr.
1	2.6	--	--	--	3.1	1.213
1	1.9	1	4.0	2.14	4.3	1.251
2	3.95	1	3.95	2.12	7.4	1.264
4	7.75	1	3.87	1.94	10.1	1.290
2	4.02	0.5	2.01	1.09	6.0	1.245

Assume: Sp. Gr. Mineral-free Coal = 1.2, Sp. Gr. Pyrite = 5.0, Sp. Gr. Non-Pyritic Minerals = 2.5

*% Theoretical Ash $\cong$ 0.5 + Wt. % Non-Pyritic Minerals + Wt. % Pyrite (0.73)

The ready separation of coal from mineral partings within the coal bed is an example of the kind of bonding weakness that commonly exists between the layers of material which comprise a complete coal bed. Upon handling and primary crushing further breakage takes place along similar planes. When coal is crushed to even finer sizes by some differential method, to take full advantage of the planar arrangement of minerals on a microscopic scale, it will then be possible to design economical cleaning plants for fine coal. In such a plant coal will be reduced to fine sizes according to predetermined procedures based on mineral relationships established for that coal. Subsequent separation will depend upon the market for which the coal is being prepared.

Limitations in Application of New Factors

One of the principal reasons these new factors have not been given serious consideration in the solution of coal cleaning problems is that very little is known about the minerals in coal other than that they are undesirable impurities. Another limitation may perhaps be related to the first: there is a lack of qualified personnel now engaged in research on these problems. Investigations of the nature of the minerals in coal and of the variations in the mineral matter content of coal beds on a systematic basis should have been supported for many years.

There has been too much concern with sudden changes in bed characteristics which may result in increased ash content or increased sulfur content of prepared coals, and not enough interest and concern for the careful accumulation of data on minerals in coal which might indicate why these variations in mineral matter content and sulfur content do occur. Before new methods of liberation and separation of minerals from coal can be applied on a wide scale, a great deal of data must first be developed so that engineering can be applied most effectively.

As in any other widespread modern industry, standards and standard tests provide a common basis for exchange of information and intelligence for the coal industry. Rigid or nearly rigid adherence to standard tests is a commendable practice. And this may be especially true if there has been a battle over the acceptance or modification of the standards. Yet it appears that for many tests the data are merely recorded, collated, reported, and subsequently filed for reference. If the tests are at all worth-while doing then the data from these tests should be evaluated and re-evaluated so that further testing or re-analysis of the data may have greater significance. One such test is the Hardgrove grindability test. Recent testing of the Hardgrove grindability method indicates that mineral matter is an important factor in determining the Grindability Index, and that perhaps high mineral matter content coals (high ash coals) are given Indexes that are too high.

Recommendations

A discussion of significant factors followed by a discussion of the limitations in the application of these factors would be valueless without a few recommendations as to what should be done. These are a few recommendations:

(1) New methods of evaluation of coal cleaning methods should be based on tests other than simple sink and float.

(2) Size reduction methods must be developed for coal which will permit maximum liberation of mineral matter, while at the same time limiting the amount of extreme fines produced.

(3) Sieving fine coal has been costly, but newly designed sieving machines are now being offered which will permit close sizing with a high throughput at relatively low cost. Air cleaning of such closely sized coal should be investigated.

(4) Although many coal cleaning machines now on the market have established certain lower size limits for feed material, it is possible that where good liberation of pyrite and other minerals can be assured this lower limit can be pushed yet lower. For example, the Dutch State Mines heavy media cyclone will treat fine coals down to 48 mesh or at best 60 mesh. At such sizes satisfactory products have been prepared, but the limit could be pushed to 100 mesh or possibly even to 140 mesh if the prime consideration was to separate coal, with specific gravity of about 1.30, from pyrite which has a specific gravity of 5.0.

Acknowledgment

Much of the work reported here has been conducted as part of the program supported jointly by the coal industry and the electric utility industry as represented by Bituminous Coal Research, Inc., Association of Edison Illuminating Companies, and Edison Electric Institute. Their interest and support is gratefully acknowledged.

REFERENCES

(1) Mitchell, David R., "Coal Preparation," A.I.M.E., New York (1950)

(2) Geer, M. R., and Yancey, H. F., "Operating Results With the Feldspar Fine-Coal Jig," U. S. Bureau of Mines R. I. 5412 (1958)

(3) Krijgsman, C., "The Dutch State Mines Heavy Medium Cyclone Washing System," Parts I and II, Mining Congress Journal, 45, pp. 47 and 91 (1959)

(4) U. S. Bureau of Mines Minerals Yearbook 1958, p. 100 (1959)

(5) "Mining, Stripping, Preparation in 1959," Coal Age, p. 80, Feb. 1960

(6) "Mining, Stripping, Preparation in 1958," Coal Age, p. 80, Feb. 1959

(7) Deul, Maurice, "The Principal Geological, Chemical and Physical Factors Controlling the Mineral Content of Coal," Preprints of papers presented at Boston Mass., American Chem. Soc., Div. of Gas and Fuel Chem., Vol. II, p. 21 (1959)

Figure 1. Euhedral pyrite crystals in Meigs Creek No. 9 coal from Harrison County, Ohio.

⊢——⊣ = 40 Microns

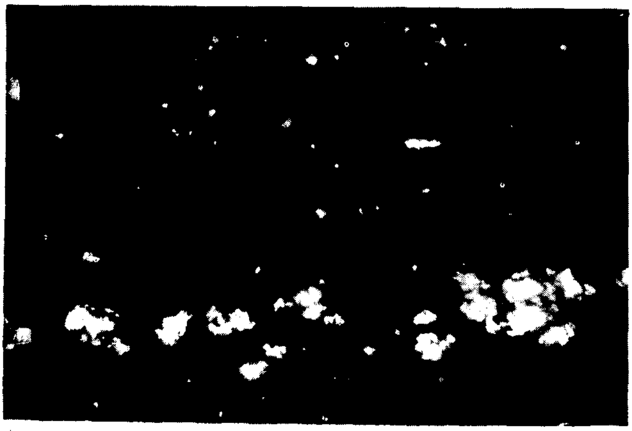

Figure 2. Disseminated pyrite in Meigs Creek No. 9 coal from Harrison County, Ohio.

⊢—⊣ = 40 Microns

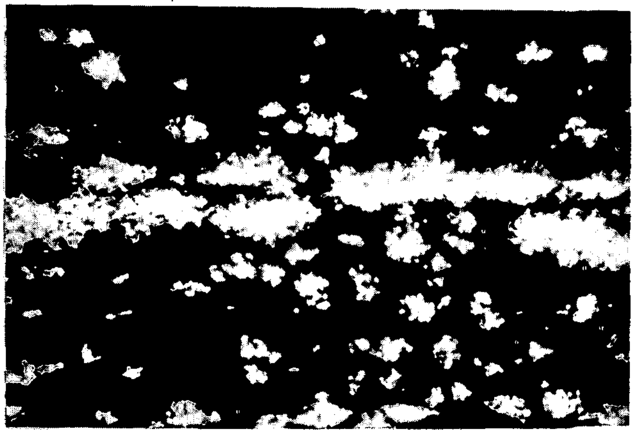

Figure 3. Disseminated pyrite in Meigs Creek No. 9 coal from Harrison County, Ohio.

⊢—⊣ = 40 Microns