Final Report

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*Automated microscopy methods
for measuring pyritic sulfur
content of coal and determining
degree of liberation of pyrite in
coal: Final report*

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AUTOMATED MICROSCOPY METHODS FOR MEASURING PYRITIC
SULFUR CONTENT OF COAL AND DETERMINING DEGREE OF
LIBERATION OF PYRITE IN COAL

FINAL REPORT

by

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ABSTRACT

Due to environmental concerns about acid rain there is an increasing interest in evaluating the performance of coal desulfurization processes. Size, shape and association of pyrite particles within a coal matrix is used to quantitatively determine the efficiency of these processes. Manual microscopy provides such information but it is a laborious, time-consuming and operator-dependent operation. With the introduction of image analyzers, automated microscopy has become a reliable way to acquire and process such data. The objective of this project is to develop an automated procedure, to be implemented in an IBAS image analyzer, to determine size, shape and degree of liberation of pyrite particles in a coal matrix. This procedure is to work in real time conditions and with minimal intervention from the operator. Our approach is to create from the original microscopic image a three level image with the following components: epoxy, coal macerals and pyrite to simplify the calculations. Enhancing the original image by histogram scaling and median filtering, we segment it and form the three level image. After the boundaries of the pyrite particles are defined, we mask the surroundings of the particle to estimate the degree of liberation. The percentage of epoxy included in the mask is defined as the degree of liberation of the particle. Size and shape factor values are simultaneously calculated for each of the analyzed particles. These particles are classified according to their maximum diameter, shape factor and degree of liberation by the program. The procedure has been tested and compared with manual measurements on different mesh size coals with encouraging results. Improvements in the coal sample preparation and on the program are needed to obtain more accurate results.

1. INTRODUCTION

Because of environmental concerns about acid rain there is an increasing interest in evaluating the performance of coal desulfurization processes. Sulfur occurs in coal in the forms of organic sulfur and pyrite and both are liberated during coal combustion. The organic sulfur is very difficult to remove, but there are several physical and chemical processes to remove pyrite. The efficiency of these processes can be quantitatively determined by looking at the size, shape and association of pyrite particles within a coal matrix. For instance, crushing is effective in removing pyrite up to a certain size; small, round particles encapsulated in coal are much harder to liberate than large, elongated particles which are partially encapsulated in coal.

Manual microscopy provides the information about size, shape and association, but it is a laborious, time consuming and operator-dependent operation. Automated microscopy permits the acquisition and processing of much more data in a repeatable and reliable way. With the introduction of image analyzers the methods of [1] have been improved considerably. Although a good deal of automated work in sizing and shape determination of pyrite has been done, not much has been done in determining the association of pyrite in coal by automated methods [2-5].

There are several issues to consider in developing an automated procedure to determine size, shape and degree of liberation. The procedure should be capable of processing large amounts of data on real time, it should scan a larger number of fields that could be done manually, and it should process each of these fields at a rate that cannot be done manually. The procedure must permit the use of different magnifications in order to obtain more accurate measurements.

Our approach to determine size, shape and degree of liberation is to create from the original image a three-level image with the following components: epoxy, coal macerals and pyrite. In the epoxy component we include epoxy and clay. In the coal maceral component we include liptinite, vitrinite, semifusinite and fusinite. Several difficulties in creating the approximate image are caused by the optical system attached to the IBAS analyzer that is used in this project, by the coal sample preparation and by the computational capabilities of the analyzer.

The most significant difficulties encountered in the development of the procedure are due to the illumination level and the lack of resolution of the gray level values provided by the optical system associated with the IBAS. To obtain a good discrimination of the darker components, epoxy and liptinite, it is necessary to increase the level of illumination which makes the camera to saturate and display fusinite and pyrite with the same gray level value. Under this condition accurate discrimination of pyrite is not possible. On the other hand, by reducing the illumination the closeness of the gray level values of the darker components (epoxy, clay and liptinite) makes the discrimination of these components very difficult.

Another issue is the definition of pyrite particles and their boundaries. Because of relief within or on the surroundings of a particle, the presence of a halo caused by the large difference in the gray level values between pyrite and the other components, and the conglomeration of small particles forming a particle, it is necessary to develop a procedure to define the particles and their boundaries in a consistent and accurate way.

In the following sections we present the procedure that was developed for the IBAS image analyzer, and describe the different difficulties that were

encountered in its development and the solutions we provided. Also we show experimental work comparing the automated and manual procedures, and the data obtained for different coals at different crushing sizes. Finally, we propose future work to improve the procedure, to analyze the data and obtain a predictive model for sulfur reduction, and to develop a possible crushing index that could be used to determine the optimal crushing size for different coals.

2. DESCRIPTION OF AUTOMATED PROCEDURE

2.1 Objective

The objective of this project is to develop a computer-based procedure to determine size, shape and degree of liberation of pyrite particles in a coal matrix. The procedure is to work in real time conditions with minimal intervention from the operator.

2.2 Automated Procedure

We have developed an automated procedure for the IBAS image analyzer that is capable of:

1. Scanning over a desired number of microscopic fields on the surface of a coal pellet. At each field it focuses automatically and detects the presence of pyrite in the field before proceeding. Scale parameters are provided to permit the use of different optical magnifications.

2. Calculating as a percentage the degree of liberation of pyrite particles present in a field, along with their corresponding sizes and shape factor values. It also classifies the measured particles according to the degree of liberation versus size and shape factor.

For computational efficiency the procedure uses mostly routines available in the IBAS menu. It was necessary to write programs in FORTRAN to

supplement the available IBAS routines, and such programs have been incorporated into the menu of routines of the IBAS. A copy of the IBAS program we developed is given in Appendix A, together with copies of the FORTRAN programs used to implement the routines START, EXTRAC and CLASS. A flowchart of the procedure is shown in Fig. 1, and in the following sections we discuss the details of the procedure.

As a preliminary step it is necessary to initialize certain arrays used in the classification by means of START. The number of fields to be scanned, the automatic focusing and the identification of the coal sample are set before starting the processing. To avoid unnecessary processing of fields where no pyrite is present, the program checks for the area percentage of pyrite in a field and if it is less than a certain value no processing is done on that field. Particles which are not completely included in the field are not considered in the analysis since it is not possible to define their boundaries.

2.2.1 Image Enhancement. The digitized image provided by the analyzer is obtained from an optical system, which is basically a microscope and a video camera, attached to it. In order to get a good view of the different components of the sample it is necessary to increase the illumination. However, this brings about the saturation of the camera and makes the brighter components, pyrite and fusinite, appear with the same gray level value (255), which would cause erroneous measurements. It is thus important that before the processing is started the camera be set to manual (the reason for this will be given later), and the illumination source and the antiflex lens (if being used) be adjusted by the operator by going over several fields and insuring that pyrite and fusinite are not being confused.

Fig. 1. Flowchart of Automated Procedure.

Because of the lack of illumination there is not enough resolution in the gray level scale to discriminate the darker components (epoxy, clay and liptinite) of the image. In Fig. 2 we display a typical gray level histogram of a field. The IBAS segmentation procedure is based on thresholding using the valleys and peaks of the histogram [6]. It is obvious that in the case of the field whose histogram is given in Fig. 2 this is an impossible task, since there is no valley that could be used to set a threshold to discriminate epoxy and clay from coal macerals and pyrite.

To make this discrimination possible in general, we enhance the original image in two ways. First, we scale the gray level values so that darker components are given an expanded part in the final histogram, and at the same time we contract the range of gray level values corresponding to the brighter components. When we perform these scaling operations, spurious noise is introduced into the image. To get rid of this noise and to improve the definition of peaks and valleys in the histogram we apply median filtering to the scaled image. A histogram corresponding to the scaled and median filtered image is shown in Fig. 3. Notice that now there are definite peaks and valleys in the histogram and the threshold to discriminate epoxy from the other components can be easily chosen. It is very important to mention that this threshold can be used in the discrimination of all other fields.

To illustrate the performance of the procedure in discriminating the different components after the image enhancement is performed on the original image, we show the pictures in Figs. 4-6. Fig. 4(a) displays a field of Black Creek coal (28x0) with liptinite within the vitrinite. Fig. 4(b) shows the corresponding three-level image where black corresponds to epoxy, gray to coal macerals and white to pyrite. In Fig. 5(a) we have a field of Illinois No. 6 coal (100x0) which shows a piece of fusinite that appears as

Fig. 2. Histogram of Original Image.

Fig. 3. Histogram of Enhanced Image.

bright as pyrite. The corresponding three-level image is shown in Fig. 5(b), where black corresponds to epoxy, white to coal macerals and gray to pyrite. Note that the closeness of particles in the field causes errors in determining the degree of liberation. The liberated pyrite particle that is between the fusinite and the vitrinite particles (See Fig. 5(a)) appears touching them in Fig. 5(b), and would be classified as partially liberated. A similar situation is depicted in Figs. 6(a), (b).

The benefits of the above image enhancement are: a much easier discrimination of the three different components of the approximate image, and the attainment of a threshold value that can be used in the automatic discrimination of all fields. The median filter provides a way to clean up the spurious noise introduced by the scaling operation, and at the same time to smooth out the flat regions and preserve the edges of the particles.

It should be mentioned that the reason to have the camera in the manual, rather than in the automatic, setting is to avoid the illumination adjustment that the camera does in the automatic setting from field to field. This would change the segmentation threshold.

There are a couple of IBAS routines (NORMGR, LINHST) that can be used to enhance the image, or to perform histogram equalization, but they do not provide enough flexibility so that only the darker components be enhanced and thus we decided against using them. Also it was not possible to get a consistent threshold for all fields with those routines.

2.2.2 Definition of Pyrite Particles and their Boundaries.

To estimate size, shape and degree of liberation of pyrite particles in coal is necessary to be able to define these particles and their boundaries. There are various reasons why these definitions are hard to do. In many situations, because of polishing problems or oxidation, the pyrite particle is

(a)

(b)

Fig. 4. (a) Original Image, (b) Three-level Image.

(a)

(b)

Fig. 5. (a) Original Image, (b) Three-level Image.

(a)

(b)

Fig. 6. (a) Original Image, (b) Three-level Image.

not homogeneously bright, and darker areas can appear inside or around the particle. These areas can be mistaken by the analyzer as something different from pyrite and cause problems in the segmentation.

Relief within a particle can be dealt with by filling in the corresponding darker area in the discriminated object that corresponds to the pyrite using the routine AFILL; relief around a particle is a little more difficult to counteract but the OPEN routine can be used to handle it. OPEN performs a specified number of dilations and contractions on the discriminated or binary objects corresponding to coal macerals. The OPEN operation will not affect, in general, pyrite particles which are encapsulated because in that case the relief around the particles is considered as coal maceral by the analyzer.

In Fig. 7 we illustrate the relief that sometimes occurs in and around pyrite particles. Figure 7(a) is a picture of an Illinois No. 6 (100x0) microscopic field that shows two big partially encapsulated particles in the middle of it. The darker areas inside and in the upper part of these particles are due to relief. The corresponding three-level image is displayed in Fig. 7(b) where black corresponds to epoxy, white to coal macerals and gray to pyrite. AFILL has filled out the darker areas within the binary objects corresponding to pyrite. The routine OPEN, by eroding and dilating the binary object corresponding to coal macerals, gets rid of the relief in the upper part of the two big pyrite particles located in the middle of the field. The image in Fig. 7(b) occurs before this operation.

An additional difficulty is caused by conglomerates of small pyrite particles that an experienced operator would consider one particle but the analyzer detects as a group of small pyrite particles close to each other. To approximate the particle definition provided by the operator in these cases,

(a)

(b)

Fig. 7. (a) Original Image, (b) Three-level Image.

and also to simplify the calculation of degree of liberation (which could become ambiguous in cases where the particles appear very close to each other), we use the CLOSE routine. In this case, the initial dilations gather together particles which are close to each other (the closeness depends on the mode used in the routine) and after they are joined the erosion simply tries to recover the original shape keeping the joined particles together. The performance of this operation is satisfactory in many situations depending on the number of times the dilation/erosion operations are performed and the chosen mode.

To illustrate the use of the CLOSE routine we show the photographs of an Illinois No. 6 (28x0) coal microscopic field in Figs. 8(a), (b). Comparing the original (Fig. 8(a)) image with the three-level (Fig. 8(b)) image, where black corresponds to epoxy, gray to coal macerals and white to pyrite, we see that conglomerates of pyrite particles which are about 6-8 pixels apart are joined by CLOSE to form a new particle.

Finally, it is difficult to define a pyrite particle's boundary because of the large difference in the gray level values of pyrite and the other components, which causes a halo to appear around the pyrite particles. This halo can be characterized by using an image trace which displays all gray level values that appear in a line of the image. In Fig. 9(a), we show a trace that went over a pyrite particle which is identified as the component that has a gray level value of 255. Concentrating on the surrounding of this particle (See Fig. 9(c), which is an enlargement of the trace section where the pyrite is) it can be seen that the gray level values descend in a stair-case manner to the gray level values corresponding to the components surrounding the pyrite. The gray level values in this transition region are the ones that form the halo. To accurately determine the degree of liberation

(a)

(b)

Fig. 8. (a) Original Image, (b) Three-level Image.

we need to define the boundaries of the pyrite particles so that we can look at their surroundings, but these transition regions or halos do not permit a precise definition of the boundary. For the purpose of determining the degree of liberation, since we are interested in whatever is around the pyrite particle, we consider the halo as part of the particle. To counteract the halo, we dilate the particle enough to cover it. Depending on the mode used in the DILATION routine a ribbon, two or three pixels wide, is added to the original boundary of the object corresponding to the pyrite particle. In Figs. 9(b) and (d) we give the trace of the enhanced image, at the same location as the one before, and an enlargement of the trace around the pyrite. Notice that the difference among the gray level values of the different components is clearer than that in Fig. 9(a), and that the change from the pyrite gray level to that of the surrounding component is much steeper in Fig. 9(d) than in Fig. 9(c).

2.2.3 Determination of Degree of Liberation. The above steps were intended to facilitate the creation of an approximate image from the original image. We have enhanced the image so that it is easier to segment it, and have defined pyrite particles and their boundaries so that the measurements can be done accurately.

To calculate the degree of liberation, we consider the three level approximate image where the pyrite particles have been processed so as to counteract the halo effect and the relief within and around the pyrite particles. As shown in Fig. 10, we mask the surrounding of each of these particles in order to see what components are surrounding them. This mask is a two pixels wide ribbon that goes around the boundaries of the defined particles. To determine the degree of liberation we then measure the

(a)

(b)

Fig. 9. (a) Trace of Original Image, (b) Trace of Enhance Image.

Fig. 9(c). Enlarged Section of Trace in 9(a).

Fig. 9(d). Enlarged Section of Trace in 9(b).

percentage of the area of the mask that is being occupied by the epoxy component as shown in Fig. 10.

These area percentages are calculated by a routine called EXTRAC, which simultaneously finds the maximum diameter and the shape factor of each of the particles. Setting the scale factor corresponding to the magnification used, the size measurements are given in microns. EXTRAC classifies the different analyzed particles within a determined range of the maximum diameter which is appropriate for the magnification being used. It also classifies the pyrite particles as encapsulated, liberated or partially encapsulated using parameters L1 and L2 to set the thresholds used to define these categories. Finally, EXTRAC stores the data from each of the fields in a floppy disk, and presently (for testing purposes) it prints out the information for each one of the fields. The shape factor was chosen as the ratio of the minimum diameter to the maximum diameter, so that for round particles this value should be close to unity while for elongated particles it should be close to zero.

The mask is created by means of the CONTUR routine which detects the boundary of the binary objects corresponding to pyrite in the approximate image. The masking is then the product of the boundary obtained from CONTUR and the approximate image.

The size and shape determination, although is done simultaneously with the degree of liberation calculation, is done on a different image plane than the one used for the degree of liberation. The reason for this is that when attempting to determine the degree of liberation we need to look at the surrounding of the pyrite particles, and consequently we dilate them changing their size and shape. Thus, we make size and shape measurements on the particles that have been closed, or consolidated, and corrected for halo effects. It should be mentioned that the median filtering gets rid of very

Fig. 10. Calculation of Degree of Liberation.

small particles, with areas of less than about 4 pixels. This is no problem since these small particles should be measured with a different magnification to make the calculations accurate and reliable.

The data that is accumulated after all the fields of interest are measured is classified by the routine CLASS that we introduced into the IBAS menu. This program classifies all pyrite particles that fall within a specified range of the maximum diameter according to their degree of liberation versus maximum diameter and shape factor. It also provides an overall classification of the particles, depending on the values of L1 and L2, into the three classes of liberated, encapsulated and partially encapsulated. In Fig. 11 we display the print out of START, EXTRAC and CLASS.

3. EXPERIMENTAL WORK

The objectives of the experimental work were three: (1) to learn how well measurements from the manual and automated procedures compare, (2) to look into the significance of the data at different crushing levels, and (3) to evaluate the advantages of different pellet preparation procedures. We experimented with various coals, different top sizes and with samples made using different preparation techniques.

3.1. Experimental Results

For our experiments we used the following coals: Illinois No. 6 (28x0, 100x0, and 400x0), Middle Kittanning (28x0) and Black Creek (28x0). Illinois No. 6 was the most difficult to analyze due to the diverse shape of the pyrite, and the abundance of clay and other inorganic matter in it. Black Creek was of interest because of the presence of liptinite in it which permitted us to test the discrimination of the procedure. The Middle

SIZE, SHAPE AND DEGREE OF LIBERATION OF PYRITE IN COAL

CLASSIFICATION

1=ENCAPSULATED
2=PARTIALLY ENCAPSULATED
3=LIBERATED

SCALES

1 PIXELS
5 FOR 8X
6 FOR 16X
4 FOR 40X
7 FOR 63X

SAMPLE ...
SCALE = 4
LX LEVELS: L1= 10 , L2= 50

CNT	LX	DMAX	SF	CLS
1	42.86	1.79	.76	2
2	53.25	9.00	.52	3
3	16.67	6.09	.37	2
4	0.00	3.99	.67	1
5	65.52	5.96	.55	3
6	51.92	5.37	.54	3
7	70.59	5.01	.61	3
8	33.33	3.79	.92	2
9	63.16	.72	.71	3
10	24.49	4.28	.81	2
11	69.44	26.00	.55	3
12	0.00	2.45	.64	1
13	28.21	18.27	.53	2
14	65.52	1.90	.82	3

(a)

ABSOLUTE FREQUENCIES

LIBERATION VS. MAX. DIAMETER

	10	20	30	40	50	60	70	80	90	100
0										
7.7	31	7	2	4	4	2	5	2	3	2
10.5	22	4	1	3	3	5	3	1	1	1
13.2	9	1	0	3	1	2	0	1	0	1
16.0	11	3	1	1	2	1	0	0	0	0
18.7	2	1	2	1	0	0	0	0	1	0
21.5	4	1	0	1	0	0	0	0	0	0
24.2	2	2	0	1	1	0	0	0	0	0
27.0	2	0	0	0	0	2	1	0	0	0
29.7	5	0	1	0	0	0	0	0	0	0
32.5	0	0	0	0	0	2	0	0	0	0
35.2	3	0	0	0	0	0	0	0	0	0
38.0	1	0	0	0	0	0	0	0	0	0
40.7	2	1	1	1	0	0	0	0	0	0
43.5	0	1	0	0	0	0	0	0	0	0
46.2	1	0	0	0	0	0	0	0	0	0
49.0	0	0	0	0	0	0	0	0	0	0
51.7	0	0	0	0	0	0	0	0	0	0
54.5	0	0	0	0	0	0	0	0	0	0
57.2	1	0	0	0	0	0	0	0	0	0
60.0	0	0	0	0	0	0	0	0	0	0

LIBERATION VS. SHAPE FACTOR

	10	20	30	40	50	60	70	80	90	100
0										
.1	0	0	0	0	0	0	0	0	0	0
.2	0	0	0	0	0	0	0	0	0	0
.3	4	2	1	0	0	0	0	0	0	0
.4	15	5	2	3	1	0	0	0	1	0
.5	21	2	1	4	6	0	3	1	2	1
.6	12	4	1	0	3	7	2	1	1	2
.7	14	3	1	1	0	4	1	1	0	0
.8	19	3	1	2	1	3	2	1	1	0
.9	7	2	1	5	0	0	0	0	0	0
1.0	4	0	0	0	0	0	1	0	0	1

TOTAL NUMBER OF PARTICLES = 187

PERCENTAGES

ENCAPSULATED PARTICLES = 51
 PARTIALLY ENCAPSULATED PARTICLES = 29
 LIBERATED PARTICLES = 19

(b)

Fig. 11. Example of Printout of IBAS Program.

Kittanning was easier to analyze because of the more solid pyrite and less clay and liptinite.

The difficulty in evaluating the performance of the degree of liberation program is that there is no standard to compare the results with. Despite the inaccuracy of an operator in determining the degree of liberation as a percentage, we considered manual measurements the standard to compare the automated measurements against. We compiled a list of cases in which manual and automated measurements had a large disagreement. We expect that by analyzing these cases, we should get a better understanding of what changes to make in the program and/or in the sample preparation to improve the process.

In Fig. 12 we display the degree of liberation measurements obtained manually and using the IBAS program for about 100 particles. Only 25 particles were analyzed in the Black Creek and 50 in the Illinois No. 6 (400x0) samples because the first one had hardly any pyrite, and because the pyrite in the second coal sample was mostly liberated or encapsulated. Notice that according to Fig. 13 for the Illinois No. 6, 28x0, sample which was prepared using regular techniques the absolute error (absolute value of difference between manual and automated measurements) indicates that there is a small probability of making a large error of 80 percent or more. For a pellet of Middle Kittanning, 28x0, made with a higher proportion of epoxy to coal powder and polished better, the results show improvement. The absolute error distribution (Fig. 14) in this case is more concentrated in the small errors; in 96 percent of the cases the absolute error is between 0 to 40 in the Middle Kittanning (28x0) compared with 88 percent for the Illinois No. 6 (28x0). We believe the improvement is mainly due to the changes in the pellet preparation. The cases in which manual and automated measurements had a large difference will be discussed in the next section.

IBAS VS. MANUAL – ILL. 6 RAW 28X0

Fig. 12(a)

IBAS VS. MANUAL – MID. KITTANING RAW 28X0

Fig. 12(b)

IBAS VS. MANUAL - ILL. 6 RAW 100X0

Fig. 12(c)

IBAS VS. MANUAL — BLACK CREEK RAW 28X0

Fig. 12(d)

IBAS VS. MANUAL – ILL. 6 RAW 400X0

Fig. 12(e)

To test the repeatability of the results for different experiments, we made automated measurements for different scannings of the pellet surface. The Illinois No. 6 (28x0) results are shown in Fig. 15(a), (b) and they indicate that the procedure provides similar results for different scannings. The addition of the results of these two experiments gives the results shown in Fig. 15(c). Similar results were obtained for the other coals. Notice that in these experiments we used an objective magnification of 40x which is appropriate for pyrite particles in the range of 5 to 60 microns in maximum diameter. It is possible that the repeatability of the results might not hold for larger particles, unless the number of fields scanned is considerably increased.

Size and shape distributions for Illinois No. 6 (28x0) are displayed in Fig. 16, and they are comparable to previously obtained distributions.

In Fig. 17 the degree of liberation distribution for Illinois No. 6 (100x0) and Middle Kittanning (28x0) are given. Notice first the similarity of the distributions for 28x0 Illinois No. 6 (Fig. 15(c)) and Middle Kittanning; and secondly that comparing the distributions for the 28x0 and 100x0 Illinois No. 6 it is easy to see that pyrite is being liberated as the coal is crushed to finer sizes.

3.2. Difficulties

Rather than to try to describe the cases in which we found a large disagreement between the manual and the automated degree of liberation measurements, we illustrate them by means of photographs in Fig. 18. These are photographs of microscopic fields of a Middle Kittanning (28x0) pellet that was specially prepared with a larger proportion of epoxy to coal powder than regular pellets. We have thus tried to avoid the situation of particles being very close to each other that was illustrated before in Figs. 5 and 6.

Fig. 13

Fig. 14

Fig. 15(a)

Fig. 15(b)

Fig. 13(c)

Fig. 16(a)

Fig. 15(b)

Fig. 17(a)

Fig. 1(b)

Similar cases as the ones illustrated here also occur in the Illinois No. 6 coal, and to a lesser degree in the Black Creek coal.

The difficulty in determining size and degree of liberation of pyrite in certain fields is clearly shown in Fig. 18(a). There are so many small pyrite particles distributed in the coal particle that measurements are difficult to make by either manual or automated procedures.

Fig. 18(b) displays small pyrite particles in clay. The difficulty in detecting clay is that its gray-level value is very close to that of vitrinite. Thus, in fields where clay occurs it is erroneously considered by the image analyzer as a coal maceral.

The case of pyrite particles appearing as a conglomerate, rather than a discrete particle, is illustrated in Figs. 18(c), (d). Due to oxidation or problems with polishing many of the pyrite particles in these fields appear separate, although an experienced operator could determine, by looking through the microscope, that they are actually discrete particles. Since the image analyzer only uses gray-level values to define the particles, it cannot make such determination.

The darker areas, caused by relief, that sometimes appear in pyrite particles, and the halo surrounding them are illustrated in Figs. 18(e), (f). In Fig. 18(g) we have the rare case of a pyrite particle encapsulated in a fusinite cellular structure. Due to the dark ring that appears around the pyrite particle and which seems originated from the cellular structure, this pyrite particle is classified as liberated.

Finally, in Fig. 18(h) we present the situation that occurs whenever a large pyrite particle falls in the margin of the frame. Since such particle is not fully included in the frame, it is not analyzed and thus it is deleted from the field. However, smaller particles which actually form part of the

Fig. 18(a)

Fig. 18(b)

Fig. 18(c)

Fig. 18(d)

Fig. 18(e)

Fig. 13(f)

Fig. 18(g)

Fig. 18(h)

large particle, but are separated enough from it so that the routine CLOSE does not join them to it, are not deleted. Measurements made on these small particles are meaningless.

Many of the above difficulties could be avoided by improving the sample preparation. Better polishing would minimize the relief in pyrite particles, using less reflectant epoxy would make the discrimination of epoxy, clay and liptinite a lot easier.

4. CONCLUSIONS

4.1. Summary of Results

We feel the main objective of the project has been achieved. Presently, we have a working automated procedure to estimate size, shape and degree of liberation of pyrite particles in coal. This procedure has been implemented in the IBAS image analyzer of the Petrography Laboratory of the Coal Preparation Division, and tested on various coals and top sizes.

The developed procedure has limitations imposed mainly by the optics of the system, the sample preparation and the image analyzer. Basically the procedure depends on gray-level information to measure size and shape and to determine the degree of liberation. To make the calculations easier we tried to compress the available information. This is why we created the three level image from the original image with 256 levels. We want to keep just the necessary information. In doing so we faced difficulties with the optics, the preparation of the pellet and the image analyzer.

The automated nature of the procedure requires that parameters needed in the program (scaling values, segmentation thresholds, number of dilations/erosions, etc.) be set at the beginning of the process and that they remain valid for all fields. To expect that such parameters be the

appropriate ones for each field is unrealistic since variations in focusing, composition of each field, etc. make each field different from the others, almost to the point of requiring manual setting of those parameters at each field. We tried to minimize the parameters variation from field to field by enhancing the original image. However, the procedure still requires a learning period for each coal, in which the operator must go over several fields and judiciously set the required parameters for each magnification. Special care should be given to the selection of the appropriate magnification for measuring particles in a certain size range.

Sample preparation plays an important role in minimizing the cases for which the procedure cannot accurately estimate size, shape and degree of liberation. For instance, by increasing the ratio of epoxy to coal powder in the sample results in that particles are more separate, making more accurate the determination of liberated and partially liberated particles. Better polishing would help minimize the effects of halo and relief in the calculations. Finding ways to make the epoxy less reflective, by perhaps using certain additives, would make the discrimination of epoxy, clay and liptinite easier.

Computationally the procedure is efficient. Instead of collecting measurements for each field it classifies the particles considered, and updates the degree of liberation versus shape factor, and versus size distributions at each field. The overall distributions are obtained at the end of the scanning. The computation time is increased by the transfer of data to and from the diskette. A hard disk system would help in this respect. The computational burden of processing image frames of 512 by 512 pixels is augmented by increasing the epoxy content in the samples, because pyrite particles occur less frequently and more fields need then to be analyzed.

4.2. Potential for Further Development

Our procedure can still be improved in various ways. One is by applying it to different coals of various mesh sizes, so that we get experience in the setting and the significance of the program parameters. Comparison of the automated acquired data with manual data should be continued. A listing of cases in which manual and automated acquired data disagree should be compiled, so that analysis of such cases would give us clues about what changes to make.

The next step in improving the procedure is to consider the integration of data from different magnifications. Accurate measurements can be made choosing the appropriate magnification. The control parameter that is used in the procedure to choose the magnification is the maximum diameter.

Analysis of the collected data and of the error of the automated measurements compared with the manual ones should provide us with a way to select threshold values so that the particles can be reliably classified as liberated, encapsulated or partially encapsulated.

Finally, to measure the efficiency of coal desulfurization processes statistical regression analysis should be performed on the size, shape and degree of liberation data obtained with our procedure to find a model capable of predicting sulfur reduction. The dynamics of the coal cleaning processes must be considered in the analysis. In the case of the gravimetric cleaning process it would be very important to apply our procedure and come up with crushing indices for various coals. A crushing index should provide the mesh size after which crushing coal to finer sizes does not improve the pyrite sulfur reduction.

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APPENDIX A

The following are the listings of the program for the IBAS, and of the FORTRAN subroutines used to implement the routine START, EXTRAC and CLASS which we introduced in the IBAS menu. Subroutine SZ was used to implement START, ST was used to implement EXTRAC and SW was used to implement CLASS. START has four integer parameters: NCLS = number of classes, SCL = magnification scale factor, L1 and L2 are the thresholds for the classification of encapsulated, partially liberated and liberated. EXTRAC has the parameters NCLS, SCL, L1 and L2 defined before, and LOW and HIGH are integer parameters that define the range of the maximum diameter of the particles to be measured. Finally, CLASS has as parameters NCLS, LOW, HIGH, L1 and L2 which have been already defined. The introduction of routines into the IBAS using the FORTRAN special package is detailed in the IBAS manual.

IBAS PROGRAM LIST

PRGM # 804

PYRITE LIBERATION CHAPARRO 4-30-87

FUNCTION	INTEGER	VARIABLES:		REAL
		LOGICAL		
1 START	NCLS 21 SCL 4 L1 10 L2 50			
2 SCANIN	FX 10 FY 10 VEL 6000 FLG# 1	FRAME	DX 700.0 DY 800.0	
3 FOGSET	RGMD 1 FLG# 3			
4 ID. NO				
5 LAB:	LBL# 1			
6 TVON		ONLINE		
7 MVSCAN	IFOC 1 RFIL 2 WFIL 1 SNMD 1	AUTO		
8 MVWAIT				
9 TVINP	INP 1			
10 LUTAB	SEL 30			
11 DISC2L	INP 1 OUT 2 LEV1 253 LEV2 255	BINARY		
12 CLOSE	INP 2 OUT 2 PHAS 255 CNT 4 MODE 7			

13 MFRAME

WDSX 500
 WDSY 500
 X0 6
 Y0 6
 RAD 128

CENTER

14 IDENT

INP 2
 OUT 2
 MARG 1

8-CONN

15 DISC2L

INP 2
 OUT 2
 LEV1 1
 LEV2 255

BINARY

16 OCHECK

INP 2
 LEV1 1
 LEV2 255
 FLG# 5

LVAX .2000E-01
 AX .8961

17 IF FLG

FLG# 5

18 GOTO

LBL# 8

19 SCALIM

INP 1
 OUT 3
 INLO 20
 INHI 70
 OTLO 1
 OTHI 180
 PHLO 0
 PHHI 0
 SCMD 3

20 SCALIM

INP 1
 OUT 1
 INLO 71
 INHI 253
 OTLO 181
 OTHI 250
 PHLO 0
 PHHI 0
 SCMD 3

21 AFILL

INP 2
 OUT 2

22 MEDIAN	INP	2	
	OUT	6	
	SIZE	5	
	RANK	13	
23 COPYIM	INP	6	
	OUT	2	
24 DILATE	INP	2	
	OUT	2	
	PHAS	255	
	CNT	3	
	MODE	5	
25 ADD	INP	1	
	OUT	1	
	INP2	3	
	NRMD	3	
26 MEDIAN	INP	1	
	OUT	3	
	SIZE	5	
	RANK	13	
27 MEDIAN	INP	3	
	OUT	1	
	SIZE	5	
	RANK	13	
28 ADD	INP	1	
	OUT	1	
	INP2	2	
	NRMD	2	
29 DISPLY	INP	1	
30 DISC2L	INP	1	
	OUT	1	
	LEV1	95	
	LEV2	250	
31 OPEN	INP	1	
	OUT	1	
	PHAS	255	
	CNT	3	
	MODE	7	
32 CLEAR	INP	3	
	PHAS	0	

BINARY

33 DILATE

INP 2
OUT 3
PHAS 255
CNT 1
MODE 5

34 CLEAR

INP 4
PHAS 0

35 CONTUR

INP 3
OUT 4
PHAS 255
PHCO 255
MODE 7

36 MASK

INP 1
OUT 5
INP2 4
PHIN 255
PHOU 0

37 DISPLY

INP 5

38 COPYIM

INP 2
OUT 1

39 ADD

INP 5
OUT 2
INP2 2
NRMD 2

40 MFRAME

WDSX 500
WDSY 500
X0 6
Y0 6
RAD 128

CENTER

41 IDENT

INP 1
OUT 1
MARG 1

8-CONN

42 OCHECK

INP 1
LEV1 1
LEV2 255
FLG# 5

LVA% .1000E-02
AX 1.295

43 IF FLG

FLG# 5

44 GOTO	LBL#	8	
45 IDENT	INP	2	8-CONN
	OUT	2	
	MARG	1	
46 IDENT	INP	3	8-CONN
	OUT	3	
	MARG	1	
47 CLEAR	INP	4	
	PHAS	0	
48 COPYIM	INP	6	
	OUT	4	
49 MFRAME	WDSX	496	
	WDSY	496	CENTER
	X0	8	
	Y0	8	
	RAD	128	
50 IDENT	INP	4	8-CONN
	OUT	4	
	MARG	1	
51 CLROVL	INP	4	
52 CLROVL	INP	3	
53 CLROVL	INP	2	
54 CLROVL	INP	1	
55 EXTRAC	NCLS	21	
	LOW	5	
	HIGH	60	
	SCL	4	
	L1	10	
	L2	50	
56 LAB:	LBL#	8	
57 LOOP	LBL#	1	
	LCNT	69	
	CNT#	100	

58 CLASS

NCLS	21
LOW	5
HIGH	60
L1	10
L2	50

59 RESET

SCANN

60 PAUSE

TOTAL PROGRAM LENGTH 820 BYTES

```

SUBROUTINE SZ
CALL USER
RETURN
END

C
C

SUBROUTINE USER
INTEGER D(10,21),E(10,11)
INTEGER D1(10,80),E1(10,11)
REAL DIFMX(84)

INTEGER SCL

COMMON/PCPDAT/IVPCP(1000),ICDM,ICRED,ISGMNT,NWPAR,IPPAR
IBR=ICRED+1
GO TO (10,20,30),IBR
10 NCLA=IVPCP(IPPAR)
SCL=IVPCP(IPPAR+1)
L1=IVPCP(IPPAR+2)
L2=IVPCP(IPPAR+3)

DO 1 N=1,NCLA
DO 1 M=1,10
D(M,N)=0.

IF(N.GT.11)GO TO 1
E(M,N)=0.
E1(M,N)=0
1 CONTINUE
NTOT=0
NENCP=0
NPLIB=0
NLIB=0

CALL OPEN(7,11HFORT07,2)
WRITE(7,200)NTOT,NENCP,NPLIB,NLIB
WRITE(7,100)((D(M,N),M=1,10),N=1,NCLA)
WRITE(7,100)((E(M,N),M=1,10),N=1,11)
ENDFILE 7
100 FORMAT(1X,10I6)
200 FORMAT(1X,16,1X,16,1X,16,1X,16)

DO 6003 M=1,10
DO 6003 N=1,80
6003 D1(M,N)=0
DO 6011 M=1,84
6011 DIFMX(M)=0
NE=0
NP=0
NL=0
CALL OPEN(8,11HFORT08,2)
WRITE(8,6001)((D1(M,N),M=1,10),N=1,80)
WRITE(8,6001)((E1(M,N),M=1,10),N=1,11)
WRITE(8,6002)NE,NP,NL
ENDFILE 8
6001 FORMAT(1X,10I6)
6002 FORMAT(1X,16,1X,16,1X,16)
6010 FORMAT(1X,10F6.1)

CALL OPEN(9,11HFORT09,2)
WRITE(9,6010)(DIFMX(M),M=1,84)
ENDFILE 9

```



```

      WRITE(2,500)
500  FORMAT(//,10X,'SIZE, SHAPE AND DEGREE OF LIBERATION
      $ OF PYRITE IN COAL')
      WRITE (2,501)
501  FORMAT(//,30X,'CLASSIFICATION',//,33X,'1=ENCAPSULATED',
      $ /,33X,'2=PARTIALLY ENCAPSULATED',/,33X,'3=LIBERATED')

      WRITE(2,502)
502  FORMAT(//,30X,'SCALES',//,33X,'1 PIXELS',/,33X,'5 FOR
      $ 8X',/,33X,'6 FOR 16X',/,33X,'4 FOR 40X',/,33X,
      $ '7 FOR 63X')

      WRITE(2,503)SCL,L1,L2
503  FORMAT(//,4X,'SAMPLE ...',/,4X,'SCALE =',I3,/,4X,
      $ 'LX LEVELS: L1=',I3,4X,'L2=',I3,/)

      WRITE(2,1000)
1000 FORMAT(//,4X,'CNT',3X,'LX',7X,'DMAX',7X,'SF',
      $ CLS ',//)
20  RETURN
      END

```

C
C

```
ST.FUR
SUBROUTINE ST
CALL USER
RETURN
END
```

C
C
C

```
SUBROUTINE USER
LOGICAL LFCBM(18),LFS,LINTER(2)
REAL RPARA(18),SK(2)
REAL A0(50),A1(50),A2(50)

REAL LIB(50)
REAL DMAX(50),MINX(50),DELSF(50)
REAL MAX(50)
INTEGER SCAL
INTEGER D(10,21),E(10,11)

REAL DIFMAX(21)
REAL L1,L2
REAL DLIB(11),DELSF(11)
INTEGER NLIB(11)
INTEGER CLASS(50)
REAL MAXMA,MIMMA
COMMON/PCPDAT/IVPCP(1000),ICDM,ICRED,ISGMNT,NWPAR,IPPAR
IBR=ICRED+1
GO TO(888,889,889),IBR
CONTINUE
NCLASS=IVPCP(IPPAR)
MIMMA=IVPCP(IPPAR+1)
MAXMA=IVPCP(IPPAR+2)
SCAL=IVPCP(IPPAR+3)
L1=IVPCP(IPPAR+4)
L2=IVPCP(IPPAR+5)

IF(SCAL.EQ.1)SK(1)=1.
IF(SCAL.EQ.3)SK(1)=1.577
IF(SCAL.EQ.6)SK(1)=.7673
IF(SCAL.EQ.4)SK(1)=.2985
IF(SCAL.EQ.7)SK(1)=.1891
SK(2)=SK(1)

CALL OPEN(7,11,FORT(7),.E)
READ(7,5000)NTDT,NENCP,NPLIB,NLIB1
READ(7,5000)((D(M,N),M=1,10),N=1,NCLASS)
READ(7,5000)((E(M,N),M=1,10),N=1,11)

ENDFILE 7
DO 1 I=2,13
LFCBM(I)=.FALSE.
RPARA(I)=0.
CONTINUE
LFCBM(1)=.TRUE.
RPARA(1)=0.
LINTER(1)=.FALSE.
LINTER(2)=.FALSE.
LFS=.TRUE.
K=1
```

888

1

```

10 CALL EXTRAC(1, LFCBM, RPARA, SK, 4, LINTER, LFS)
   IF (LFS) GO TO 20
   A0(K)=RPARA(1)
   K=K+1
   GO TO 10
20 CONTINUE
   NPART=K-1
   LINTER(1)=.FALSE.
   LINTER(2)=.FALSE.
   K=1
   LFS=.TRUE.
   RPARA(1)=0.
   LFCBM(11)=.FALSE.
   LFCBM(12)=.FALSE.
30 CALL EXTRAC(2, LFCBM, RPARA, SK, 4, LINTER, LFS)
   IF (LFS) GO TO 40
   A1(K)=RPARA(1)
   K=K+1
   GO TO 30
40 CONTINUE
   K=1
   LFS=.TRUE.
   LINTER(1)=.FALSE.
   LINTER(2)=.FALSE.
   RPARA(1)=0.
50 CALL EXTRAC(3, LFCBM, RPARA, SK, 4, LINTER, LFS)
   IF (LFS) GO TO 60
   A2(K)=RPARA(1)
   K=K+1
   GO TO 50
60 CONTINUE
   K=1
   LED=.FALSE.
   LFCBM(9)=.TRUE.
   LINTER(1)=.FALSE.
   LINTER(2)=.FALSE.
   LFS=.TRUE.
   RPARA(9)=0.
   RPARA(17)=0.
   LFCBM(17)=.TRUE.
100 CALL EXTR2(4, LFCBM, RPARA, SK, 0, LINTER, LFS, LED, LEDGE)
   IF (LFS) GO TO 90
   DMAX(K)=RPARA(9)
   MAX(K)=DMAX(K)
   MINX(K)=RPARA(17)
   K=K+1
   GO TO 100
90 CONTINUE
   DO 2 K=1, NPART
   AE=A2(K)-A1(K)
   AC=A1(K)-A0(K)
   IF (AE.LT.0.) GO TO 889
   IF (AC.LT.0.) GO TO 889
   AEC=AE+AC
   IF (AEC.EQ.0.) GO TO 889
   LIB(K)=(AE/(AE+AC))*100.
   IF (LIB(K).GE.0. AND. LIB(K).LE.L1) CLASS(K)=1
   IF (LIB(K).GE.0. AND. LIB(K).LE.L1) NENCP=NENCP+1
   IF (LIB(K).GT.L1. AND. LIB(K).LE.L2) CLASS(K)=2
   IF (LIB(K).GT.L1. AND. LIB(K).LE.L2) NPLIB=NPLIB+1
   IF (LIB(K).GT.L2) CLASS(K)=3
   IF (LIB(K).GT.L2) NLIB1=NLIB1+1
   IF (MAX(K).LE.0.) GO TO 889
   ELSF(K)=MINX(K)/MAX(K)

```

```

      DO 2002 K=1,NPART
      NC=K+NTOT
      WRITE(2,2000)NC,LIB(K),DMAX(K),ELSF(K),CLASS(K)
2000  FORMAT(2X,I6,3F10.2,I3)
202   CONTINUE
      WRITE(2,2001)
2001  FORMAT(/)

C
C      CLASSIFICATION
C
      NCL1=NCLASS-1
      IF(NCL1.LE.0)GO TO 23

      DO 3 J=1,NCLASS

      DIFMAX(J)=(MAXMA-MIMMA)/(NCLASS-1)
3     DIFMAX(J)=DIFMAX(J)*(J-1)+MIMMA
      DLIB(1)=-0.1
      DELSF(1)=-.1
      DO 4 J=2,11
      DLIB(J)=10.*(J-1)
      DELSF(J)=.1*(J-1)
4     CONTINUE
      DO 5 K=1,NPART
      DO 55 J=2,11
      IF(LIB(K).GT.DLIB(J-1).AND.LIB(K).LE.DLIB(J))I=J-1
      IF(LIB(K).GT.DLIB(J-1).AND.LIB(K).LE.DLIB(J))GO TO 66
55    CONTINUE
66    CONTINUE
      DO 69 J2=2,NCLASS
      IF(DMAX(K).GT.DIFMAX(J2-1).AND.DMAX(K).LE.DIFMAX(J2))
      *      D(I,J2-1)=D(I,J2-1)+1
      IF(DMAX(K).GT.DIFMAX(J2-1).AND.DMAX(K).LE.DIFMAX(J2))GO TO 70
69    CONTINUE
      GO TO 5
70    CONTINUE


      DO 71 J3=2,11
      IF(ELSF(K).GT.DELSF(J3-1).AND.ELSF(K).LE.DELSF(J3))
      *      E(I,J3-1)=E(I,J3-1)+1
      IF(ELSF(K).GT.DELSF(J3-1).AND.ELSF(K).LE.DELSF(J3))GO TO 5
71    CONTINUE
5     CONTINUE
      NTOT=NTOT+NPART
      CALL OPEN(7,11HFORT07,2)
      WRITE(7,6000)NTOT,NENCP,NPLIB,NLIB1
      WRITE(7,5000)((D(M,N),M=1,10),N=1,NCLASS)
      WRITE(7,5000)((E(M,N),M=1,10),N=1,11)

5000  FORMAT(1X,10I6)
      ENDFILE 7
6000  FORMAT(1X,I6,1X,I6,1X,I6,1X,I6)
      GO TO 889
23    WRITE(2,24)
24    FORMAT(10X,'** NO. OF CLASSES TOO SMALL **',/)

889   RETURN
      END

```



```

      L22=(L2+5)/10
      NENCP=0
      NPLIB=0
12      DO 12 I=1,L11
          NENCP=NENCP+L(I)
          L12=L11+1
13      DO 13 I=L12,L22
          NPLIB=NPLIB+L(I)
      NLIB1=NTOT-NENCP-NPLIB

      WRITE(2,1000)NTOT
1000    FORMAT(/,30X,'TOTAL NUMBER OF PARTICLES =',I6,/)
      WRITE(2,4000)NENCP,NPLIB,NLIB1
4000    FORMAT(/,30X,'ENCAPSULATED PARTICLES =',I6,/,30X,
$      'PARTIALLY ENCAPSULATED PARTICLES =',I6,/,30X,
$      'LIBERATED PARTICLES =',I6,/)
5000    FORMAT(1X,I0I6)
24      FORMAT(10X,'** NO. OF CLASSES TOO SMALL **',/)

```

```

      N1=0
      N2=0
      N3=0
      N4=0
      CALL OPEN(8,11HFORT08,2)
      READ(8,6001)((D1(M,N),M=1,10),N=1,80)
      READ(8,6001)((E1(M,N),M=1,10),N=1,11)
      READ(8,6002)NE,NP,NL
      ENDFILE 8
      CALL OPEN(9,11HFORT09,2)
      READ(9,6010)(DIFMX(M),M=1,84)
      ENDFILE 9
6001    FORMAT(1X,I0I6)
6002    FORMAT(1X,I6,1X,I6,1X,I6)
6010    FORMAT(1X,10F6.1)
      DO 900 I=1,10
      DO 901 J=1,20
901      N1=N1+D1(I,J)
      DO 902 J=21,40
902      N2=N2+D1(I,J)
      DO 903 J=41,60
903      N3=N3+D1(I,J)
      DO 904 J=61,80
904      N4=N4+D1(I,J)
900      CONTINUE
      IF(N1.EQ.0.AND.N2.EQ.0.AND.N3.EQ.0)IT=1
      IF(N1.NE.0.AND.N2.EQ.0.AND.N3.EQ.0)IT=2
      IF(N1.NE.0.AND.N2.NE.0.AND.N3.EQ.0)IT=3
      IF(N1.NE.0.AND.N2.NE.0.AND.N3.NE.0)IT=4
      DO 100 M=1,10
      DO 100 I=1,NCLASS
          J=NCLASS*(IT-1)+I
          D1(M,J)=D(M,I)
100      D(M,1)=0.
          NCL=NCLASS+1
          DO 200 I=2,NCL
          J=NCLASS*(IT-1)+I
200      DIFMX(J)=DIFMX(I)
          DO 300 M=1,10
          DO 300 N=1,10
              IF(IT.EQ.1)E1(M,N)=E(M,N)
              IF(IT.EQ.1)GO TO 300
              E1(M,N)=E1(M,N)+E(M,N)

```



```

300      E(M,N)=0.
          IF(IT.EQ.1)NE=NENCP
          IF(IT.EQ.1)NP=NPLIB
          IF(IT.EQ.1)NL=NLIB1
          IF(IT.EQ.1)GO TO 333
          NE=NE+NENCP
          NP=NP+NPLIB
          NL=NL+NLIB1
333      CONTINUE
          NTOT=0
          NENCP=0
          NPLIB=0
          NLIB1=0
          CALL OPEN(7,11HFORT07,2)
          WRITE(7,6000)NTOT,NENCP,NPLIB,NLIB1
          WRITE(7,5000)((D(M,N),M=1,10),N=1,NCLA)
          WRITE(7,5000)((E(M,N),M=1,10),N=1,11)
          ENDFILE 7

          NTOT=NE+NP+NL
          CALL OPEN(8,11HFORT08,2)
          WRITE(8,6001)((D1(M,N),M=1,10),N=1,80)
          WRITE(8,6001)((E1(M,N),M=1,10),N=1,11)
          WRITE(8,6002)NE,NP,NL
          ENDFILE 8
          CALL OPEN(9,11HFORT09,2)
          WRITE(9,6010)(DIFMX(M),M=1,84)
          ENDFILE 9
          WRITE(2,45)
          WRITE(2,3001)(NLIB(1),1=1,11)
          WRITE(2,3000)(DIFMX(N+1),(D1(M,N),M=1,10),N=1,80)
          WRITE(2,3002)(NLIB(1),1=1,11)
          WRITE(2,3000)(DELSF(N+1),(E1(M,N),M=1,10),N=1,10)
          WRITE(2,1000)NTOT
          WRITE(2,4000)NE,NP,NL

          GO TO 889
23      WRITE(2,24)
889      RETURN
          END

```

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AUTOMATED MICROSCOPY METHODS FOR MEASURING PYRITIC SULFUR CONTENT OF COAL AND
DETERMINING DEGREE OF LIBERATION OF PYRITE IN COAL

DOE