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

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ABSTRACT

The degree of pyrite liberation is a key to determine whether a batch of ground coal obtained through a grinding process is acceptable. In this regard, a synthesis so-called on-line image analysis system to be used as a part of a coal cleaning process has been developed. This system is designed to replace the traditional method in the assessment of pyrite liberation of ultrafine coal. The on-line image analysis system consists of two parts: an automated image analysis computer program and an automated sample handling system which is an assembly of an optical microscope, a video camera, a X-Y table, an autofocus unit, and a personal computer. The automated image analysis computer program performs the analysis of coal particles without any intervention of a human operator. The image analysis computer program is a rule base decision-making algorithm and is the creation of an extensive study of image characteristics of coal particles such as shade of gray, particle size etc. In general, the image analysis computer program developed in this project can identify different particles in a coal image as good as a human operator does. On the other hand, the sample handling mechanisms are controlled through the interaction between the step motors and an feedback unit attached to a personal computer. Naturally, a computer program is needed in order to send commands to move the X-Y table. For example, the control of the autofocus mechanism was achieved by comparing the development of particle edge in the images of different focal planes. It was found that an image is brought to focus when most of the edges is detected. In summary, the findings of this project have led to believe that the on-line image analysis can be used as a part of the coal cleaning process.

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EXECUTIVE SUMMARY

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 in the 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. It is believed that such an automation process for image analysis of coal particles is very feasible in the laboratory operation involving polished pellet. Some laboratory studies conducted at SIUC have demonstrated that pyrite analysis can be accomplished in a matter of few minutes rather than a few hours if conducted manually.

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.

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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) has been found to be insufficient. Rather, a set of rules simultaneously evaluating the distinct optical and physical characteristics of coal particles (including pyrites) must be established. The research results obtained at Southern Illinois University at Carbondale (SIUC) have led to development of several criteria for analyzing images of coal with different characteristics.

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. This work has included the development and design of an interactive image focus mechanism. In other words, the step for bringing an image into focus can 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 particular, 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.

The specific achievements of this project over the past two years are:

- A. Established an extensive database regarding the image characteristics of coal macerals.
- B. Derived a set of knowledge base to identify different coal macerals.
- C. Developed an automated image analysis computer program for analyzing coal particles.
- D. Assembled a set of instrumentation into an automated imaging system. This has included the image acquisition system as well as X-Y table/autofocus system.
- E. Provided a synthesis of putting an on-line image analysis system as a part of a coal cleaning process.

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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.

INTRODUCTION AND BACKGROUND

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 non-sequential 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 analyze 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 extract 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

vitritinite. 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 vitritinite. 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 vitritinite 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 conveyer 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. 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. The will required 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 provide 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

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 non-pelletized 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. 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 DISCUSSIONS

During the past one year the research efforts toward the development of an on-line automated image analysis system as well as the knowledge based image analysis computer software has been conducted. The specific achievements of this project include (1) the development of a computer controlled X-Y stage, (2) the establishment of an extensive database of the image characteristics of coal particles, (3) the development of an image analysis computer program, and (4) the establishment of the criteria for characterization of ultra-fine coal particles. The details of the results obtained in this project are summarized in the following;

Hardware of An On-line Image Analysis System

In this project, the components of an envisioned on-line image analysis system have been developed. This on-line image analysis is designed to serve as a quality evaluation mechanism for the coal pulverization process as well as the separation process of ultrafine coal particles in a coal cleaning stream. Figure 1 shows a schematic diagram indicating the role of the on-line image analysis system as a part of the coal cleaning process. It is envisioned that upon the completion of a grinding (or separation) process the ground coal will need to be transported into a storage house while the assessment of liberation (or separation) is being conducted through an on-line image analysis system developed in this project. In Figure 1 the darkened blocks represent the storage houses. When the image analysis of is completed a decision-making command will be sent to the storage house to indicate either forwarding ultrafine coal to the next station or returning it for additional grinding (or separation). Undoubtedly, the on-line image analysis in reality causes a delay in the coal cleaning process. However, the on-line image analysis represents one of the key elements in an automated coal cleaning process. It should be pointed out that the development of an automated coal cleaning process beyond the proposed tasks of this project. A brief discussion regarding some aspects of the on-line coal cleaning system is given in a section to follow.

In an on-line image analysis system (Figure 2), a sample feed mechanism is needed to collect coal ground from the coal cleaning stream. Such a sample collection mechanism can be achieved through a periodical vacuum siphon process. It is possible that the coal ground can be directly deposited into a pellet caster (or a glass plate). The glass plate is intended for analyzing particles with 3-dimensional feature under a microscope. However, the development of an image analysis system for analyzing 3-D particles is beyond the proposed tasks of this project.

Upon being deposited in place, the sample will be delivered to a sample preparation station through a conveyer system. In the sample preparation station, the pellet caster will be filled with epoxy resin (as the pellet material) and then put aside awaiting for the epoxy to become hardened. The last step in the sample preparation station will be the automated pellet polishing mechanism in which a sequence of coarse to fine polishing steps will be applied to the sample. It should be pointed out that, in this project, the sample preparation procedures were carried out manually. When the sample preparation is completed, the coal sample will be delivered to the image analysis system (containing an optical stage) through another conveyer system. The development of this conveyer system (i.e. X-Y table) was a part of this project. The X-Y table (Figure 3) consists of a platform equipped with two stepping motors and a computer interface. The table has a stepping capability of 0.0025" in two mutually orthogonal axes. A C-language based computer program has been developed to control the motion of the X-Y table through an I/O interface. At present, the X-Y table is controlled through an interaction between an operator and the computer. It is believed that this system control program can be integrated as a part of the image analysis program.

In the envisioned process, the X-Y table will bring coal samples under an optical microscope or a long distance microscope attached with a video imaging system. Furthermore, through the micro-stepping in X- and Y-direction, different locations in a sample as well as different samples can be inspected in a sequence. Typically, an imaging system consists of an image acquisition mechanism and an image analysis computer program. The image acquisition system developed in this project consists of an optical microscope, a CCD video camera, a frame grabber (i.e. a data acquisition board), and a personal computer. Figure 4 shows a typical set-up of an image analysis system. The video camera divides an image into a number of pixels. At present, an image is mapped into 480x512 pixels.

In order to bring an image into the focal plane of the microscope, a study leading to the development of an automated focusing mechanism was conducted. Two basic methods for determining the in-focus status of an object using an imaging system were investigated. These methods are based on (a) the shift in gray level distribution and (b) the development of particle boundary. Figures 5 and 6 show a comparison between an unfocused and a focused image of the same coal sample. Typically, when an image is brought to focus, there will be a shift in the peaks of the histograms among the images with different degree of focus. To be more specific, the peaks for the focused image will appear to be sharper than that of the unfocused one.

However, in this study, the differences in the peaks among the images of the same coal sample under different focal planes were found to be insignificant. Therefore, a methodology based on a shift in the peaks of histogram was found not feasible to develop into a controlling mechanism for the automated focus of the imaging system. On the other hand, a significant increase in particle boundary (edge) was obtained when an image is being focused. In other words, an increase in the pixels with a gray level related to the edge of coal particles can be used to detect whether an image is in focus or not. An autofocus mechanism (Figure 4) utilizing the edge detection principle was assembled and attached to the optical microscope of the imaging system used in this project. The autofocus assembly contained a step motor assembly (the black multiple shafts attached to the lower left side of the optical microscope), a data acquisition/feedback interface unit (the box with four slots to the left of the personal computer), and a manual step motor override (the black box with a silver cylinder on the top). The data acquisition/feedback interface contains a computer chips with image identification routines allowing for the detection of particle edge. When the X-Y table and the autofocus unit are integrated together, the image acquisition sequence can be fully automated.

Image Characteristics for Knowledge Base Development

Over the past two years, a large number of coal images were obtained. These images were obtained under a microscope at a magnification of 400x. A commercial image analysis software was used to determine the image characteristics of ultra-fine coal particles. The main emphasis of this work was to establish a statistically meaningful database regarding the image characteristics of coal leading to the development of some decision making criteria for an automated image analysis computer program. In other words, the manual image analysis served as the calibration mechanisms for the automated image analysis computer program being developed. Note that this automated image program has been designed to perform the analysis of coal particles without any human operator.

Typically, the manual measurement of the image characteristics of coal particles has included

- 1) Adjust the threshold of the entire image,
- 2) Identify the specific type of constituent of coal, and
- 3) Perform measurement on each individual particle.

This procedure is a very laborious and time consuming. In general, it takes approximately 6 to 8 hours to complete all the measurement for an image. Table 1 shows a typical worksheet provided with the key features of the particles

in a coal sample obtained during the manual measurement process.

Table 1 The worksheet of image analysis data

No.	MT	GL	SF	A(μm^2)	B(μm)	L(μm)	n/f
1	P	213	0.77	413.75	22.52	29.41	f
2	P	226	0.69	6.25	1.86	2.69	n
3	P	215	0.67	6.25	1.59	2.36	f
4	I	181	0.52	420.00	19.02	36.68	f
5	I	181	0.54	362.50	18.57	34.66	f
6	I	167	0.65	32.50	5.19	7.94	f
7	I	182	0.31	21.25	2.50	8.00	f
8	I	161	0.57	26.25	3.97	6.93	n
9	I	152	0.58	2.50	1.21	2.12	n
10	V	121	0.48	9305.00	88.60	183.30	f
11	V	112	0.81	3421.25	80.18	98.41	f
12	V	98	0.68	2820.00	64.56	96.56	f
13	V	103	0.32	2772.50	41.92	132.52	f
14	V	95	0.86	2466.25	72.54	84.34	f
15	V	121	0.52	840.00	30.75	59.51	n
16	V	97	0.59	1233.75	39.31	66.90	n
17	V	91	0.75	1293.75	48.18	64.19	f
Average	---	24	0.96	----	---	---	---

Note:

ML=Maceral Type (P=Pyrite, I=Inertinite, V=Vitrinite),
GL=Gray Level, SF=Shape Factor, A=Area, B=Breadth,
L=Length, n/f=non-free or free.

From the results shown in Table 1, several general characteristics of coal particles can be summarized as follows,

- A. In general, the gray level (GL) relationship among coal particles is $GL_{\text{pyrite}} > GL_{\text{inertinite}} > GL_{\text{vitrinite}}$.
- B. The inertinite particles appear to be long and slender. As a result, the shape factor of the inertinite particle is smaller than that of pyrite and vitrinite. In most of the cases, the shape factor of a pyrite particle tends to be close to 1 due to its roundness.

- C. Typically, the vitrinite particles are very large in comparison with pyrite and inertinite particles. The pyrite particles, in most of the cases, are smaller than that of inertinite particles. Another rule of thumb is that the typical size of a pyrite particle is less than 8 microns for the Illinois #6 coal.
- D. The average gray level of a given image appears to be smaller than the lowest gray level of the vitrinite particle. It is believed that this finding can be used as a criterion to terminate the search for particle in an image.
- E. Based on the data collected thus far, it was found that the band width in gray level for pyrite and inertinite, and vitrinite is, in general, at 10, 16, and 32 respectively.
- F. By taking the gray level difference between particles of adjacent gray value, it was found that the two largest values usually represent the gray level differences between pyrite to inertinite and inertinite to vitrinite. This implies that the particles leading to the two largest values (i.e. ΔG_1 and ΔG_2) in gray level differences are the particles that separate pyrite, inertinite, and vitrinite particles.

It should be pointed out that the above findings are based on the data collected thus far. One of the key findings is that the gray levels for a given material in coal is not a constant when measured from different images. This is due to the fact that the composition of particles of an image greatly interfere the overall light reflectance detection of the photonic sensor of the CCD camera. As a result, the image analysis of coal using a fixed gray level to identify the same maceral for different image frames is not possible. Therefore, it is recommended that the image analysis of coal must be conducted on a frame by frame basis. This can be done by incorporating the findings A to F given above. It should also be pointed out that not every image meets all the descriptions in rules A to F. Naturally, a logical assessment mechanism must be embedded in the image analysis program.

Automated Image Analysis Software

One of main objectives of this project is to develop a computer program that performs the decision making algorithm in the image analysis of coal particles without any human intervention. In other words, there will be absolutely no need of any operator to decide upon the type of material and the area of a particle in an image.

Figure 6 gives a flowchart of the image analysis program being developed in this project. The C-language based image analysis program developed in this project requires to input an image at a format of 480x512 pixels. Based on the rule based data presented in the previous section, it is realized that the key to success for a coal image analysis program relies on the establishment of all particles (clusters) in an image. Therefore, upon the input of an image, the computer program will determine the number of particles in the image. The specific steps in determining the particles in an image are given as follows,

- A. Search for the brightest location in the image frame.
- B. Connect the pixels surrounded to the brightest location if their gray levels fall within a bandwidth. The bandwidth is defined as the difference in gray level between the current pixel and the brightest pixel. In this project, the bandwidth is set at 30. This step should lead to the definition of a particle.
- C. Take out the pixels associated with the particles that have been defined.
- D. Repeat the steps (A) to (c) for the next particle.
- E. Exit the analysis routine when the average gray level of the image is detected.
- F. Present the interactive menu for the results presentation.

It has been found that, in all the images analyzed, a coal maceral particle always exhibits a gray level higher than the average gray level of the entire image. Therefore, the particle searching algorithm stops when the bright pixel in the remaining image has a gray value equal to the average gray level of the original image.

When the particles are identified, the analysis of particle shape factor, area, and gray level can take place. After the analysis of particle characteristics, a decision making mechanism containing the rule based criteria will analyze each particle as well as its overall standing in an image to determine its material type and its liberation status. Later, a recheck of these results is conducted in order to anticipate a variety of special cases. For example, the gray level bandwidth of an inertinite particle can be within 10 gray levels and can be misinterpreted as a pyrite particle. Consequently, an additional decision making criterion must be imposed. On the other hand, a particle with an area of few pixels (e.g. less than five pixels) may be classified as background noise instead of being

identified as a inertinite or vitrinite particle. Also, in the present study, only the particles that have an area less than 1,400 square microns (approximately 21 microns in diameter) can be possibly classified as the pyrite particles. This is due to the fact that the mean particle size of pyrite for the finely pulverized Illinois #6 coal is approximately at 8 microns. It should be pointed out that the mean size of pyrite for this decision making criterion can be revised according to a more accurate data base.

The image analysis computer program is written with some interactive graphics features. The computer program occupies a memory space of approximate 86,000 bytes (more than a thousand lines in computer command). This program is designed to interact with an operator for the input of images and the visualization of the output features. The output features of this image analysis program are (a) the review of the initial gray level image, (b) the histogram of the image, (c) the image in pseudo colors, (d) the identification of pyrite particles, and (e) a table that summarize all the particles in the image, (f) option for hard copy of the results summary. The execution of the image analysis computer program starts with an open menu (Figure 8) followed by a request of input for an image file. A few minutes later, a result menu (Figure 9) appears on the monitor indicating the completion of the image analysis. The result menu gives 6 options for reviewing the results obtained through the automated image analysis program. For example, a selection of option #2 will lead to a graphic representation of the histogram of an image such as the one shown in Figure 10. The selection of option #5 will provide a summary of the particles contained in an image (Figure 11). Perhaps, the most illustrative feature of this automated image analysis computer program is when one compares the same coal image before and after (Figure 12) it is analyzed. In Figure 12, the two bright particles (pyrite particles) in the gray scale image are singled out and darkened at the image illustrated by pseudo colors. In addition, the inertinite particles are also identified and painted with pink color. In general, it is believed that the image analysis computer program contains all the necessary options that we envisioned. For most of the images tested, the automated image analysis computer program was able to account for the same number and type of coal particles as an operator would obtain. The time saving in the analysis of coal particles through this automated image analysis computer program is illustrated in Table 2.

Table 2 A comparison of the time required to analyze a coal image through an operator (with a commercial image analysis program) and through the automated image analysis program developed in this project.

	JAO3.IMG	JAO4.IMG
Operator	340.0 min.	450.0 min.
386/25Hz, 4M RAM	4.0 min.	16.0 min.
486/33Hz, 8M RAM	0.8 min.	3.1 min.

On-line Image Analysis System Versus On-line Coal Cleaning System

It should be pointed out that the on-line image analysis system developed in this project was designed as a part of a coal cleaning process. The term "on-line" is only intended to indicate an automation in image analysis in which the pelletized coal samples will be brought to an inspection station through an automated conveying system. In the mean time, the pulverized coal is being stored and awaiting for a decision to be moved forward or returned for additional grinding. The automated conveying mechanisms provided through the X-Y tables as well as the autofocusing step motor are the on-line mechanisms being referred to in this project. When an attached coal characterization process does not cause any interruption in the forwarding (or conveying) coal ground, it should be referred to as a part of the "on-line coal cleaning process". As a matter of fact, an on-line image analysis system can be considered as a part of the on-line coal cleaning process when it involves the inspection of 3-D particles. This is because that the image analysis of 3-D samples may require a minimal sample preparation thus posts no interruption in the coal cleaning process.

It should be pointed out that the development of an image analysis system for 3-D particles is beyond the proposed tasks of this project. However, some preliminary experiments have been conducted to explore the possibility of analyzing 3-D coal particles. In general, unlike what is being used in the 2-D coal samples, it is practically impossible to characterize a particle with one image acquisition process. This is due to the fact that a 3-D particle reflects light according to its irregular surface topography, thereby, the same material can reflect light in different gray scale due to the difference in light reflecting angles. In other words, the database developed for the 2-D coal particles is totally useless for analyzing the 3-D particles. For a given light reflecting, a calibration of the gray scale for different macerals is necessary prior to the material identification process. In summary, it requires (a) the knowledge of the surface

topography and (b) the reflectance characteristics of a maceral due to different light reflecting angle in order to analyze a 3-D particles.

Another potential method to analyze 3-D particles is inspect them under both reflective and transmitted light source. In this method, the images obtained from the reflecting and transmitting light sources will be compared to determine whether the liberated pyrite particles are presented. From the amount of liberated pyrite particles, the degree of pyrite liberation may be estimated. Figure 13 gives an illustration of the images of 3-D coal particles under reflective and transmitting light.

Optical Microscope Versus Scanning Electron Microscope (SEM) in Image Analysis

In the past, the application of image analysis has been associated with the image obtained through the SEM. This is due to the fact that in such type of analysis the optical features (of materials) at a microscopic scale (e.g. at a magnification factor larger than 1000X) is usually desirable. Typically, the region of interest is at an area under 100 square microns. For the image analysis of coal particles, a maximum magnification factor of 400X is proposed to cover an region of approximately 250,000 square microns. This is due to the fact, under a magnification of 400X, an image frame can contain approximately up to 100 coal particles which is considered to be statistically meaningful in the representation of the maceral composition in coal. On the other hand, when a much higher degree of magnification (e. g. 1000X) is being used the particles composition may not sufficiently reflect the natural maceral distribution of ground coal. In addition, under a magnification of 400X, an image viewed through an optical microscope is as clear as that viewed through a SEM. In this regard, the use of optical microscope actually receives less restrictions in the operating environment such as sample size, specimen preparation, etc.

It should be pointed out that when a CCD camera is used as a part of an imaging system the original image is usually some what smeared out. In this regard, the resolution of an image is controlled by the CCD camera rather than the original image acquisition device such as an optical microscope or a SEM. Practically speaking, for the image acquisition environment used in this project the use of optical microscope in an imaging system is as good as a SEM. If a higher magnification factor is desirable, the use of SEM in an imaging would require to analyze a lot more image frames to establish a statistically meaningful data.

CONCLUSIONS

In summary, the primary aim of this research is to develop a faster and more accurately way to characterize coal particles in order to assess the pyrite liberation status of ultrafine coal. To be more specific, the achievements of this project are

- 1) Established an extensive database regarding the image characteristics of coal macerals.
- 2) Derived a set of knowledge base to identify different coal macerals.
- 3) Developed an automated image analysis computer program for analyzing coal particles.
- 4) Assembled a set of instrumentation into an automated imaging system. This has included the image acquisition system as well as X-Y table/autofocus system.
- 5) Provided a synthesis of putting an on-line image analysis system as a part of a coal cleaning process.

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Figure 1 Schematic of an on-line image analysis system.

Figure 2 Schematic flow chart indicating the application of the on-line image analysis system in the coal cleaning process

Figure 3 The X-Y table equipped with two step motors.

Figure 4 The imaging system containing an autofocus unit.

Figure 5 Unfocused coal image.

Figure 6 Focused coal image.

Figure 7 Flowchart of an image analysis computer program.

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COAL IMAGE ANALYSIS

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Press any key to continue

Figure 8 The open menu of the image analysis program.

**RESULT OF
COAL IMAGE ANALYSIS**

- 1 -- Show Image Grey Level**
- 2 -- Show Image Histogram**
- 3 -- Show Pyrite Particles**
- 4 -- Show Individual Pyrite**
- 5 -- List Image Particles**
- 6 -- Output Image Evaluation Result**
- 7 -- Quit**

Make a Selection and Press <Return> :

Figure 9 The result menu of the image analysis program.

Figure 10 The histogram developed during the image analysis

COALIMAGEEVALUATION

PARTICLE	TOTALGL	AREA	AVERAGEGL	FREE	TYPE
1	97418	386	252.00		PYRTIE
2	34711	139	249.00		PYRTIE
3	496	2	248.00		INERTIE
4	225	1	225.00		V

PERCENTAGE OF FREE PYRTIE: 0.00%

Press any key to see the image...

Figure 11 The summary of results provided by the image analysis program.

Before

After

Figure 12 Graphical illustration of a coal samples being analyzed through the image analysis program

Reflecting Light

Transmitting Light

Figure 13 The images of a 3-D coal sample under reflecting and transmitting light.

PROJECT MANAGEMENT REPORT**June 1, 1994 through August 31, 1994****Project Title: CHARACTERIZATION OF COAL PARTICLES USING
RULE BASE ON-LINE IMAGE ANALYSIS**

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COMMENTS

SCHEDULE OF PROJECT MILESTONES

Milestones:

- A. Sample preparation (Task 1).
- B. Determine the image characteristics of pyrite and coal macerals (Task 2).
- C. Development of a rule base liberation criterion (Task 3).
- D. Verification study (Task 4).
- E. Design of an on-line system (Task 5).
- F. Reporting.