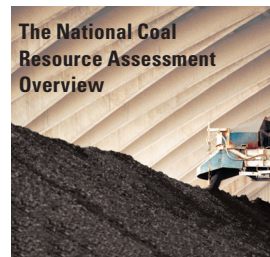


Chapter G

Estimation of Coal-Cleaning Costs: A Spreadsheet-Based Interactive Software for Use in the Estimation of Economically Recoverable Coal



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Chapter G of
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Introduction

The U.S. Geological Survey (USGS), in collaboration with State geological surveys, has been involved in the estimation of minable coal resources and categorizing them according to the estimated cost of mining and cleaning the coal.

The purpose of this project was to develop an easy-to-operate, interactive software package for the estimation of coal-cleaning cost. The accuracy of cost estimates will depend on knowledge of the quality, on the responsiveness of coal to treatments, and on the mining technology used. The software is based on knowledge of coal mined in the past and the cleaning technology of the present.

Study Approach

The coal-cleaning process depicted in the default flowchart (fig. 1) is realistic for Illinois No. 6 coal. The equipment prices used in this study are real prices as listed by manufacturers. The hourly operating cost data for equipment are based on experience gathered by industry consultants. Both sets of data were purchased from Western Mine Engineering, Inc., Spokane, Wash. Communications from Western Mine Engineering, Inc., indicate that actual equipment prices are discounted by various percentages. All price and cost data are from the 1999–2000 year. Labor wages, salaries, and benefits used in the default case are author's estimates based on personal information provided by coal industry officials.

Tailoring the Process to Specific Needs

This section describes the basics of process flow selection; that is, what one should know about the coal and its responses to various treatment options and how to select

the best options and equipment. The process of coal cleaning must be tailored to the specific characteristics of the raw coal at hand and the quality of the clean coal that can be achieved using specific equipment. Coals from different beds have different properties. Coal from the same bed, mined at different locations, may not display the same response to coal cleaning. The recovery of clean coal or the separation into two or more size fractions can be radically different from mine to mine, even when the same coal bed is mined. The accuracy of cost estimation, but especially the quality of clean coal, is highly dependent on the user's knowledge of the characteristics of the coal to be cleaned. The default case used in this model yields a cost estimate that is considered accurate for the coal characteristics assumed, deviating from a real-world plant only to the extent of price discounts given by equipment manufacturers.

The raw coal characteristics are best utilized for coal cleaning if representative float-sink analysis, including the quality characteristics of each specific gravity fraction, is determined. The choice of coal-cleaning equipment in a flowchart depends primarily on the complexities of the coal. Coal complexity in this regard is indicated by how closely mixed the coal and the noncombustible material (ash) are in the raw coal. Pure coal has a specific gravity in the range of 1.23 to 1.72.¹ Pure ash is heavier, with a specific gravity of more than 2.3. Coal and ash are mixed across all specific gravity categories and particle sizes. Coal-cleaning technologies and machines typically use specific gravity differences between coal and ash to separate the two. The exception is the flotation process, which uses differences in surface properties of coal and ash. The amount of raw coal (in percentage of total) occurring near the specific gravity chosen for separation of coal from ash determines how complex the cleaning process has to be. The easier-to-clean coal would contain only small

¹Specific gravity is usually expressed in grams per cubic centimeter (g/cm³).

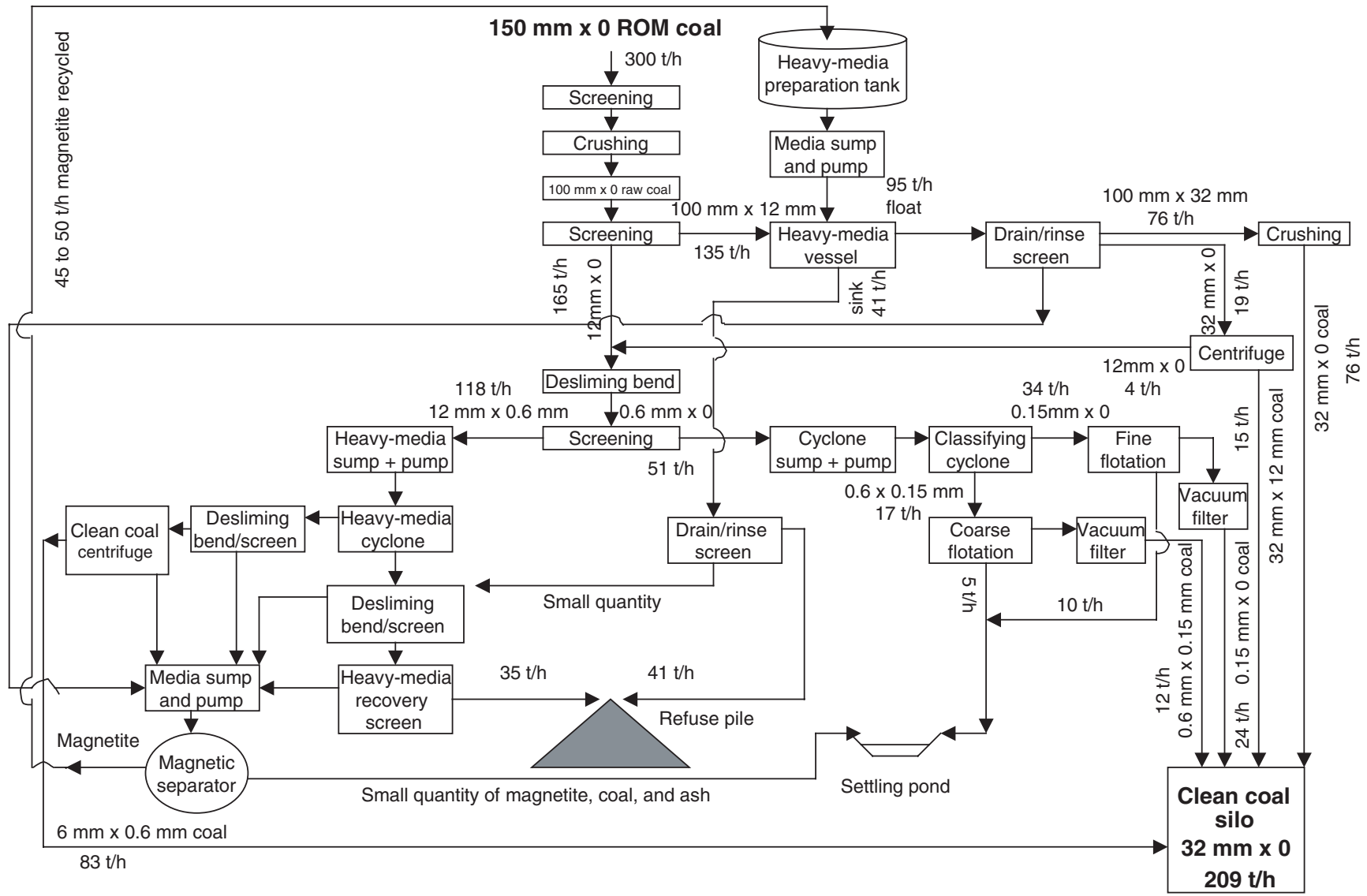


Figure 1. Default coal-cleaning flowchart. ROM coal, run-of-mine coal; mm, millimeters; t/h, tons per hour. Tonnage figures are rounded off. Quantities under 1 ton are not indicated. One (short) ton = 2,000 pounds.

amounts of material with the separation specific gravity.² The complexity of coal increases as coal and ash are more evenly distributed. The higher the amount of material near the separation specific gravity, the more difficult it becomes to separate coal from ash. The most commonly used separation specific gravity is 1.5 to 1.6. The user may choose a different specific gravity of separation depending upon the characteristics of the raw coal and consumer-determined clean coal specifications.

The choice of equipment for coal cleaning depends on how easy or difficult the coal is to clean. For example, the first stage of separation of large-size coal (4 inches or 100 mm maximum) may use jigs if the coal is easy to clean but may have to use heavy media separators if the coal is moderately or extremely difficult to clean.³ This is because heavy media separators⁴ more accurately separate materials on the basis of their specific gravity than jigs; that is, their coal yield is higher than that for jigs. Similarly, for smaller size coal, heavy media cyclones are more efficient than water-only cyclones or concentrating tables. The finest size coal is generally cleaned by flotation if it is found to be floatable. Not all fine coal is floatable, however, so that in some cases the finest fraction is sometimes discarded and flotation is partially or entirely avoided. Flotation technology makes use of the different surface properties of coal and ash. In particular, certain chemicals added to the coal slurry make coal hydrophobic, but not the ash. The hydrophobic coal particles attach themselves to the air bubbles in flotation cells and are carried to the surface. Flotation can be very efficient in separating some coals. About 40 to 50 percent of all U.S. coal production is subjected to flotation at present. Various types of flotation systems are available. They differ from one another in the manner in which coal is brought in contact with air bubbles. Most plants use variations of conventional flotation cells. However, column flotation is gaining acceptance because of its higher efficiency and low space needs. The use of heavy media and flotation indicate more intensive cleaning as compared with jigs and tables or water-only cyclones.

Flowchart Selection

A default flowchart has been developed after studying the washability of Illinois No. 6 (Herrin) coal, described in Circular 462 of the Illinois State Geological Survey (ISGS)

²Separation specific gravity = specific gravity at which the separation of fractions is desired.

³Jigs use water as the separation medium. Coal is placed on a screen that pulsates up and down in water. Lighter material consisting primarily of coal forms the uppermost layer. Heavier material, consisting primarily of non-combustible ash, forms the lower layer on the screen, thus helping separation of coal from ash.

⁴Heavy-media separators use a mixture of water and powder of iron oxides to adjust the density of the mix to the desired level, generally close to that of coal (1.5 to 1.6). Crushed coal added to this mix segregates into a lighter fraction consisting mostly of coal and a heavier fraction consisting mostly of ash.

(1971). The initial default flowchart was approved by Mr. Bob Milligan, plant manager, Galatia Coal Cleaning Plant, Harrisburg, Ill., and by Dr. Latif Khan, mineral beneficiation engineer at ISGS. After the submission of the final project report in July 2000, reviewers selected by the USGS suggested a few changes in the default flowchart that have been incorporated in this report (see fig. 1).

This section describes in a step-by-step fashion the procedure to select an appropriate flowchart to meet specific coal-cleaning requirements. Default values and choices are provided for cost estimation.

Step 1.—Prepare a float-sink analysis of the run-of-mine (ROM) coal. It should include the weight percentages of the raw coal in each specific gravity category. The categories start at a specific gravity of 1.3 and may go as high as specific gravity 2.0, at increments of 0.1. The ash, sulfur, and Btu values of the material in each specific-gravity category should also be analyzed. Figure 2 represents the float percentages for Illinois No. 6 (Herrin) coal based on Illinois State Geological Survey Circular 462.

According to figure 2, about 75 percent to 82 percent of the Illinois No. 6 coal should float at a specific gravity of 1.6. At the specific gravity of 1.4, the float fraction is about 65 percent to 75 percent. These numbers are indicative of the coal-recovery rates obtained. Therefore, in the default process chart, we have used a 70-percent recovery rate. This assumption represents a moderately difficult to clean coal, as described later in step 3.

Step 2.—Determine the specifications of the coal product desired. Test the coal in the laboratory by using various types of equipment to determine the product quality (Btu and sulfur contents and ash yields) obtainable. Use Step 1 data to determine the specific gravity at which the first coal separation is desired to occur. A default separation specific gravity of 1.6 is assumed in this package for the heavy-media separator. Alternatively, the user may replace the heavy-media vessel with a jig.

Step 3.—Assess how difficult the coal is to clean. The float-sink analysis from Step 1 will allow this assessment. If the separation specific gravity chosen is 1.6, check the percentage of your coal within range 1.5 and 1.7. This range is called “near gravity range.” Table 1 will help in assessing how easy or difficult the coal is to clean.

A typical example of a moderately difficult to clean coal is presented in table 2 from Symonds (1991). Although the source of table 2 does not indicate the source of coal, the data were chosen because of this coal’s similarity with Illinois No. 6 coal. The coal described in table 2 would, according to the same source, result in yields similar to those presented in table 3.

Step 4.—Select the flowchart equipment depending upon the degree of difficulty determined in Step 3. The greater the degree of difficulty, the more efficient the equipment type needed. The higher efficiency equipment recovers more of the coal because it more effectively separates the lighter coal from the heavier components (ash). Table 4 lists each type of

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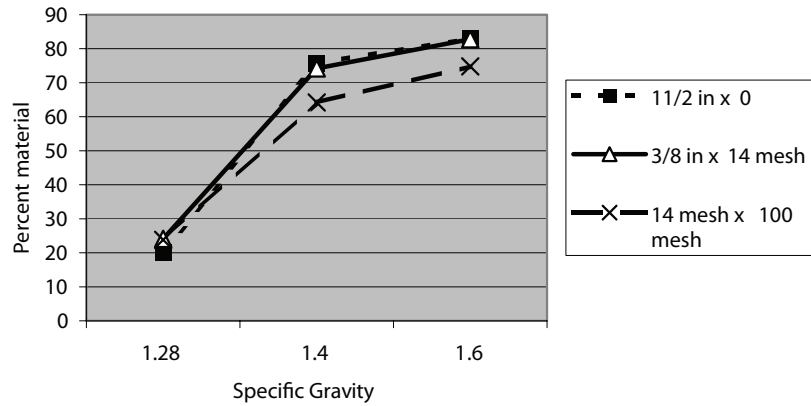


Figure 2. Float-sink data for Herrin No. 6 coal, Illinois Basin.

Table 1. Near gravity material as measure of degree of coal cleaning difficulty.

Percentage of near gravity material	Degree of difficulty
0–5	Easy
6–10	Moderate
11–20	Difficult
20 or more	Extremely difficult

Table 2. Example of properties of coal with moderately difficult washing characteristics.

[Wt %, Weight percent; Ash %, Ash yield in percent; Sulf %, Sulfur content in percent; Btu/lb, British thermal units per pound]

	Specific gravity		Fractional analysis				Cumulative float				Comments
	Sink	Float	Wt %	Ash %	Sulf %	Btu/lb	Wt %	Ash %	Sulf %	Btu/lb	
Float	1.30	40.1	5.9	3.4	13,575	40.1	5.9	3.4	13,575		
1.30	1.35	11.6	12.7	6.8	12,486	51.8	7.5	4.1	13,329		
1.35	1.45	11.4	17.1	7.8	11,796	63.1	9.2	4.7	13,052		
1.45	1.50	3.4	20.1	8.4	11,308	66.6	9.8	4.9	12,963		
1.50	1.55	3.5	25.5	10.0	10,449	70.1	10.5	5.2	12,837	Middlings material	
1.55	1.70	4.9	29.2	10.4	9,858	75.0	11.8	5.5	12,644	Middlings material	
1.70	1.80	2.1	37.2	12.8	8,594	77.0	12.4	5.7	12,534		
1.80	2.00	1.2	49.2	10.2	6,673	78.2	13.0	5.8	12,446		
2.00	Sink	21.8	80.9	6.7	1,618	100.0	27.8	6.0	10,087		

Table 3. Clean coal yields at specific gravity 1.6 and quality characteristics after treatment of coal in table 2.

[N.A., Not available. Btu/lb, British thermal units per pound]

Equipment	Clean coal yield (%)	Ash (%)	Sulfur (%)	Btu/lb
Heavy-media vessels	72.5	10.8	5.2	12,789
Heavy-media cyclones	72.5	10.9	5.2	12,780
Jigs	70.0	11.0	5.3	12,759
Tables	66.0	10.8	5.2	12,792
Water-only cyclone	64.0	11.5	5.3	12,624
Spirals	60–80	N.A.	N.A.	N.A.
Flotation	80.0	10.0	5.0	12,700

Table 4. Equipment selection guide.

[mm, millimeters; N.A., not available]

Equipment type	Particle size	Effective specific gravity	Error probability (Ep) ¹
Heavy-media vessels	100 mm–6 mm	1.3 to 1.7	0.025
Heavy-media cyclones	6 mm–0.6 mm	1.4 to 1.8	0.033
Jigs		1.55 to 1.9	0.091
Baum jig	100 mm–0.8 mm		
Batac jig	15 mm–0.15 mm		
Slurry jig	4 mm–0.15 mm		
Concentrating tables	6 mm–0.1 mm	1.55 to 2.0	0.086
Water-only cyclones	9 mm–0.15 mm	1.55 to 2.0	0.14–0.20
Spirals	4 mm–0.15 mm	1.6 to 2.0	0.15
Flotation	0.6 mm and finer	N.A.	N.A.

¹The error probability (Ep) is empirically determined in research laboratories. A low Ep value indicates higher separation efficiency; a high Ep value indicates lower separation efficiency.

equipment, its efficiency, and the particle-size range for which each type is best suited. Although most equipment types can be used over a broad range of specific gravity, their error probabilities indicate that some are more efficient than others.

Step 5.—Using the expected weight percentage of coal in each specific-gravity category from the float-sink data in Step 1, determine the quantities of material that will need to be processed. Based on these quantities, select the size and number of units of each type of equipment. If previous testing indicates that the coal is floatable, both the fine- and the coarse-flotation circuits may be retained. In certain cases, only one of the two circuits would be desirable; for example, if the fine or the coarse material fraction is exceedingly small. Alternative use of spirals or tables has been provided in place of the coarse-flotation circuit in the default flowchart. Besides familiarity with the equipment and common practice in the region, space considerations can determine the choice between spirals and tables.

In addition to the documentation provided from textbooks and from ISGS washability studies, the raw-coal and clean-coal specifications used in the default flowchart are based on consultations with Mr. Bob Milligan, plant manager, Galatia Coal Cleaning Plant, Harrisburg, Ill. The ash- and sulfur-removal rates, as well as the Btu value of clean coal, are confirmed to be realistic.

Size of Equipment and Amount Needed

If specific gravity of separation is important for the choice of equipment type at various stages of the flowchart, equipment size and amount needed are determined by plant capacity and the particle-size distribution of raw coal. It is, therefore, essential to determine the size distribution of several representative coal samples. The following factors influence coal size distribution: coal type, mining method, frequency of

Table 5. Default size distribution of coal.
[mm, millimeters]

Coal size fraction	Percentage of feed material
100 mm × 12 mm	44
12 mm × 0.6 mm	39
0.6 mm × 0.15 mm	6
0.15 mm × 0	11

Table 6. Angle of screen inclination in degrees as a function of screen width and short tons per hour capacity.

[1 foot = 0.3048 meter; ft, foot]

Screen width (ft)	Short tons per hour passing over the screen deck											
	15	30	45	60	75	90	120	150	180	210	240	270
2	16	17	22	25	28	30						
3		16	17	20	23	25	28					
4			16	17	20	22	25	27				
5				16	17	19	22	25	27			
6					16	17	20	22	25	27		
7						16	19	21	23	25	26	
8							17	20	22	24	25	26

handling, free-falling of coal during transfer, and method of screening (dry or wet).

This software is based on the following default size distribution of coal feed, typical of many Illinois coals. However, the user will be able to use a size-distribution pattern of choice.

Extensive equipment data were purchased for the project from Western Mine Engineering, Inc., Spokane, Wash. Only the data on sieve bends were separately acquired. The equipment prices and operating-cost data have their limitations because of the discrete nature of the data. The available equipment capacity may not exactly match the need. Therefore, the user is given the choice to select, with a click of the “mouse,” the equipment closest to the user’s required hourly processing capacity needs. Often, this will be a higher capacity than calculated.

Equipment selection is a complex process. In some cases, the available data include the processing capacity of the equipment per hour. In other cases, such as the screens, there is no easy way to provide the capacity data in a tabulated form.

In the following part of the report we discuss the factors affecting the hourly processing capacity of some of the equipment. Before making any changes in the plant capacity, the user must take into account the following considerations, make the required capacity calculations for the equipment in the flowchart, and then make the appropriate selection from the tables.

Screens.—The screen capacity depends on many parameters, the first being the characteristics of the coal itself, its

size distribution, moisture content, and so on. In addition, the screen width, its inclination, and the thickness of the coal layer on the screen are important determinants of capacity. For practical purposes, a combination of screen width and inclination are used to determine the processing capacity, assuming that the screen inclination is varied between 16° and 30°. Higher screen inclination increases the capacity but decreases the quality of screening. Similarly, a thicker layer of coal on the screen increases the screen capacity but decreases the quality of screening. We recommend table 6 for screen selection, adapted from Leonard and Harding (1991, p. 255). Multiple screens should be used where processing capacity must be high.

Spirals.—Spirals have a basic feed rate of about 3 tons per hour (tph) at a 30 to 35 percent solids-by-weight concentration. The concentration can be varied between 25 percent and 40 percent. The number of spirals to be used depends upon the tons of feed to be processed hourly. (See Leonard and Harding, 1991, p. 440).

Cyclones.—Manufacturers’ data on cyclones include the processing capacity per hour, generally given in gallons per minute. The cyclone feed may vary in its solids content from 20 to 30 percent. Approximate capacities of cyclones are generally about 50 tph for a 20-inch-diameter (50.8-cm-diameter) cyclone to 75 tph for a 24-inch (61-cm) cyclone. This corresponds to about 10 tph for every 200 gallons per minute cyclone capacity (Leonard and Harding, 1991, p. 390–392).

Concentrating tables.—Table capacity depends on the characteristics of the coal, the number of strokes (vibrations)

per minute, and the stroke amplitude. The basic rate is about 10 tons per hour but can vary between 7.5 and 15 tph, depending upon feed composition and amenability of coal to washing. The water-to-coal ratio is usually about 2:1. The number of tables used will depend upon the amount of material to be processed hourly (Leonard and Harding, 1991, p. 426).

Flotation cells.—Flotation cells vary in type, size, and capacity by manufacturer. The most important factor in determining cell capacity is the coal to be processed. For a typical Illinois operation, flotation cells of 500 ft³ (14.15 m³) volume are used at a feed concentration of 2.5 percent solids by weight. Under these conditions, such a cell would process about 6.5 tons of feed per hour (B. Milligan, Galatia Coal Cleaning Plant, oral commun., 2000). We have used this capacity to select the number of cells required and we recommend it for other users of the software.

Magnetic separators.—Magnetic separators, used for the separation of magnetite from waste, have a capacity of about 80 grams per foot of drum length per minute. According to Leonard and Harding (1991, p. 394–395), a coal-cleaning plant with 100-tph capacity requires about 20 inches (50.8 cm) of drum length. A 300-tph plant (the default capacity in this case) would require 60 inches (152 cm) of drum length. The closest choice would be a 36-inch (91.4 cm), 2-drum magnetic separator for the default capacity. A similar calculation will allow the appropriate choice if plant capacity is changed.

Vacuum filters.—The hourly capacity of vacuum filters depends primarily on the surface area of the filter and the percentage of solids in the slurry to be filtered. A reasonable capacity for a slurry containing 35 percent solids is about 50 pounds per hour per square foot of filter surface area. (Leonard and Harding, 1991, p. 548.)

Default Operating Parameters

The default flowchart shown in figure 1, included as a separate file “Defmassflow1.ppt,” is designed for the default coal characteristics (float-sink analysis) from figure 2, table 3, and the size-distribution pattern in table 5. The default plant capacity is 300 tons of run-of-mine (ROM) coal—equivalent to an annual capacity of 2 million short tons (1.8 metric tons) ROM coal. The clean-coal recovery is about 1.4 million short tons (1.3 metric tons) per year.

Economic Data

Equipment data—purchase price and hourly costs—were purchased from the consulting/engineering firm Western Mine Engineering, Inc., Spokane, Wash. The appropriate equipment types for coal cleaning selected from these are listed in a spreadsheet format in files accessible from the default flowchart within the software.

The user may change the default-flowchart settings within certain limitations. Care must be taken to verify the appropriateness of the entire mass flow if the user chooses to do so. At the end of every calculation, the user needs to choose a different file name to save the calculations. Failing to do so will not damage the software but will change the default settings. The user will then have to reenter them.

The chosen equipment, their purchase prices, and hourly operating costs are automatically listed in a separate table. Motors and pumps are included in the actual equipment list. An algorithm in the spreadsheet is provided to calculate the cleaning cost per ton of clean coal. The algorithm accounts for the cost of transporting the equipment and installing it, together with the pipes, belts, and other instrumentation. These costs are accounted for as a fixed percentage of investments needed for equipment purchase. The factor used in this case is 43 percent of the price of equipment. Provision is also made for the working capital equivalent to the value of 3 months of plant production. The user has the option to change any of the economic parameters, if so desired.

Computer Specifications

It is recommended to have a PC with a minimum of 10 GB hard drive, 128 MB RAM, and an Excel Visual Basic applications package at least of the 1997 version. The computer speed is less important, but a minimum speed of 500 MHz is recommended. This software will not work on an Apple computer.

Caution.—The flowchart was created in the “PowerPoint” software of the “Office97” package. Because of this, the chart drawing may show slight differences in the size of boxes, depending upon the monitor on your computer.

To use the software package, follow these steps:

1. Copy the program to a hard drive.
2. Of the seven files copied, you will be using two: “Book3.xls” and “project.xls.”
3. Double-click on “Book3.xls.” Click on “Enable macros.” A table briefly flashes on the screen and disappears. It takes a few seconds until the next window appears on the screen. It announces the name of the software and the date July 12, 2000. The next window follows in a few seconds.
4. A small window (step 1) with the option “Prepare the process flow chart” will appear on the screen. The default plant capacity is shown, and a choice is given to change it. Click “OK.”
5. The default mass flowchart will appear on the screen. The boxes containing “D” on the left side of the equipment box are intended to give the user

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access to data tables from equipment that can be selected. The boxes with “D” on the right side of equipment box provide access to the motors and (or) pumps that go with the equipment. To choose a different equipment size, the user is provided with a choice of the number of units of the equipment required to meet the capacity requirement. Baum jigs are offered as an alternative for heavy-media vessels. Likewise, the user may opt for spirals or tables in place of the coarse-flotation circuit.

If the user changes the default plant capacity but intends to use the default mass-flow percentages, the appropriate mass flows will be automatically calculated. The user can change the mass-flow pattern by clicking the mouse on the tons/h number near the chosen equipment. Changing one mass percentage will automatically change the other at that equipment. If any change is made in the mass-flow pattern, all tonnages will change. Therefore, the user must verify the tonnages throughout the flowchart. The user also must verify that an appropriate number of units is chosen, depending upon the amount of material processed at each stage.

6. At the top of the screen showing the flow diagram, the user has a choice to click on “Use Default List” and “Show My List.” If the user has not made choices other than those provided by default, either selection will show the same default list and other cost calculations. If the user did make any equipment changes, they will be shown with a click on “Show My List.” At the bottom of the screen the user is provided with four choices: “Flow Chart,” “Costlist_Defau,” “Costlist,” and “Ratio List.” “Costlist_Defau” shows the default equipment chosen but not the cost-per-ton calculations. “Costlist” and “Show My List” show the same tables when clicked on.
7. The cost data are in current dollars in year 2000. For future use of the software, provision has been made at the bottom of the appropriate columns to enter cost-change indexes. Cost indices may be obtained from Western Mine Engineering, Inc., Spokane, Wash.

In the table for the calculation of costs per ton of clean coal, the user may choose values for items in blue. The values for hourly plant capacity and hourly clean coal production are automatically taken from the flowchart. The values for investment in plant equipment and hourly operations and maintenance costs are taken automatically from the tables calculated previously. Depreciation is assumed to be “straight line” over the entire life of equipment but on one-half of the investment.

The cost per ton of clean coal is calculated under the following assumptions:

1. Discounts given by equipment manufacturers vary and are not considered.
2. Investments needed to purchase land and buildings to house the equipment are location-dependent and, therefore, not included.
3. Funds required for purchase of equipment and to pay for operating expenses are assumed to be borrowed. The default interest rate is 15 percent.
4. No return on investment on borrowed money is included in the cost per ton.
5. The funds to pay for transport and installation (43 percent of purchase price) are assumed to come from company savings. In the default case, the cost per ton of clean coal would increase by 4 cents (to \$1.62 per ton) if a 15-percent return on investment were assumed on these funds.

The cost of coal cleaning in the default case is \$1.58 per ton of clean coal. This cost estimate is realistic and comparable to actual cost of cleaning Illinois coal in a modern coal-cleaning plant.

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