ON-LINE WASHABILITY ANALYSIS FOR THE CONTROL OF COARSE COAL CLEANING CIRCUITS

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ABSTRACT

In view of the success of recent laboratory studies using X-ray computed tomography (CT) to determine coal washability and with the availability of high-speed CT systems, it now seems possible to design an on-stream washability system for the control of coarse coal-cleaning circuits. Design features for such a system are examined and possible control strategies are discussed for different applications.

INTRODUCTION

Conventional coal washability information is generally obtained in the laboratory by the tedious sink-float analysis using hazardous halogenated organic compounds in large quantities (Leonard, 1979). The principle behind this procedure (sink-float) is nothing more than particle fractionation by specific gravity. Although knowledge of the washability characteristics of various streams within a coal preparation plant is of great utility for process control and optimization, up to now, on-stream utilization of washability data is limited because of the lack of any instrumental method for the rapid determination of the washability curve. Typically, the return time for coal washability analysis using conventional sink-float testing will be about one day.

X-ray computed tomography (CT) had its origin in the medical services (Herman, 1980) and has now been applied to non-medical and industrial applications (Banholzer et al., 1987). CT techniques have an inherent advantage in providing very detailed images of the internal structures of opaque materials in a nondestructive manner. Applications of X-ray CT techniques in coal technology have been reported since the mid 1980's. Coal microtomography was studied by Flannery et al. (1987) and coal structure was investigated by Maylotte et al. (1982) and Spiro et al. (1987). For quantitative analysis of particulate systems such as coal washability analysis, a previous study (Lin et al., 1991) done at the University of Utah indicates that X-ray CT can provide sufficient information to construct the washability curve within minutes of sample collection. A step-by-step procedure for the determination of coal particle density using X-ray CT has been developed. In addition, with the use of an appropriate algorithm, the successful construction of coal washability curves using X-ray CT analysis has been demonstrated. Figure 1 shows the washability curve for a coal sample as obtained both by the conventional sink-float analysis and by the CT-based method. From these results, it is evident that the coal washability curve derived from the CT-based technique is in good agreement with the results obtained by the conventional sink-float analysis.

This paper discusses important aspects for the design and development of a CT-based system for on-line coal washability analysis in order to control coal cleaning circuits. In the first part of this paper, the hardware and software required to implement the on-line coal washability system are discussed. The second part of this paper deals with the use of such coal washability data for optimization and control of coarse coal-cleaning circuits.

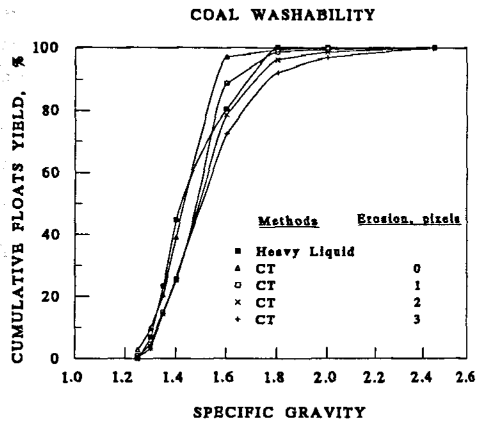

Figure 1. A comparison of the coal washability curve constructed using CT techniques with the coal washability obtained by the traditional float-sink method (Lin et al., 1991).

SYSTEM DESIGN AND DEVELOPMENT

A conceptual representation of the major components of the proposed CT-based system for on-line coal washability analysis is shown in Fig. 2. The system is composed of the following items: (1) CT machine, (2) computer controlled sample transport mechanism, (3) integrated image analyzer, (4) sample container and (5) output device. Figure 3 illustrates the proposed X-ray CT analyzer and sampling system for on-line coal washability analysis.

Specifications of X-ray CT Equipment

There are four different geometries for x-ray CT scanners (Hues et al., 1977). Details of the equipment configuration have been described in the literature (Miller et al., 1990). In order to apply CT technology for on-stream coal washability analysis, the limitations and areas of technical difficulty are summarized as follows.

The quality and utility of the CT data obtained ultimately depends on the resolution of the machine employed. Medical X-ray CT systems usually have a beam width of a few millimeters (Peshmann et al., 1985). Industrial CT machines used for non-destructive testing can have much smaller beam widths, even as small as 15-50 microns. Generally finer resolution is associated with long scanning times (Armistead, 1988; Seguin et al., 1985). Today, most commercial CT scanners have scan times from hundreds of milli-seconds to minutes. For example, the GE 9800 series has a scan time of 2 seconds with an x-ray beam width of 1 millimeter. The Radapt-1 CT scanner from Bio-Imaging has a scan time of 15 minutes and a beam width of 250 microns.

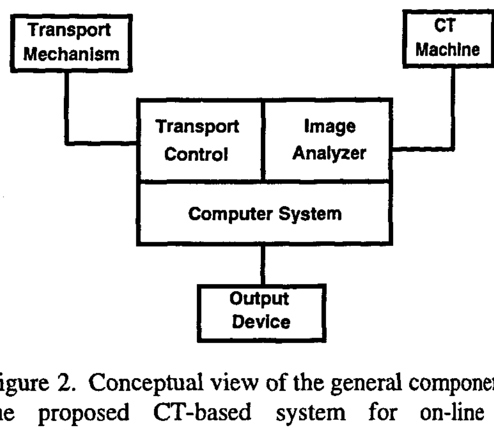

Figure 2. Conceptual view of the general components of the proposed CT-based system for on-line coal washability analysis.

In selecting an appropriate CT scanner for on-stream coarse coal washability analysis, features like X-ray energy, beam width, and the time required to make a scan or series of scans should be considered. For instance if the beam width is 1 mm, then the smallest size of coal particles that can be distinguished and classified would be no less than several millimeters. Since the densities of the particles are generally lower than 2.5 g/cc, the x-ray energy of most medical CT scanners will fulfill the demands for coal washability analysis. For on-line coal shability analysis, the scan time for each two-dimensional image should be less than a couple of seconds.

Movable Sample Chamber Design

The movable chamber as indicated in Fig. 3 should be constructed using a double wall construction technique. The outer wall is made up of a light-weight, non-metallic material (plastic, PVC, etc.). The inner wall is made up of a porous non-metallic material. The purpose of the porous inner wall is to create a physical barrier whose average density is less than 1.0 g/cc. This improves the accuracy of the measurement since the inner wall would have a density lower than any solid material inside the container, an important consideration that impacts data quality (Cortes et al., 1991). The volume of the container is established such that there would be sufficient particles (based on sampling theory) inside the container to provide statistically meaningful results. An external indicator would be provided so that it can be aligned in the CT machine in order to successfully scan the first layer of particles. A sample positioner would be clamped to the transport mechanism to prevent unnecessary movement during the scanning process. The end cap of the container should be spring loaded so that there would be constant pressure on the particles and minimize particle movement during the CT measurement. Figure 4 shows the schematic drawing of the sample container or movable chamber.

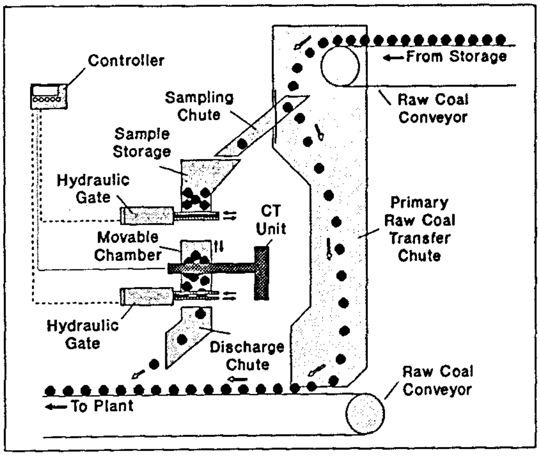

Figure 3. A schematic view of the proposed X-Ray CT analyzer and sampling system for on-line coal washability analysis.

Based on sampling theory, it is estimated that a representative sample of 100-mm top size coal would require approximately 200 kg. Thus a cylindrical sample chamber to contain this amount of material would be 600 mm in diameter and 800 mm in length.

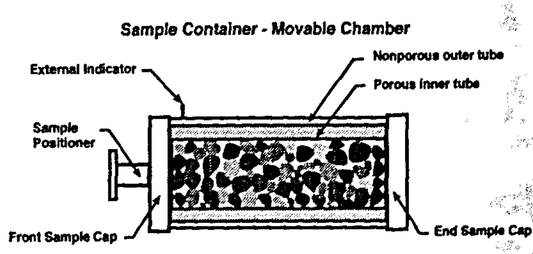

Figure 4. Schematic representation of the sample container loaded with particles.

Software Considerations

Figure 5 shows one of the CT images obtained from a 2-D slice of a randomly packed bed of particles in a cylindrical container. The thickness of this slice is about one millimeter. The 2-D pixel values of the image represent the average x-ray attenuation of the material within a voxel (volume element) space (1 mm × 1 mm × 1 mm). Typically, the image for each slice contains 256 × 256 or 512 × 512 pixels. The total number of slices used varies from 50 to several hundred depending on the amount of coal to be analyzed and its particle size. In this regard a large amount of image data is generated and appropriate software development is necessary to manipulate this large amount of CT data.

In addition to the appropriate computer system for manipulation and analyzing large amounts of CT data, several algorithms are needed to properly implement the 2-D or 3-D analysis for the coal particle population. To illustrate the complexity of the manipulation and analysis, sequential stacks of 2-D X-ray CT scans obtained from the randomly packed coal particles are shown in Fig. 6. The scale bar (CT number at the right-hand side of the figure indicates the relative density of the material. Algorithms considered for 3-D particle analysis should include 2-dimensional or 3-dimensional reconstruction, surface extraction, particle isolation and particle density classification. For coal washability analysis, the major steps for treating the CT data from serial slices are: (1) construct 2-D or 3-D image, (2) threshold the data, (3) extract the contour surface, (4) label each particle, (5) measure and classify the density of each particle and (6) establish the washability curve.

To effectively implement these algorithms, the following obstacles should be considered. The first problem for 2-D or 3-D analysis is the identification of the contour surface. As noted, the x-ray beam of the CT scanner has a fixed beam width of 1 mm. When the scanning beam hits the edge of the particle the resulting CT number of that particular voxel is expressed as the average value for the particle and the adjacent air surrounding the particle. This creates an artificially low CT value for the voxels at the edges of a particle. The second problem is particle contact in a packed bed as shown in Figs. 5 and 6. Boundary erosion techniques associated with the watershed algorithm commonly used in mathematical morphological analysis (Serra, 1982) can be used to solve both problems.

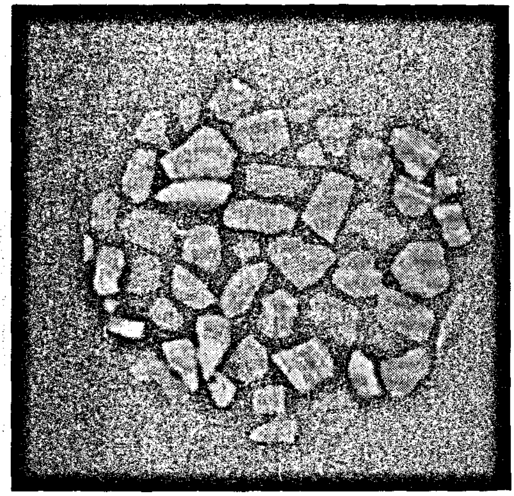

Figure 5. Example of a 2-D CT image obtained from a randomly packed bed of coal particles (19.1 × 9.5 mm in size).

Based on review of manufacturers data, the CT scan time is expected to be 2 sec/scan using a GE-9800 CT scanner. Computational time for 100 scans of 2-D CT images, 256 × 256 pixels in size, is about 30 seconds with the use of 50 MHz 80486DX chips in a personal computer. Table 1 shows the total estimated processing time for all the steps required to finish 100 CT images with the use of a GE-9800 CT scanner. The estimated total response time is about 5 minutes.

TABLE 1. Estimated time of each procedure required for a complete (100 CT images) coal washability analysis using CT-based on-line system.

Procedures	Estimated Time Required (sec)
CT measurement	~200
Computer analysis	~30
Sample packing and discharge	~70
Total	~300

In actual operation, such as the cylindrical sample chamber (600-mm diameter by 800-mm length) containing 200 kg of minus 100-mm coal, an image with 512 × 512 pixels in size will be required to obtain the desired resolution. In this case, a computer with computation power greater than the 80486DX PC will be required to keep the time frame for computer analysis within 30 seconds per 100 scans. For this case, it is expected that the complete washability analysis can be accomplished in less than 30 minutes. With a used medical scanner, a GE-9800, the cost for this on-line system is estimated to be less than $500,000.

Besides coal washability information, particle size distribution of the sample can be obtained since the volume (particle size) is required in order to determine the density of each particle. Of course an empirical relationship based on density can be established to calculate ash content of the sample. The greatest advantage with the use of X-ray CT for on-line coal washability analysis is that the sample can be collected without concern for the presence of moisture, fine slimes or magnetite particles.

Operating Procedure

Detailed procedures for coal washability analysis using the proposed system (Fig. 3) are as follows:

1. An automated cross-stream belt sampler will be used to collect a representative sample. The first hydraulic gate will open and allow the sample to pass into the movable chamber. The gate will close and CT analysis will begin. While the analysis is going on, the next sample will be collected in the upper chamber. After completing the analysis, the lower gate will then open and allow the sample in the movable chamber to drop onto the belt. The lower gate will close and the movable chamber will move back for the next sample.

2. The external indicator on the movable sample chamber allows the CT operator to position the sample container such that the first CT slice would be taken right after the external indicator, such as a fixed pin. This would be the first cutting plane and would be the zero coordinate in the axial direction.

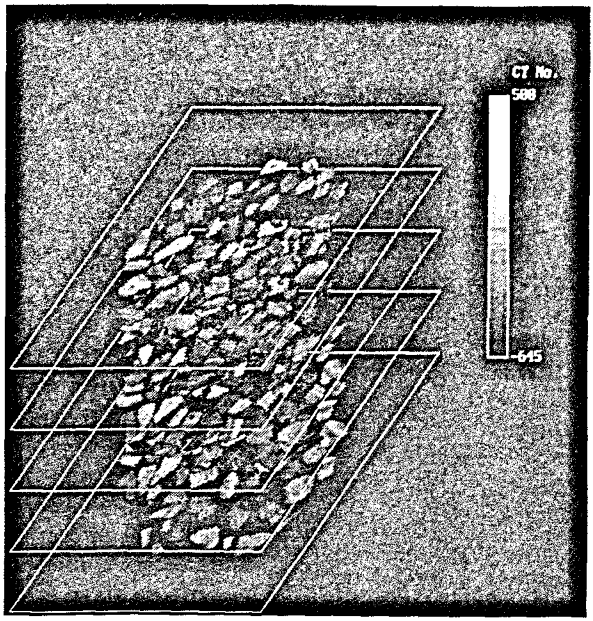

Figure 6. Sequential stacks of 2-D X-Ray CT scans in a randomly packed bed of coal particles.

3. The CT equipment performs a scan creating a cross sectional X-ray attenuation profile.

4. The scanned data are placed in computer storage.

5. The CT computer performs numerical operations to convert the attenuation coefficient data into density data.

6. Upon completion of the scan, the transport controller advances the sample a pre-determined distance (a multiple of the X-ray beam width used) to begin the scan for the next section. Subsequently, the calculated density data for that cross section are moved into the integrated image-analysis computer for three-dimensional reconstruction.

7. Scanning continues until the whole sample container has been analyzed.

8. The reconstructed 2-D/3-D image is then mathematically manipulated to identify and isolate each particle in the sample container. For each particle in the sample container, the corresponding volume and location is then calculated.

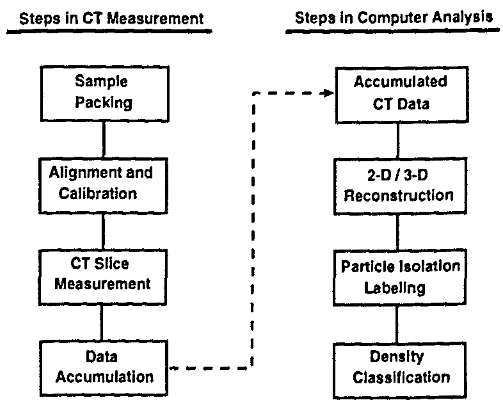

Figure 7. Block diagram of the steps for the measurement of coal washability using the CT-based system for on-line analysis.

9. Upon completion of the particle identification process, the mass of each particle is calculated based on the data from the 2-D/3-D density map, and the volume of each particle obtained from the particle isolation stage given in Step 9 is established.

10. The particles are then classified according to their densities and a washability curve is constructed.

11. The final data are presented by the output device in tabular or graphical form and are sent to the main computer center for control action.

The necessary steps for the measurement of coal washability using the CT-based system are shown in Fig. 7.

APPLICATIONS

There are many potential applications for an on-line washability analyzer. The feasibility of these applications is largely dependent on the system characteristics, i.e., accuracy, speed and cost. Some of the most promising applications for the on-line CT system proposed here include variability analysis, blending control and on-line efficiency determination.

Variability Analysis

The feed to a coal preparation plant may be subject to significant variations in terms of size, quality and mineralogical association. Factors responsible for these variations include fluctuations in seam characteristics, modifications in mining practices and changes in the mix of coal entering the plant from multiple sections and/or mines. With the possible exception of coal quality, these variations are considered to be unmeasurable using current on-line technologies. This is unfortunate since the magnitude and frequency of these disturbances must be known prior to the implementation of on-line control, while a historical record of these disturbances must be collected prior to the implementation of statistical process control (SPC). The latter application is becoming increasingly important in light of the growing emphasis placed on ISO 9000 standards.

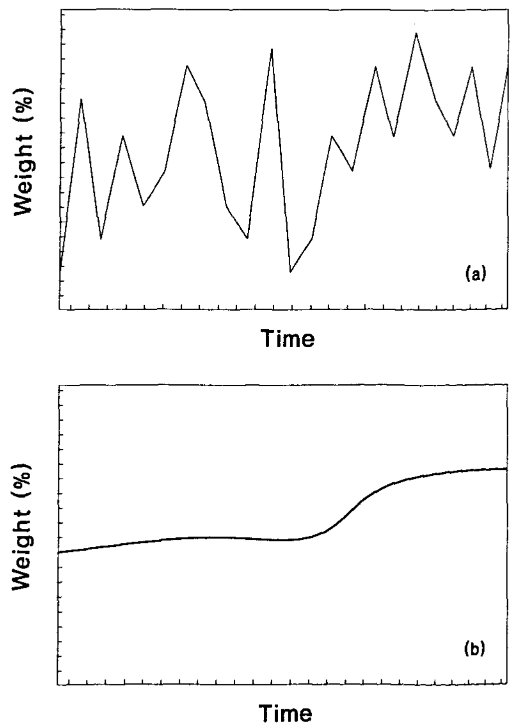

Figure 8. Hypothetical diagram showing the weight percentage of material with a specific gravity greater than a given cut-point plotted as a function of time. (a) raw data, (b) filtered data.

Figure 8 represents a typical set of data that might be obtained using the CT analyzer. In this diagram, the weight percentage of material with a specific gravity greater than a given cut-point is plotted as a function of time. Two types of variations may be noted in the data. The random variations or "noise" are caused by disturbances associated with the natural characteristics of the material and the analyzer. This information is important for establishing control limits used in SPC. SPC techniques allow one to systematically identify and minimize sources of variability, leading to improved plant performance. The second type of variation is a result of a systematic change in the characteristics of the material being analyzed, i.e., a true change in washability. A knowledge of systematic variations is integral to the design of on-line control systems. In some cases, it may be necessary to use filtering techniques to distinguish between random and systematic variations. For example, the systematic change in washability shown in Fig. 8a is difficult to identify from the raw process data. However, the simple boxcar average shown in Fig. 8b can be used to remove the masking effect of the random variations and allow the step change in washability to be observed.

Assuming that a step change in washability can be detected by the CT analyzer, it is possible to implement the simple feed-forward control scheme shown in Fig. 9. In this system, the washability in the feed stream is measured by the CT unit and a projected clean coal ash is calculated based on the current cut-point. If the projected clean coal ash is higher than the desired clean coal ash, the cut-point must be reduced. This type of control system is impossible to implement using existing technology since ash analyzers cannot provide information related to mineralogical association. The ability to distinguish middling from extraneous rock is important since a change in either of these will affect the feed ash, but only the former will have a large impact on the clean coal ash. On the other hand, any type of feed-back control loop is inherently inferior since it requires off-spec material to be generated prior to any control action.

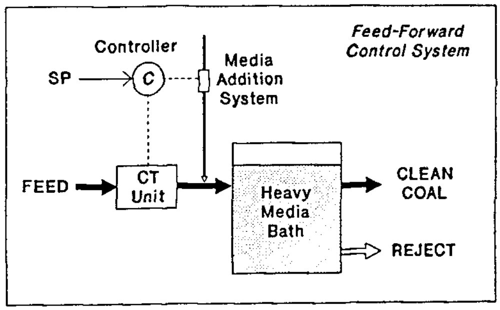

Figure 9. Schematic diagram of a simple feed-forward control scheme for a coarse coal separator utilizing the on-line CT washability analyzer.

Blending Control

Blending is widely used to reduce the variability of the feed to a coal preparation plant. Although complicated and costly, blending systems can be easily justified on the basis of increased plant capacity (Osborne, 1988) and improved product consistency (Mahr, 1981). Blending is particularly important when the feed coal is supplied from several different sources.

Figure 10 shows a potential application of the CT analyzer in coal blending. In this simplified case, coal is supplied from two different sources. It is assumed that Coal A possesses a better washability than Coal B and the plant is operating at its maximum feed rate. In one control scheme, Coal A and Coal B pass sequentially through the CT analyzer and the washability of each is determined (see Figs. 10b and 11). Based on the washability data, a projected clean coal ash is calculated and this value is compared to the desired clean coal ash. If the projected ash is improving, a larger proportion of Coal B must be added to the mix, i.e., the A/B ratio must be decreased. At a constant plant feed rate, this ratio can be calculated from:

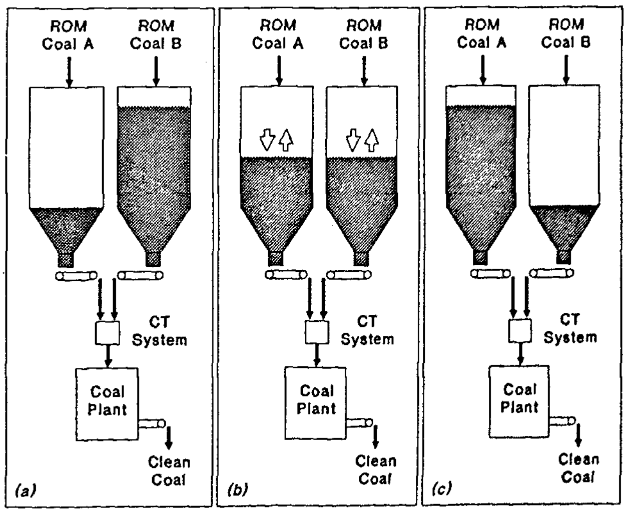

Figure 10. Potential application of the CT washability analyzer in a coal blending control scheme showing (b) feed washability control and (a and c) supervisory cut-point control.

$$A/B = (f-b)/(a-f)$$

where f is the desired product ash, a and b are the product ash values projected from the washability data, and A and B represent the mass flow rates of Coal A and Coal B, respectively. As can be seen, the goal of this particular control scheme is to absorb short-term changes in coal washability through variations in silo level without requiring a change in cut-point. Unfortunately, the potential exists for a silo to either fill or empty if long-term changes in the coal washability occur. In this case, a supervisory control scheme is used to adjust the plant cut-point. For example, if the silo containing Coal A empties, i.e., the good coal is completely consumed, the cut-point must be lowered and yield sacrificed to maintain a constant product ash (see Fig. 10a). Alternatively, the system could be designed to issue an alarm to the plant operator who could choose to maintain the same cut-point and ship the lower quality coal to a different market.

An additional application related to coal blending pertains to the purchasing of coal and crediting tonnage. For example, it is common practice for a company to buy coal from various contract mines and provide payment based on clean coal tonnage. With current technology, this frequently requires costly single- and multi-point float-sink tests. The CT analyzer could provide a rapid and cost-effective method for crediting tonnage.

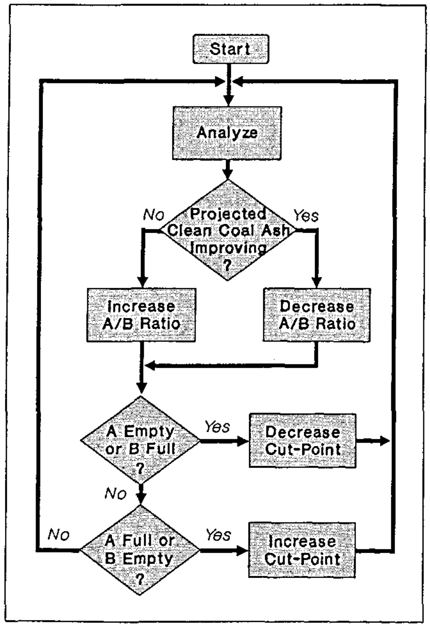

Figure 11. Logic diagram for a coal blending control scheme utilizing the CT washability analyzer.

On-Line Efficiency Analysis

One of the most exciting potential applications of on-line CT analysis is the determination of separator efficiency. A schematic of this procedure is illustrated in Fig. 12. In this case, CT analysis is conducted on each of the process streams and the washability is determined. These data are then used to construct a partition, distribution or Tromp curve for the separator. This on-line partition curve can be used to provide the plant operator with a variety of information including actual cut-point, probable error (E_p) and error area (A_e). Also, the shape of the partition curve and its relative symmetry can be used as a diagnostic tool to identify problems in the plant, e.g., equipment failures or improper operating conditions (Leonard and Leonard, 1981). Because these efficiency measures are affected by a wide variety of plant parameters, many of which are difficult to quantify, the on-line CT analyzer is ideally suited for use in an expert control system.

CONCLUSIONS

The conceptual development of a CT analyzer for the determination of on-line coal washability has been presented. This concept was previously demonstrated in an off-line configuration at the University of Utah. The proposed on-line device includes a CT scanner, sampling system and the necessary hardware/software to convert CT slice information into three-dimensional particle data. This system is capable of providing information related to particle size and quality, as well as mineralogical association.

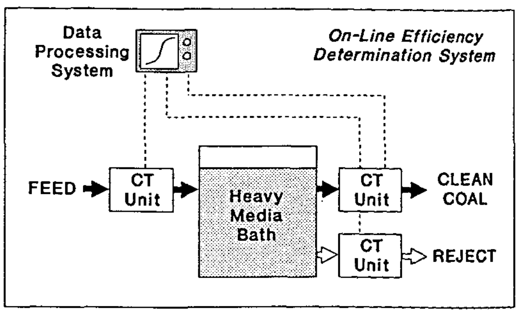

Figure 12. Schematic diagram for a CT-based system to determine an on-line partition curve.

Several potential applications of the on-line CT analyzer have been discussed including variability analysis, blending control and on-line efficiency determination. A preliminary feasibility analysis suggests that the CT analyzer is economically justifiable based on the present cost of complicated blending systems and losses in clean coal production. Unfortunately, there are obstacles to overcome prior to the commercial implementation of the system. The most obvious of these is the cost of the system and the speed of the analysis. Furthermore, the resolution of the analyzer may need to be improved if it is to be applied to the analysis of intermediate and finer sized coals. It appears, however, that sufficient benefits exist to warrant the research and development effort required for the production of a commercially viable CT washability analyzer.

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