1 of 1

TECHNICAL REPORT
September 1 through November 30, 1993

Project Title: **CHARACTERIZATION OF COAL PARTICLES
USING RULE BASE ON-LINE IMAGE ANALYSIS**

DOE Grant Number: DE-FC22-92PC92521 (Year 2)
ICCI Project Number: 93-1/6.2B-1P
Principal Investigator: S. C. Max Yen, Southern Illinois
University at Carbondale
Other Investigator: Philip T. C. Chu, Southern
Illinois University at Carbondale
Project Manager: Dr. Ken Ho, Illinois Clean Coal
Institute

ABSTRACT

Different materials in coal reflect light in a different manner and, therefore, can be identified based on their image of light reflectance characteristics (i.e. shade of gray). Furthermore, liberated and nonliberated pyrite particles are surrounded by media of different shades of gray. With these two pieces of information, the degree of pyrite liberation and the degree of purity of coal macerals can be analyzed through a computer program. Ultimately, this image analysis computer program will acquire and analyze different frames of coal image automatically without any intervention of an operator. During the past one year, an in depth database of the light reflectance characteristics of different materials of coal has been established. This process is still being continued to extend the database of coal images. In addition, during this quarter, the particle recognition algorithm of the image processing program has been established. This particle recognition algorithm is based on the gray level bandwidth data (ΔG) developed in the previous study. Each pixel in a coal image was analyzed by its gray level as well as its connectivity with the surrounding pixels. A special data handling procedure was also introduced in this image processing program to overcome the limitation on the memory storage capacity of a personal computer.

MASTER

"U.S. DOE Patent Clearance is NOT required prior to the publication of this document."

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EXECUTIVE SUMMARY

In light of the need in coal characterization, especially, pyrite liberation analysis, a rule base on-line image analysis system is proposed. This proposed research represents an extension of a project funded by ICCI.

To obtain the ultraclean fuel, coal must be pulverized into particles of ultrafine sizes. As a result, the characterization of ground coal, in particular, the assessment of pyrite liberation, becomes extremely difficult. The assessment of pyrite liberation is the most important way of determining whether a batch of ground coal obtained through a grinding process is acceptable. At present, the liberation analysis is conducted manually through a microscope with commercial image analysis software. Sometimes, this procedure causes discrepancies from one operator to the other in the interpret of microscopic images. On the other hand, the amount of coal can be inspected in each experiment is limited by the particle sizes of the ultrafine coal and the magnification factor of the microscope. Therefore, a large number of samples must be analyzed in order to assess the degree of pyrite liberation. This makes the present method of liberation analysis of coal a very labor intensive and a very time consuming process. In light of that, an automation procedure based on the principles of image processing is being developed to perform the analysis of pyrite/minerals liberation of coal.

Different materials reflect light in different manners and therefore can be identified based on their image of light reflectance characteristics (i.e. shade of gray). Furthermore, liberated and nonliberated pyrite particles are surrounded by media of different shades of gray. With these two pieces of information, the degree of pyrite liberation can be analyzed through a microcomputer. To make the automated image analysis system possible, an expert knowledge base and a rule base decision mechanism utilizing the light reflectance characteristics of different constituents of coal (pyrites, vitrinite, inertinite, etc.) must be established. This will include the consideration of the effect of the actual operating parameters such as inclined incident of light, uneven focal planes of the sample. It is believed that such an automation process for image analysis of coal particles is very feasible in the laboratory operation involving polished pellet. Recently, the laboratory studies conducted at SIUC have demonstrated that pyrite analysis can be accomplished in a matter of less than one minute rather than a few hours if conducted manually. However, in this evaluation

process, the light reflectance characteristics of pyrite was predetermined manually used as an input into the image analysis program.

It should be pointed out the automation in the recognition of coal particles requires a wide spectrum of optical images of ground coal. Specifically, one should realize that every microscopic image (through an optical microscope) of ground coal exhibits distinct characteristics. This is due to the fact that the distribution of coal particles is different from one frame to another. As a result, the image features such as the average gray level of pyrites, the particles size distribution of each maceral, the material composition etc. are unique for each frame. Under such a circumstance, assessment of pyrite liberation using image analysis with one optical feature (e.g. a fixed value of gray level for pyrite) will be insufficient. Rather, a set of rules simultaneously evaluating the distinct optical and physical characteristics of coal particles (including pyrites) must be established. Recent research results at Southern Illinois University at Carbondale (SIUC) have led to development of several criteria for analyzing images of coal with different characteristics. Undoubtedly, an extensive characterization of coal images is still needed in order to develop a broad expert knowledge base about coal particles.

In addition to the development of a rule base image analysis program, a complete on-line coal characterization system must include the mechanisms for the transport of samples to a stage for measurement. To be more specific, in order to bring the coal sample pellets under an image analysis device (e.g. optical microscope), a conveyer system allowing for an in-plane travel is needed. In addition, a mechanism to bring the specimen into the focal plane of the microscope should be implemented. With today's technology in the digital I/O system, the procedure for motion control of the conveyer and staging system can be interfaced with a computer. As a matter of fact, the development of a computer controlled X-Y table has been completed and tested successfully. The work ahead will be the development and design of an interactive image focus scheme. In other words, the step for bringing an image into focus will be accomplished by the computer instead of by human operator. In this regard, an image analysis technique is necessary for the sensing and adjustment of optical depth of the test sample. Ultimately, it is believed that the procedure for characterization of coal such as pyrite liberation analysis can be fully implemented through a computer from the initial sample preparation to the final image analysis.

The completion of the studies outlined in the previous sections will bring the following advantages:

1. Improves the current coal characterization technology, in particularly, the assessment of pyrite liberation.
2. Greatly reduces the time and effort in performing liberation analysis. The new image analysis procedure developed in this research will provide faster and more accurate pyrite liberation analysis.
3. Provides a realistic assessment of a coal characterization process as a part of the coal cleaning and preparation processes.
4. Offers potentials for the commercialization of research results such as image analysis program for coal particles and design of the on-line system.

Currently, the measurement of the light reflectance characteristics of different materials in coal is still being continued in order to extend the database of coal images. In addition, during this past quarter, the particle recognition algorithm of the image processing program has been established. This particle recognition algorithm is based on the gray level bandwidth data (ΔG) developed in the study conducted last year. Each pixel in a coal image was analyzed by its gray level as well as its connectivity with the surrounding pixels. A special data handling procedure was also introduced in this image processing program to overcome the limitation on the memory storage capacity of personal computer. The specific features of this program are,

- a. Label two rows of pixels of the image file at a time.
- b. In each row, the material clusters are established for the group of pixels having a gray level bandwidth less than 30.
- c. Examine and connect the clusters of the neighboring rows that fall within the same gray level bandwidth.
- d. Assign and rank particles based on their average gray level.

The development of this particle identification algorithm represents a key step toward the completion of the automated image analysis computer program.

OBJECTIVES

The overall objectives of this project are:

1. To continue the development of a rule base automated image analysis computer program for assessment of pyrite liberation, and
2. To upgrade the image analysis system into an integrated package.

These two phases will be conducted simultaneously. In the laboratory scale, the specimens to be analyzed will be under somewhat ideal conditions. However, the image analysis computer algorithm to be developed in this stage is essentially the foundation for any rule base coal characterization procedure. In addition, the completion of the first goal will represent a drastic improvement of the current technology in the coal characterization such as liberation assessment. For the integrated system, we will attempt to emulate the automated image analysis into a part of the overall coal cleaning process. Under this constraint, a conveyer system as well as an auto-focusing mechanism will be designed and built.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

INTRODUCTION AND BACKGROUND

The key emphasis of this research project is to develop an automation process for the determination of pyrite/minerals liberation as well as particle size distribution of ultrafine coal obtained during and/or after coal cleaning. To accomplish this, an image analysis computer program with an expert knowledge base for identifying different constituents (liberated and nonliberated) in coal must be developed. Since different images acquired from a coal sample exhibit different features in particle size distribution and different compositions of material, a rule base decision making algorithm must be established through an extensive laboratory study. In addition to the development of the rule base image analysis program, in this project, we will also attempt to develop and construct a system that will allow an automation in setting up the test specimen under imaging apparatus as well as an automation in bring coal image in focus. It is believed that the results of this research program can greatly reduce the intensive time and effort in the characterization of coal during the liberation and separation processes. Furthermore, the equipment and software design will lead to a new and improved standard in coal characterization.

Needs for the Evaluation of Ultrafine Coal

The coal industries, today, are facing with a very stringent requirement on the emission and/or release of sulfuric compound to the living environment set forth by Environmental Protection Agency (EPA). As a result, the need for producing ultra-clean coal effectively (Yen and Hippo 1990) has greatly increased. It has been reported by McCartney (1969) and Jao (1991) that for the Illinois #6 coal the mean particle size of pyrite is less than 10 micron. Therefore, from the viewpoint of statistics, coal must be ground to ultrafine sizes in order to liberate the microscopically dispersed pyrite particles and to obtain the clean coal that meets the EPA requirements. The development of the procedure for effectively producing ultrafine coal is a difficult task and has been pursued by many researchers. On the other hand, to evaluate the degree of success of each of the newly developed coal pulverization procedures, a method for examining the ultrafine coal is needed. The traditional method (ASTM, 1973) for evaluation of coal fines is a two step approach. First of all, ground coal is subjected to centrifuge in heavy media for the separation of fraction with different specific gravities. Secondly, each fraction of a given specific gravity is then subjected to TGA for element analysis or SEM for the microscopic observation. However, these steps are quite time consuming and labor intensive. For example, the

drying process after the centrifuge usually takes a few hours while the SEM inspection requires a tedious sample preparation. Clearly, the liberation analysis procedures recommended by ASTM is not suitable for the high volume ultrafine coal production which requires a quick analysis of coal particles. In our view, an effective characterization procedure for analyzing pyrite/mineral liberation should require a minimal specimen preparation. The actual measurement of ground coal particles should be conducted by taking the advantage of high speed data processing of computer. This is to ensure that a large number of samples can be accounted for whereby the liberation assessment will be statistically meaningful and will be accomplished in a very short time. Ultimately, a high magnification device (such as optical microscope) is needed to examine the ultrafine coal particles. To develop into an on-line quality assurance mechanism, the sample preparation, sample inspection, and liberation analysis must be integrated into an automated mechanism. It is believed that the recent development of image analysis technique and long distance microscope may make such an integrated system possible.

Optical Microscopic Image Analysis

Image analysis (Dawson 1987, Gonzales et al 1987) is a relatively new technique that is being applied to scientific and engineering research. Basically, image analysis is used to determine the optical characteristics (e.g. intensity of light reflectance) of objects. This is then followed by a logical assessment of the measured data and a comprehensive numerical calculation.

Typically, an optical microscopic image analysis system consists of a microscope, a CCD camera, a monitor, and a personal computer equipped with a data acquisition board (frame grabber). The microscope is to provide a proper image for observation, the video camera along with the data acquisition board are to record the various optical characteristics of different objects, and finally computer software is used to analyze data in order to distinguish different materials, and particle sizes. When an object is presented under a microscope several of its characteristics such as shades of gray, physical dimensions (length, width, area), shape, boundaries, texture are noticeable. Most of these characteristics, in general, are distinct among different objects. In the image analysis, an image is divided by a set of horizontal and vertical grids (or pixels). Within each grid area, optical characteristics are electronically recorded and analyzed through a computer system. Also, using a proper calibration procedure, the actual area represent by a group of grids can be calculated. Such an analysis procedure is referred to as the optical

microscopic image analysis.

Recently, the utilization of optical microscope with the Automated Image Analysis (AIA) has resolved some problems involving the visual interpretation of the objects at microscopic levels. For example, AIA has been applied successfully by Yen et al (1991) to determine the fiber angle orientation and fiber volume ratio of composite materials, and by Huggins et al (1982), Straszheim and Markuszewski (1985 and 1986) to analyze the particle size distribution of ultrafine coal, to identify different minerals and macerals in coal and to assess the pyrite liberation after coal grinding. This is primarily based on the principle that, in general, different materials have different light reflectance. Such characteristics appear as different shades of gray (or colors) under the video camera observation and can be distinguished and analyzed through computer programs.

Current Application of AIA to Liberation Studies

At present, for pyrite liberation analysis (Yen and Hippo 1990, Blankenship 1991, Jao 1991), a pellet is prepared by mounting samples of ground coal in epoxy resin. This pellet is subjected to several steps of polishing. The polished pellet was then brought to an optical microscope for examination and analysis using a commercial image analysis software. This software can only perform a limited number nonsequential routines in image enhancement and image analysis such as picture sharpening, and area counting. In other words, a sequential logical analysis of pyrites with different surroundings (i.e. liberated and nonliberated) is beyond the capacity of this computer program. Therefore, an interaction between operator and the computer program is necessary make a single measurement.

After the image of the desired area of the sample is adjusted for better human interpretation, a threshold gray level value is set for the pyrite particles. The operator records the area of the pyrite particles, their total number on the examined frame and the total area. Then, based on visual inspection, the person has to decide whether or not the pyrite particle is free and label it accordingly. This process is repeated until at least a total of about 200 pyrite particles are analyzed (Florek, 1991). Obviously, this procedure was laborious and time consuming. Even visual inspection is a rather daunting task and the operator is always doubtful as to whether or not the pyrite particle is free. In addition to these problems, due to the extreme brightness of the pyrite particles, the pixels in their neighborhood acquire a glow that makes it all the more difficult to establish the properties of the surroundings. Therefore,

the results varied, depending on the decision made by different operators.

The most challenging task in making image analysis into an automated process is image segmentation, wherein, the classification of image regions into different objects. This is primarily because of the complexity of the image and the contrast variations in the particular video camera setting and in the light source of the object. For this purpose, numerous images of a sample must be analyzed to determine their distribution of shades of gray (i.e. histograms), pixel values along a line, etc. These information are then used to establish an expert knowledge database regarding the relative gray levels of different macerals in coal. This is followed by a decision making through a rule base artificial intelligent (Batchelor 1974, Pavlidis 1977) to detect the liberation of each individual particle.

Development of the Rule Base for Image Analysis of Coal

In analyzing a typical gray level image, one usually determines the pixel distribution of different gray levels (this is referred to as the histogram). During the inspection of ground coal particles, it is possible that the use of histogram may provide the information leading to the pyrite liberation analysis. This is because that different materials in coal appear to have distinct gray levels when a coal image is viewed through the computer monitor. In general, the distinction in gray levels may be interpolated as (a) a gray level with zero pixel in a histogram represents the division between two types of maceral, or (b) the difference in gray level between macerals is greater than that of within the same maceral. In other words, there should be a distinct boundary between pyrites to inertinite and inertinite to vitrinite. Clearly, the images with different composition of particles will result in histograms of distinct characteristics. This suggests that analysis of coal images must be conducted on an individual frame basis.

Theoretically, there should be only four gray levels (or ranges of gray level) with zero pixel in an image. This will naturally divide the ground coal into voids/boundaries (in black), epoxy background, vitrinite, inertinite, and pyrite. However, the data extracted from the histogram of several coal images have shown many gray levels with zero pixel. This will definitely bring confusing in the determination of boundaries between different macerals. On the other hand, since pyrite is the brightest among all the particles in an image, development of an computer algorithm searching for the upper gray scales of zero pixel may be worthy.

To further study the optical characteristics of ground coal, an gray level averaging technique was introduced (Yen and Chu, 1993). In general, in a particle there exists a distribution of (perhaps, continuous) gray levels. One can identify a particle much easier by using its average gray level. In addition, it was found that using the gray level averaging technique particles of the same kind (e.g. vitrinite, inertinite, pyrite) tend to group closer in their gray values. In other words, the relative distance in gray level between vitrinite to inertinite and inertinite to pyrite becomes larger. As a result, the distinction among pyrite, inertinite, and vitrinite using the average gray value approach is possible. More importantly, it was found that, for most of the images studied, the gray level spreads between vitrinite to inertinite (ΔG_1) and inertinite to pyrite (ΔG_2) tend to be the two largest values among the difference in gray level between two particles with adjacent light reflectance. In this regard, the particles that define the two largest differences in gray level are those which define the lowest gray level for pyrites, the highest and the lowest gray levels for inertinite, and the highest gray level for vitrinite. Furthermore, it was found that ΔG_1 usually greater than ΔG_2 .

Several special cases that do not fit the descriptions given in the previous paragraph have also been identified. For example, it is likely to have an image without the presence of pyrites and/or vitrinite. Also, it is possible that the particles involved in obtaining the first two largest gray level difference (i.e. ΔG_1 and ΔG_2) are not the particles define the boundaries between vitrinite to inertinite and inertinite to pyrite. To resolve these cases, it is necessary to investigate the spread in gray level of each individual maceral and mineral, the shape factor and size of each particle, the location where ΔG_1 and ΔG_2 were calculated, etc. Each distinct case of gray level characteristics of an image will then become a case of the overall expert data base for decision making algorithm. Undoubtedly, extensive laboratory characterization of coal samples is necessary to build into a broad data base.

Integrated On-line Image Analysis Stage

It is believed that the automated image analysis system proposed here can be used as a part of the coal cleaning process. The automated image analysis system can be used at the down stream of the liberation process and/or the separation process. Based on this concept, there will be

a mechanism to collect coal samples from the cleaning process, a process for sample preparation, a conveyor system to transport coal samples into the inspection station, a mechanism to bring the test sample into the focal plane of the image instrument, and finally the computer program for the characterization of the liberation status. All these subsystems can be integrated into a single interactive feedback and control package illustrated by Figure 4. This integrated system emulates the quality inspection process used in the manufacturing industry. However, the computer programming and data acquisition in this proposed feedback/control system is far more complicated.

Two components of the on-line system have been put together. An X-Y table consists of two stepping motors with platform and a computer interface system have been received. The table has a stepping capability of 0.0025 in. with a resolution of 0.0001 in.. A C-language based computer program was developed to manipulate the motion of the X-Y table. It should be pointed out that this system control program can be integrated as a part of the image analysis program. In the envisioned process, this table will bring coal samples to a position under the viewing path of a long distance video imaging system through the computer algorithm. Next, a z-axis motion has to be introduced to provide an automation mechanism in focusing. This will require an elaborated programming in pattern recognition as well as depth detection through an image correlation.

A long distance imaging system was also integrated during this quarter. This system consists of a long distance microscope (up to 660x), a color CCD video camera, a color frame grabber, and a 486 computer. The light source of the long distance imaging system is provided through a fiber optic ring light attached with the long distance microscope. The minimum working distance of the long distance microscope is 10 mm. It is necessary to calibrate the long distance imaging system so that an optimal working distance for observing coal pellet is obtained.

EXPERIMENTAL PROCEDURES

The overall goals of this project are (1) to continue the development of a rule base automated image analysis system for assessment of pyrite liberation and (2) to upgrade the image analysis system into a bench scale package. These two phases will be conducted simultaneously. In the laboratory scale, the specimens to be analyzed will be under some what ideal conditions. However, the image analysis computer algorithm to be developed in this stage is essentially the foundation for any rule base coal characterization procedure. In addition, the completion of the first goal will represent a drastic improvement of the current technology in the coal characterization such as liberation assessment. In the bench scale, we will attempt to emulate the automated image analysis into a part of the overall coal cleaning process. Under this constraint, a conveyer system as well as an autofocusing mechanism will be designed and built. The specific tasks to be conducted in this proposed study are summarized as follows:

Task 1: Sample preparation

Ultrafine coal (Illinois #6 coal) samples that have different degree of liberation will be used in this study. These samples were prepared through a previous CRSC/DOE project and are available at the Civil Engineering and Mechanics Department, Southern Illinois University. Both pelletized and particulate coal samples are needed. To prepare the pellet sample, ultrafine coal particles will be mixed with epoxy resin and cast into a plastic cylinder. Upon cured, the circular surfaces of the pellet will be subjected to several steps of polishing until they are mirror like. To prepare the nonpelletized sample, ultrafine coal particles will be spread on a thin glass plate. A light brushing will be applied to minimize the overlapping of coal particles. Finally, a second glass plate will be used to clamp the coal particles in place.

Task 2: Determine the Image Characteristics of Pyrite and Coal Macerals

In this task, the expert knowledge base regarding the image characteristics of each coal constituents such as pyrite and vitrinite are to be developed. Normally, the light reflectance of each material in coal will have a band width of shades of gray. However, the gray levels of a material can shift under different light sources. Therefore, it is necessary to determine the gray levels of each material in coal as well as to determine its relative difference in gray levels with other macerals/minerals. Sometimes, in a random sample, the

gray level data may not be sufficient to differentiate one material from the other. In this case, particle characteristics such as shape factor (length to width ratio), particle size, surface texture will then be useful in assisting decision making. Therefore, in this task, we will attempt to measure as many image features as possible for pyrite, minerals, macerals in coal. The image analysis will be primarily conducted using a commercial image analysis software. In the meantime, we will develop an image analysis computer program of the similar capacity.

Task 3: Development of a Rule Base Liberation Criterion

So far, there is no commercial software which can do liberation analysis without the intervention of an operator. In this project, a computer program (to be added on the one being developed under an ICCI grant) will be developed to perform pyrite liberation assessment as well as the analysis of coal particles. It is known that a liberated pyrite particle will be surrounded by the epoxy matrix of the pellet rather than the coal. As a result, base on the analysis of the gray level of the material surrounding to a pyrite particle. The status of liberation may be determined. On the other hand, the liberation status can also be determined based on the difference in gray between a particle and its surrounding. Ultimately, the variation of gray levels of an image containing the liberated and nonliberated particles can be modeled by Fourier series. Based on this mathematical model, the characteristics of the functional changes for liberated particle can be established. In this proposed study, the liberation criteria based on the gray levels of the surrounding to the pyrite particles will be developed into a computer program. Also, the distinct features of different image frame will be documented and will be implemented into the criteria for coal characterization. This program will take an image (in terms of a computer file) and perform the liberation analysis. Interactive computer graphics will be developed and used to show the image with the results of the liberation analysis. The computer program developed in Task 2 will be combined with the computer program developed in this Task to form an integrated interactive image analysis software.

Task 4: Verification Study

It is believed that the image analysis program to be developed here is capable of performing fast and accurate liberation analysis. To verify this, pyrite liberation data and the kinematics of ultrafine coal particles that obtained from the elaborated analysis through human operators will be used to compare with the results obtain

from the image analysis program developed based Tasks 2 and 3. Extensive liberation data as well as particle size distribution of ground coal that established by Yen and Hippo (1990a) will be used as a reference.

Task 5: Design of an On-line System

In our view, the automated image analysis at its ultimate application should be built in as a part of the coal cleaning process. The automated image analysis system can be used at the down stream of the liberation process and/or the separation process. Thus far, the plan for this proposed on-line system has been developed (Figure 4). The following steps are to build and to calibrate the conveyer system (X-Y table) and the automation in specimen focusing (Z-axis). For example, a vertical motion mechanism will have to be added to the existing X-Y table. The computer program for the motion control of X-Y table as well as focusing in Z-axis must be developed. In particular, the fine tuning in the focusing step must interact with the attached imaging system equipped with an image correlation program (to be developed). It should be pointed out that the focusing of the test specimen may be substituted by a feedback mechanism between operator and the computer.

RESULTS AND DISCUSSION

Currently, the measurement of the light reflectance characteristics of different materials in coal is still being continued in order to extend the database of coal images. In addition, during this past quarter, the particle recognition algorithm of the image processing program has been established. This particle recognition algorithm is based on the gray level bandwidth data (ΔG) obtained in the last year's study. Specifically, to form a particle, each pixel in a coal image was analyzed by its gray level as well as its connectivity with the surrounding pixels.

In general, an image of 480x512 pixels at its virgin form requires 246,272 bytes of memory. Upon image processing, additional computer memory space is required to store the information regarding the pixel location, cluster identity and boundary, material type, liberation status (neighboring gray level), particle size/distribution, and average gray level. As a result, a special data handling procedure was introduced in the image analysis program to overcome the limitation on the memory storage capacity of personal computer.

To begin the image analysis, the computer program grabs two rows of pixels of an image file at a time. This immediately reduces the memory storage requirement greatly. For each row, the gray level of each pixel is determined and is compared with that of the adjacent pixels to see if they fall within a gray level bandwidth of 30. If so, these pixels are labeled as one particle. It should be pointed out that the gray level bandwidth can be treated as an input to account for special cases. A data file containing the row-by-row particles list is created when the entire image is examined. Figures 1 and 2 give an illustration of this two-row pixels grouping process. The raw image of gray level values is given in Figure 1. Figure 2 shows the particle data created after the row by row grouping.

Upon the completion of the row-by-row grouping, the connectivity among the material clusters in the adjacent rows are examined. This is done by referring back the raw gray level data (as shown in Figure 1). Naturally, the same gray level bandwidth is used. Again, to alleviate the limitation on the computer memory space, the connectivity among the clusters of two adjacent rows are processed at a time. When the entire image is completely processed, the clusters are re-numbered. Figure 3 gives the result of the grouping of clusters through the adjacent rows.

When the particle grouping process is completed, several pieces of information are also developed. These data are the size and the average gray level and will be analyzed to identify material and liberation status. It should be pointed out that the development of this particle identification algorithm represents a key step toward the completion of the automated image analysis computer program.

250	76	94	90	98	92
248	240	125	120	180	94
220	250	254	115	185	80
225	220	255	125	172	85
210	215	220	110	178	179
110	100	120	120	120	198

Figure 1 An example of the pixel gray level of an image file.

1	2	2	2	2	2
3	3	4	4	5	6
7	7	7	8	9	10
11	11	11	12	13	14
15	15	15	16	17	17
18	18	18	18	18	19

Figure 2 The cluster data developed through the row-by-row grouping process.

1	2	2	2	2	2
1	1	2	2	5	2
1	1	1	2	5	2
1	1	1	2	5	2
1	1	1	2	5	5
2	2	2	2	2	5

Figure 3 The clusters data developed after the connectivity check among adjacent rows.

REFERENCE

- ASTM, (1973). Standard on the Washability of Coal.
- Batchelor, B.G., (1974). Classification and Data Analysis in Vector Spaces, Pattern Recognition - Ideas in Practice, Plenum Press, pp. 67-116.
- Blankenship, M. E. (1991). Comminution and Liberation in Herrin Illinois No. 6 Coal Employing Low Temperature Treatments. MS Thesis, Southern Illinois University, Carbondale, Illinois.
- Dawson, B. M. (1987). Introduction to Image Processing Bytes, March, pp. 169-186.
- Florek, D. M. (1991). Image Analysis: An Explanation and Evaluation of Its Use for Coal Research. A ME492 Report, Department of Mechanical Engineering and Energy Processes, Southern Illinois University, Carbondale, Illinois.
- Gonzales, R. C. and Wintz, P. (1987). Digital Image Processing, 2nd Ed., Addison-Wesley Publishing Co., 1987.
- Huggins, F. E., G. P. Huffman, and R. J. Lee. (1982). Scanning electron microscopy-based automated image analysis (SEM-AIA) and Mossbauer spectroscopy. In Coal and coal products: Analytical characterization techniques, ed. E. L. Fuller, pp. 239-258. Washington, D.C.: American Chemical Society.
- Jao, H. (1991). Size Reduction and Pyrite Liberation of Coals Employing Cryogenic Treatments. MS Thesis, Southern Illinois University, Carbondale, Illinois.
- McCartney, J. T. (1969). Pyrite Size Reduction and Coal Pyrite Particle Association in Steam Coals, Report No. 7231, US Department of Energy.
- Pavlidis, T. (1977). Structural Pattern Recognition, Springer-Verlag.
- Straszheim, W. E., and R. Markuszewski (1985). Application of Scanning Electron Microscopy and Automated Image Analysis for characterization of Mineral Matter in Coal. Am. Chem. Soc. Div. Fuel Chem., 30(1), 1985, pp. 47-55.
- Yen, S. C. and Hippo, E. J. (1990). Comminution Employing Freezing Temperature Pretreatments. Proceedings, Sixth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, Pittsburgh, PA., pp 241-248.

Yen, S. C. and Hippo, E. J. (1990a). Enhanced Coal Cleaning through Low Temperature Treatment of Coal. Final report submitted to Illinois CRSC.

Yen, S. C., Chu, T. C. P., and Jao, H. (1991). Applications of Optical Microscopic Image Analysis to Composite Materials. Experimental Techniques, Vol. 15, No. 5, pp. 22-25.

Yen, S. C. and Chu, T. C. (1993). Development of an On-line Image Analysis for Assessment of Pyrites Liberations. 2nd Quartely Report submitted to Illinois Clean Coal Institute (ICCI), Carterville, Illinois.

*Budget info removed.
ds*

DATE

FILMED

4 / 18 / 94

END