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A TECHNIQUE FOR OPTIMIZATION OF PARTICLE SIZE DISTRIBUTION FOR COAL-SLURRY PIPELINES

by

George S. DaBai

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

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Signed: George S. DaBai
George S. DaBai

Approved: Robert R. Faddick and J. Paul Mather
Dr. Robert R. Faddick Dr. Jean Paul Mather
Thesis Co-Advisors

J. Paul Mather
Dr. Jean Paul Mather, Head
Department of Mineral Economics

Golden, Colorado

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Dedicated to

my wife, Judy, and my parents,

Salameh and Weidad DaBai

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ABSTRACT

A technique that determines the optimal particle-size distribution for coal-slurry pipelines has been developed and has been proven to work. The technique involves developing cost functions for coal-slurry preparation, coal-slurry pipeline transportation and coal-slurry separation or dewatering, and determining the optimal coal-particle-size distribution both analytically and graphically. The coal-particle-size distribution was chosen to be represented by a coal-particle-size diameter referred to as the weighted mean diameter (WMD).

A case study, which assumes a coal-slurry pipeline that transports coal at the rate of 300 tons per hour (2.376 million tons per on-stream year (330 days)) a distance of 200 miles, has been undertaken. For this case study, the technique resulted in an optimal coal-particle-size distribution, 95 percent of which passes through a 14 mesh screen and contains about 25 percent that passes through a screen size of 325 mesh. It was represented by a weighted mean diameter of 0.330 mm.

For the case study described above, the total annual capital and operating coal-slurry preparation cost in December 1975 for this pipeline was found to be $596,671, or

0.126 cents/ton-mile. Pipeline transportation cost was found to be $7,365,600, or 1.55 cents/ton-mile. Coal-slurry separation or dewatering cost was found to be $1,168,517, or 0.246 cents/ton-mile. The total cost is then $9,130,788, or 1.9220 cents/ton-mile.

The tool proved to work both analytically and graphically.

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NOMENCLATURE

WMD = Weighted Mean Diameter of the Coal Size Distribution

tph = tons per hour

fps = feet per second

INTRODUCTION

Almost every paper, magazine, and television or radio program nowadays calls for expansion and diversification of environmentally acceptable U.S. domestic energy sources. This call has been created by:

1. the depletion of low-cost domestic oil and gas resources,
2. the high cost of and heavy dependence on foreign oil and gas supplies, and
3. the unreliability at the present time of nuclear systems.

These factors have produced a sharply increased interest in returning to coal, since coal is the most plentiful source of energy in the U.S.

Coal is also abundant throughout the world. Battelle (1) estimates that 90 percent of the world's reserves of bituminous coal is found in China, the United States, and the U.S.S.R., and that 90 percent of the world's reserves of lignite (brown coal) is found in Australia, the United States, and the U.S.S.R. The United States has nearly half of the world's reserves of coal.

A brief discussion of the current status of coal in the United States follows.

COAL IN THE U.S.

In the United States, coal is widespread and abundant. Coal-bearing rocks underlie 13 percent of the land of the 50 states and are present in parts of 37 states.

Resources

U.S. coal resources, as estimated by the U.S. Geological Survey (2), are much larger than the resources of oil and gas combined.

Recoverable reserves of coal are estimated to be 197 billion short tons, while total identified resources (including reserves in thick accessible beds) are estimated to be 1,581 billion tons, with a recoverability range of 40 to 90 percent, depending on mining methods and geology. Hypothetical resources (those expected to be found in unmapped and unexplored areas in known coal fields) are estimated to be 1,643 billion tons.

With these resources in the U.S., coal can provide many decades of fuel and hydrocarbon supplies to meet future energy demands. The technologies for mining, washing, transporting, and burning of coal are well known. Coal can be converted into electricity, heat, gas, and (in the future) heavy liquids and light distillates to serve almost all the

energy-consuming markets.

Production

In the U.S., coal production faces some environmental problems which in turn affect the cost and availability of coal. These environmental constraints are:

1. Land Damage: Land is altered by the method of mining used, e.g. surface and underground mining depresses the topography.
2. Health Risk to Population: There are health and safety risks in surface and underground mining.
3. Air Pollution: Air pollution is created by the burning of coal-sulphur and other particulate material such as ash.

U.S. coal production has set a record high of 638 million tons in 1975 -- an 8-percent increase over the 1974 production. Coal production is expected to increase to 664 million tons in 1976 (3). These high records are similar to the postwar boom year of 1947, when the U.S. produced 631 million tons (4).

Coal Consumption

In the early part of the century, coal supplied almost 80 percent of the nation's energy (Table 1). Shortly after WW II, coal demand dropped to less than 40 percent due to

railroads shifting from coal-fired steam locomotives to diesel engines to avoid the problem of coal handling. At the same time, home coal furnaces shifted to cleaner, more convenient, and environmentally acceptable sources of energy -- oil and natural gas.

Table 1. Energy Supplies in the U.S.

Source of Energy	Percent of Total		
	1920	1950	1973
Coal	78	38	18
Petroleum	14	39	46
Natural Gas	4	18	31
Hydro	4	5	4
Nuclear	-	-	1
Total	100	100	100

Source: Ford Foundation (5)

Future Markets

Major breakthroughs in technology will play a large role in the future domestic markets of coal.

Coal for the synthetic fuel markets will be used in the early 1980's for the production of synthetic pipeline gas and

synthetic liquid fuels. Other processes produce clean (sulfur-free) coal for burning in power plants and refineries, or for any other industrial use.

Today, there are many processes for producing synthetic fuel from coal; some are at the laboratory-bench scale stage, and some are at the pilot-plant stage, while others are at the producing stage. A summary of these processes is presented in Appendix A.

The National Academy of Engineering (6) estimated that coal production in the U.S. by 1985 will double the current annual output of 600 million tons, as shown below.

Source	1985 Production million tons/year
Eastern Underground	480
Eastern Surface	220
Western Surface	560
Total	1,260

Fuel	1985 Consumption million tons/year
Coal solids (for utilities, industrial, and residential)	950
Synthetics	310
Total	1,260

From these figures, it is anticipated that the synthetic fuel industry will be consuming about 25 percent of the total production of coal in 1985.

Transportation

Since coal is a source of energy, it must be transported to the vicinity of its use in one form or another, either in its natural state, as electricity, or as a refined product such as a gas or a liquid. Currently, the economics of coal utilization, particularly as an energy source for electric power generation, favor moving it and using it in its natural state (6)

Modes of Coal Transportation: In the U.S. there are four major modes of transporting coal in its natural form to markets; railroads, barges, trucks, and miscellaneous means such as tramway, conveyors, and slurry pipelines. Table 2 shows the 1973 share of each of these modes.

Table 2. Coal Transportation Modes in the U.S. in 1973

Mode	Percent
Railroads	52*
Barges	27
Trucks	12
Other (Tramway, conveyor and private railroads)	8
Slurry Pipelines**	<1
Total	100

* Source: U.S. Bureau of Mines (7). This figure has been updated to 65 percent in 1975 (8).

** Coal-slurry pipelines are pipelines transporting crushed coal suspended in a liquid (water).

The Western States are expected to play an important part in the United States' future energy market. Some predict that annual consumption of Western coal from Wyoming, Colorado, and neighboring states will rise from 21 million tons in 1971 to 362 million tons in 1980 (9). Because of the remoteness and the low population density of the new coal fields and because of the projected increased production, coal will have to be moved to market by all of the existing transportation modes.

The railroads alone certainly cannot transport the projected amounts of coal. Waterways (barges) are the cheapest mode of transporting coal but are limited geographically (10). Moreover, there are no waterways in the West within a hundred miles of the coal fields. Trucks are uneconomical for long distance and large volumes; therefore, coal-slurry pipelines must play an increasing role in transporting coal where water is available.

The technical journal, Chemical Engineering (9), contains Mr. Dale W. Steffes' projection that railroads and slurry pipelines will transport almost equivalent amounts of Western coal by 1980, as shown in the following.

	million of tons per year
Moved by rail for utilities and industry	165
Moved by slurry pipelines for utilities and industry	162
On site generation station (EHV)	20
Substitute natural gas (SNG) from coal	15
Total	362

Coal-Slurry Pipelines: The technology of coal-slurry pipelines has reached the stage of maturity and has been firmly established by the Ohio and the Arizona pipelines to be technically and economically feasible. The Ohio pipeline, 10 inches in diameter, transported 1.3 million tons of coal annually from Cadiz, Ohio, to the East Lake Power plant of Lake Erie, near Cleveland -- a distance of 108 miles. The Ohio pipeline was built when railroad tariffs were increased substantially. The pipeline was technically and economically successful -- so much so that it was shut down only after six years of operation (1957-1963), when the railroad lowered transportation rates from $3.00/ton to $1.90/ton (11). At this point, the pipeline operation became uneconomical in comparison to the rates of rail transportation.

In 1970, the longest and largest coal-slurry pipeline, the Black Mesa coal-slurry pipeline, went into operation.

The line is 18 inches in diameter and currently transports about 5 million tons of coal per year from the Kayenta coal mine in Arizona to the Mohave power plant in Nevada, a distance of 273 miles. This pipeline was built in an isolated region of Arizona where there was no existing railway trackage.

There are in the U.S. at least six more proposed coal-slurry pipelines, which are listed in Table 3. These proposed pipelines must be put into operation to transport coal to satisfy U.S. energy consumption; but they face two problems: the problem of "right of way" and the problem of water availability. If coal-slurry pipeline operators are granted the right of eminent domain and if water is available, these six proposed coal-slurry pipelines probably will go into operation. Thus it is a political problem, not a technical problem, that is holding these pipeline projects on the drawing board.

A typical coal-slurry pipeline system involves (1) coal-slurry preparation in which the coal is ground to the desirable size for pipelining, mixed with the liquid carrier (water), and pumped through a pipeline; (2) coal-slurry pipelining in which the coal-slurry is transported from source to terminal; and (3) coal-slurry separation, in which the coal is separated from the water to render it suitable for combustion.

The total coal-slurry pipeline system depends on the

Table 3. Coal-Slurry Pipelines in the U.S.

Name	Origin/Terminal	Length (miles)	Diameter (inches)	Capacity (million tons/yr.)
Existing Lines				
Consolidation*	Cadiz-Cleveland, Ohio	108	10	1.3
Black Mesa	Kayenta, AZ./ Nevada	273	18	5.0
Planned Lines				
ETSI**	Gillette, WY./ White Bluff, AR.	1040	38	25
Houston Nat. Gas	Walsenburg, CO./ Houston, TX.	1100	18	7
Salt River System	Star Lake, N.M./ St. Johns, AR.	180	16	-
Nevada Power	Alton, UT/ Arrow Canyon, Nevada	180	24	10
Gulf Interstate	Gillette, WY./ Oregon	800	30	16
Montana/Houston	Southern Montana/ Houston, Texas	1260***	42	30

Sources: (12, 13)

* is not in operation at this time.

** Energy Transportation Systems Inc.

*** Estimated from the map. (13)

coal-particle size and distribution. The particle size and distribution are the keys to the hydraulic transportation of solids. As the coal-particle size becomes smaller, the critical velocity* for the fine or homogeneous slurries and the deposition velocity** for coarse or heterogeneous slurries decreases. This decrease results in a low operating cost for pipeline tansportation. But pipeline transportation is only one part of the total cost of a slurry pipeline system. The other two parts of the coal-slurry pipeline system are coal-slurry preparation, and coal-slurry separation. These processes, when dealing with fine coal, will have an increasing operating cost because fine coal requires extensive crushing and grinding; and separation of fine coal-slurry is difficult and expensive.

* Critical velocity is the velocity that delineates between turbulent and laminar flow. This velocity is the velocity used for homogeneous slurries. Slurries are referred to as homogeneous when the solid particles are very fine and light, so that the solid and liquid phases may essentially behave as one. In this system, the mean velocity of the flow is high enough to keep the solid particles uniformly in suspension throughout the pipe cross section. Examples of this type of non-deposit flow are the transport of clays, drilling muds, cement, and sewage sludge.

** Deposition velocity is the velocity at which mineral solids begin to deposit; that is, when the force of gravity overcomes force of turbulence. This term is used for coarse or heterogeneous slurries. Slurries are referred to as heterogeneous when the solid particles are coarse and have a large relative density. In horizontal flow, the mean velocity of the slurry is low so that the solid particles partially settle to form a zone of increased concentration near the bottom of the pipe. Examples are coarse sands, trona, phosphate, salt, coal and nickel ores.

The opposite is true for coarse coal. As the coal particles become larger, the critical velocity for the homogeneous or fine slurries and the deposition velocity for coarse or heterogeneous slurries increase. This increase results in a high operating cost for pipeline transportation, and a low operating and capital cost for coal-slurry preparation and separation, because it costs less to crush and separate coarse coal. Therefore, an optimum coal-particle size and distribution must exist in the overall slurry pipeline system to give the lowest, total, combined cost of slurry preparation, pipelining, and separation.

Because reduction of operating and capital costs of any of the coal-slurry system components is beneficial, this study was undertaken to determine the optimum particle-size distribution for a coal-slurry pipeline system.

To develop a tool that in turn would determine the optimal coal-particle-size distribution for a coal-slurry pipeline, the following procedure was followed:

1. Cost curves, as a function of particle size, were developed for each of the following:
   a. coal-slurry preparation,
   b. coal-slurry pipeline transportation for a fixed distance,
   c. coal-slurry separation or dewatering.
2. From the cost-size curves, cost-function equations were developed.

3. A mathematical model that consists of the summation of the three cost-functions mentioned above (coal-slurry preparation, pipeline transportation, and separation) was developed.
4. An attempt was made to determine the optimum solution, both graphically and analytically.

In order to evaluate the technique discussed above, a case study was made in which a hypothetical coal-slurry pipeline was to deliver 300 tons per hour of coal for a horizontal distance of 200 miles from the coal source. The following chapters will implement each of the above steps for this hypothetical coal-slurry pipeline.

COSTS

The following discussion of costs has been divided under the headings Coal-Slurry Preparation, Coal-Slurry Pipeline Transportation, and Coal-Slurry Separation.

Coal-Slurry Preparation

The slurry preparation section of the coal-slurry pipeline transportation system has two main functions:

1. to prepare the amount (capacity) and grind of coal for terminal use, and
2. to prepare a slurry to transport this capacity.

These functions are accomplished by the use of coal-size reduction equipment, such as crushers and grinders, and other miscellaneous coal-slurry preparation equipment such as conveyor belts, screens, dust collectors, mixing tanks, meters and gauges, slurry pumps, and pipes. These are shown in Figure 1 and are discussed in detail in Appendix B.

As shown in Figure 1, coal is delivered by conveyor belts from the coal storage area to scalping screens of the required size. The fractions that pass through the screens drop onto a belt and are delivered to either the mixing tank or to the wet-grinding section, depending on the coal-slurry particle size required. The fractions on the screens are

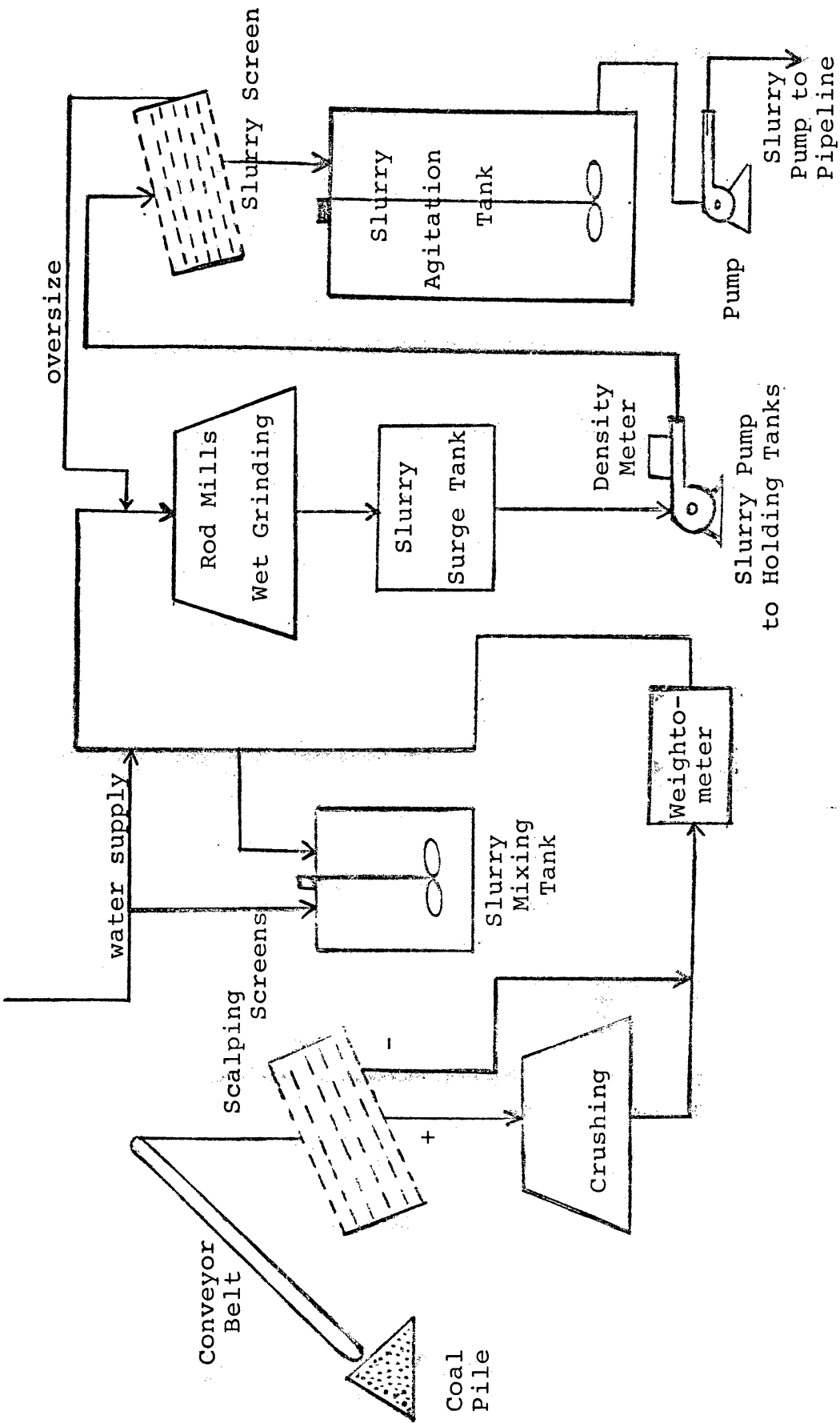


Fig. 1 - Typical Coal-Slurry Preparation Plant.

discharged into the crushers for reduction. The crushed coal is then weighed by a weightometer on the feed belt and delivered to a slurry mixing tank or rod mills for further grinding.

If the weighed coal is delivered into a slurry mixing tank, a measured amount of water is delivered to be mixed with the coal to form the desired slurry. Slurry is then pumped to the slurry holding tanks.

If the weighed coal is delivered to the rod mills for further grinding, water is delivered to the rod mills to start the wet-grinding process. The product of the rod mill is a slurry with the specified particle size needed for pipelining. Slurry overflow from the mills is charged into a slurry surge tank, from which it is pumped by centrifugal slurry pumps to the slurry holding tanks. A slurry density meter, mounted on the pump discharge line, monitors the coal concentration of the slurry and transmits the information to the plant control panels. The slurry is then being sampled automatically for immediate analysis of size distribution and solids concentration. If the slurry is suitable for pipelining, it is then pumped into the pipeline. If it is not suitable, it is returned to the wet-grinding section for adjustment.

Eleven coal-particle sizes defined as 95 to 100 percent

passing through 1-in., 3/4-in., 3/8-in., 1/4-in., 6-mesh, 8-mesh, 14-mesh, 16-mesh, 20-mesh, 30-mesh, and 35-mesh screens were used for this case study. These sizes, randomly selected, were based on the top size of the coal particles of the Black Mesa Pipeline -- 1/8-in. x 0 (14). Five particle sizes were selected to have a top particle size finer (smaller) than the Black Mesa's, 1/8-in. x 0, and five others were selected to have a top particle size coarser (larger) than the Black Mesa's 1/8-in. x 0. These are shown in Table 4 below.

Table 4. Coal-Particle Sizes Used in This Study

Particle Size - 95-100 Percent Passing Through		
Inches	Millimeters	U.S. Standard Mesh
1.0000	25.400	-
0.7500	19.050	-
0.3750	9.525	-
0.2500	6.350	3
0.1320	3.360	6
0.0937	2.380	8
0.0550	1.397	14
0.0469	1.190	16
0.0331	0.840	20
0.1232	0.589	30
0.0195	0.495	35

The coal slurry to be prepared is assumed to be 50 percent coal by weight. Based on the above assumptions, commercially available coal-slurry preparation equipment was selected, and costs were obtained. This equipment is discussed

in detail in Appendix B.

Capital equipment costs for slurry preparation can be obtained, based on the equipment discussed in Appendix B. These costs are shown in Appendix C. The total capital investment cost of a coal-slurry preparation plant to prepare 300 tons per hour of a 50 percent by weight coal-slurry now can be determined from the capital investment cost in Appendix C, and from the cost factors for installation, piping, building and site development, engineering and construction, land, and contingencies. These cost items are discussed in Appendix D. The results are shown in Table 5.

Table 5 shows only the total costs of the physical plant. Operating and maintenance costs for coal-slurry preparation are not available from the manufacturer. These costs vary from one operator to another; therefore, there is no single operating and maintenance cost. Domestic operating coal-slurry pipelines were contacted for information about these costs, and the reply was "operating cost is proprietary." No literature known to the author is available on this matter, other than the operating and maintenance costs of the total pipeline system by Aude, Thompson, and Wasp (15) of Bechtel Inc., San Francisco, California. These authors concluded that operating and maintenance costs comprise 30 percent of the total slurry pipeline system, half of which (15%) is power cost, the other half (15%) is for

Table 5. Capital Investment Cost of 300 tph Coal-Slurry Preparation Plant, Dollars

Reduction Size(inch/ mesh)	Purchased Equipment(1)	Equipment Installation(2)	Plant Piping(2)	Building & Site Development(2)	Engineering & Construction(2)	Land(2)	Contingencies(2)	Total
1 inch	609,740	262,188	60,974	365,844	347,552	36,584	140,240	1,823,122
0.75 inch	620,318	266,737	62,032	372,191	353,581	37,219	142,673	1,854,751
0.375 inch	636,168	273,552	63,617	381,701	362,616	38,170	146,319	1,902,143
0.250 inch	637,893	274,294	63,789	382,736	363,599	38,272	146,715	1,907,300
6 Mesh	640,818	275,552	64,082	384,491	365,266	38,449	147,388	1,916,046
8 Mesh	710,818	305,652	71,082	426,491	405,166	42,649	163,488	2,125,346
14 Mesh	747,818	321,562	74,782(3)	448,691(3)	426,256(3)	44,869(3)	171,998(3)	2,235,976
16 Mesh	807,818	347,362	74,782	448,691	426,256	44,869	171,998	2,321,776
20 Mesh	927,818	398,962	74,782	448,691	426,256	44,869	171,998	2,493,376
30 Mesh	1,047,818	450,562	74,782	448,691	426,256	44,869	171,998	2,664,976
35 Mesh	1,167,818	502,162	74,782	448,691	426,256	44,869	171,998	2,836,567

(1) Appendix C

(2) Appendix D

(3) From 14-mesh to 35-mesh these costs are assumed to be the same, because they have the same flow sheets.

labor and supplies. The remaining 70 percent is considered capital cost.

Based on this information, operating and maintenance costs of slurry preparation are assumed to be 30 percent of the total cost or 42.851 percent of the annual plant cost. The total annual plant cost, operating and maintenance cost, and the total cost of slurry preparation are shown in Table 6.

Coal-Slurry Pipeline Transportation

Pipeline transportation cost is dependent on the following parameters:

1. slurry throughput (capacity),
2. pipeline geometry,
3. Coal-particle size and distribution (screen analysis), and
4. slurry concentration.

Design Parameters to be Used in this Study: For the purpose of this study, seven available coals with different screen analysis and specific gravities were used. These coals and their screen analysis are shown in Appendix E. These coals and their screen analysis were used because they were the only ones available with pipeline data. Coal-screen analyses with pipeline data are hard to obtain and vary in

Table 6. Coal-Slurry Preparation Cost for 300 tph Plants for Different Coal-Particle Sizes, Dollars

Coal Size[1].	Total Capital Investment Cost - $[2].	Annual Fixed Cost-$[3].	Annual Fixed Cost $/Ton[4].	Operating & Maintenance Cost $/Ton[5].	Total Cost $/Ton
1-inch	1,823,122	291,262	0.1226	0.0525	0.1751
0.75-inch	1,854,751	296,315	0.1247	0.0535	0.1782
0.375-inch	1,902,143	303,886	0.1279	0.0548	0.1827
0.250-inch	1,907,300	304,710	0.1282	0.0550	0.1832
6 Mesh	1,916,046	306,168	0.1288	0.0552	0.1840
8 Mesh	2,125,346	339,545	0.1429	0.0612	0.2041
14 Mesh	2,235,976	357,220	0.1503	0.0694	0.2148
16 Mesh	2,321,776	370,927	0.1561	0.0669	0.2230
20 Mesh	2,493,376	398,342	0.1677	0.0719	0.2396
30 Mesh	2,664,976	425,757	0.1792	0.0768	0.2560
35 Mesh	2,836,567	453,171	0.1907	0.0818	0.2725

1. 95% passing through the shown size
2. Table 5
3. Based on capital recovery factor for 20 years at 15% (0.15976) (16)
4. Based on 2.376 million tons per year (300 tph and 330 days per year)
5. Based on 30% of total cost or 42.851% of Annual Plant Cost

accuracy, depending on the source.

For all the seven screen analysis shown in Appendix E, the following pipeline design parameters were used:

Slurry throughput (capacity)	= 300 tph of dry coal
Specific gravity of the liquid	= 1.0
Slurry temperature	= 18.0° Celsius, except for screen analysis No. 7 (24.7° C.)
Initial (injection pressure)	= 10 psi
Final (discharge pressure)	= 0 psi, free discharge
Pipe type	= Commercial steel
Pipeline length	= 200 miles
Pipewall thickness	= 0.0208 ft.

Additional pipeline design parameters to be used in this study are shown in Table 7 for each of the screen analyses used for this section of the study. From the parameters, the coal-slurry pipeline transportation cost was obtained by using the computer programs developed by Faddick (17) and described by Lavingia (18) in a thesis submitted to the Colorado School of Mines.

The computer program described in Lavingia's thesis combines hydraulic characteristics of the pipeline with economic ones, and determines the optimum pipe diameter and pipeline cost for homogeneous slurries. A similar computer program, developed by Faddick (17) at the Colorado School

Table 7. Additional Pipeline Design Parameters to be Used in This Study

Screen Analysis No.[1]	Specific Gravity[1]	Solids Concentration[2]	Headloss Intercept(A)[3]	Correlation Slope(b)[3]	Shape Factor (X)[5]
1.	1.26	40.0	3.78	0.2575	0.243
2.	1.306	45.0	134.40	1.2335	0.284
3.	1.339	50.0	89.26	1.2032	0.4545
4.	1.32	50.0	114.36	1.1797	0.6765
5.	1.34	50.0	27.42	0.8098	0.938
6.	1.385	50.0	6.18	0.3947	0.842
7.	1.381	46.7	NA[4]	NA	NA

1. Appendix E.

2. Concentration by weight percent.

3. The intercept A and slope b are the intercept and slope of the regression line of the logarithm of $\emptyset$ versus ψ. The headloss equation for heterogeneous slurries is $\emptyset = A\psi^b$. terms are discussed in detail in Appendix F.

4. NA = Not applicable to homogeneous slurries; instead rheology data such as K(slurry consistency index) = 33.84 dynes $sec^n.cm^2$, n(slurry flow behavior index) = 0.143, and τ_y(slurry yield stress) = 4.33 dynes/cm^2 were used. These terms are discussed in detail in Appendix F.

5. X is the shape factor obtained from Faddick (17).

of Mines, does the same but for heterogeneous slurries.

In these two computer programs, a range of throughputs and pipe diameters was specified to compare pipeline costs in different diameter pipes. The computer programs read rheology data for homogeneous slurries and head loss data for heterogeneous slurries and determine the Reynolds number of flow.

From the Reynolds number of flow, the flow regime was determined. The Reynolds number of flow and the regimes for the screen analysis used in this study are shown in Table 8. The computer programs then compute the annual total pipeline transportation cost, which comprises the capital cost of the pipe and the pumps and the annual operating or pumping cost. The computer programs then print out a unit transportation cost in cents per ton-mile. For more details refer to Lavingia's thesis (18).

Summary of Coal-Slurry Pipeline Transportation Costs: The cost equations in Lavingia's thesis for pipes, pumps, and motors were based on June 1974 prices (Marshal and Stevens' cost index of 386.1). In order to update these cost equations to December 1975 prices, a Marshal and Stevens index of 450.6 was used (19). Based on the Marshal and Stevens cost index for June 1974 and December 1975 of 386.1 and 450.6, respectively, the updating cost factor was

Table 8. Reynolds Numbers of Flow and Flow Regimes for Different Coal Screen Analysis

Coal[1.]	Reynolds No. Settling	Flow Regime
Eastern Coarse Coal #1	3697.89	Heterogeneous
West Virginia Coal #2	254.16	Heterogeneous
Pocahontas Seam Coal #3	109.78	Heterogeneous
Pocahontas Coal #4	16.12	Heterogeneous
West Canada Coal #5	6.58	Heterogeneous
West Canada Kaiser Coal #6	4.4	Heterogeneous
Eastern Fine Coal #7	0.06	Homogeneous

1. Appendix E.

found as follows:

$$\text{Factor} = \frac{\text{Marshall \& Stevens cost index Dec. 1975}}{\text{Marshall \& Stevens cost index Jun. 1974}} = \frac{450.6}{386.1}$$

$$= 1.1671$$

This cost factor was then used to update the cost equations developed in Lavingia's thesis for pipes, pumps, and motors. The computer programs described above were then used to determine the optimum pipe sizes and the total cost of the pipeline. The optimum pipe size was selected to correspond to the lowest pipeline transportation cost, provided that the pipeline operating velocity exceeded the deposition velocity of the slurry for heterogeneous slurries, and exceeded the critical velocity of the slurry for homogeneous slurries. These results are shown in Table 9.

Cosl-Slurry Separation

Coal-slurry, upon arrival at the destination area, must be separated from its carrier, water, in order to meet the moisture content the market specifies. This separation could be accomplished by using coal-slurry dewatering equipment.

As Figure 2 shows, coal-slurry is pumped by centrifugal pumps from the slurry receiving tank to a dewatering screen to be thickened. The thickened slurry is then delivered to

Table 9. Total Pipeline Transportation Cost of Coal-Slurry For Different Coals for a 200 Mile Line and 300 tph Throughput

Coal and Screen Analysis[1.]	Optimal Pipe Dia.(in)	Operating Velocity fps	Deposition Velocity fps	Headloss psi/Mile	Total Cost MM$	Total Cost ¢/ton-Mile
Eastern Coarse Coal #1	11	9.29	7.11	74.425	13.36	2.81
West Virginia Coal #2	12	6.77	6.43	82.904	13.38	2.82
Pocahontas Seam Coal #3	11	7.08	6.50	87.695	12.46	2.62
Pocahontas Coal #4	12	5.98	5.87	72.033	11.65	2.45
West Canada Coal #5	13	5.06	4.28	37.957	8.61	1.81
West Canada Kaiser Coal #6	13	5.01	4.23	25.833	7.38	1.55
Eastern Fine Coal #7	12	6.36	5.58[2.]	59.554	9.95	2.09

1. Appendix E

2. Critical velocity

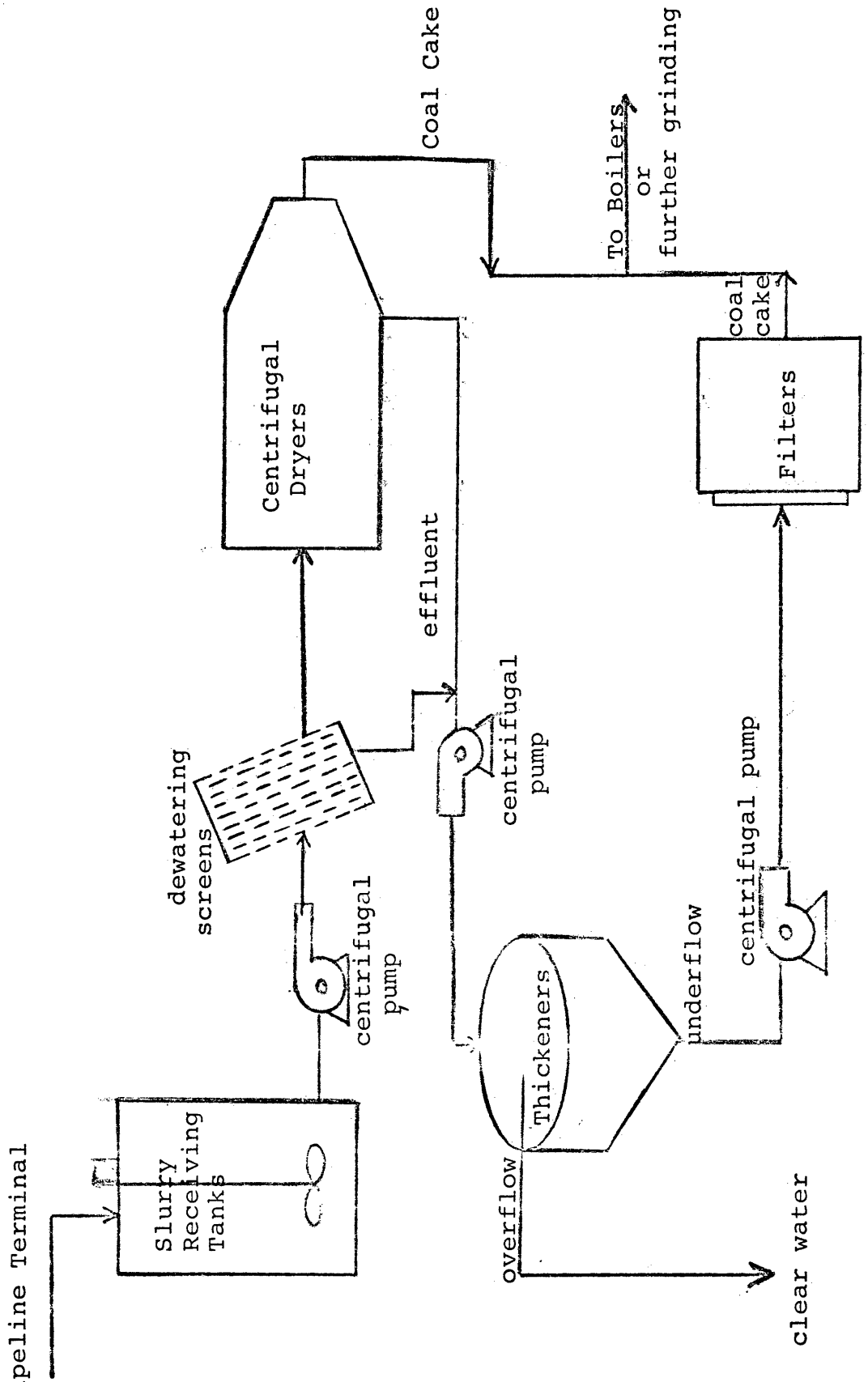


Fig. 2 - Typical Coal-Slurry Separation Plant.

centrifugal dryers, which produce a coal cake. The moisture content of the coal cake depends on the dryer used and the slurry concentration. The effluent from the slurry screen and the centrifugal dryers are pumped into a thickener (large diameter tank) where the slurry is thickened either by gravity or by chemical treatment. If chemical treatment is used, the type and amount to be added to the coal particles in suspension will depend on the kind and the size of the coal particle.

The thickened slurry is then pumped from the bottom of the thickener either to the coal cake produced from the centrifugal dryer or to a filter, if further dewatering is needed, depending on the amount of the thickened slurry out of the thickener. If a filter is needed, the product is a coal cake, which is then sent directly to the boilers in a power plant or for further drying before use in the boiler.

For this study, seven available coals with different specific gravities and particle-size distribution were used. Six of the seven coals and their screen analyses were mentioned earlier in the pipeline transportation section and are shown in Appendix E. In addition, a seventh coal with its screen analysis was used and is shown in Appendix E.

For the conveneince of the reader, the names of these coals and their specific gravities are mentioned as follows.

Coal No.	Name	Specific Gravity
1	Eastern Coal	1.26
2.	Pennsylvania Coal	1.30
3.	West Virginia Coal	1.306
4.	Pocahontas Seam	1.339
5.	Pocahontas Coal	1.32
6.	C N Coal	1.34
7.	Kaiser Coal	1.385

Based on these screen analyses, coal-slurry separation processes and equipment were selected for each coal. The selected processes and their capital costs are shown in Appendix G.

The total capital cost of the coal-slurry separation or dewatering plants were then calculated, based on capital costs described in Appendix G and plant design costs described in Appendix D. These results are shown in Table 10. The total capital and operating cost of dewatering 300 tons of 50 percent coal slurry are shown in Table 11.

Table 10. Capital Investment Cost of 300 tph Coal-Slurry Dewatering Plants, Dollars

Coal No.	Purchase Equipment (1)	Equipment Installation (2)	Plant Piping (2)	Building & Site Development (2)	Engineering & Construction (2)	Land (2) (3)	Contingencies (2)	Total
1)	450,787	193,838	112,697	279,472	256,949	27,047	103,681	1,415,471
2)	490,567	210,944	122,642	294,340	256,949	29,434	112,830	1,517,706
3)	569,515	244,891	142,379	341,709	256,949	34,171	130,988	1,720,602
4)	603,515	259,511	150,879	362,109	256,749	36,211	138,808	1,807,982
5)	1,190,515	511,921	297,629	714,309	256,949	71,431	273,818	3,316,372
6)	1,213,605	521,850	303,401	728,163	256,944	72,816	279,129	3,375,913
7)	1,299,605	558,830	324,401	779,763	256,949	77,976	298,909	3,596,933

1. Appendix G
2. Appendix D
3. Assumed identical for all coal.

Table 11. Coal-Slurry Separation (Dewatering) Costs for 300 tph for Different Coals

Coal[1.]	Total Capital Investment Cost-$ [2.]	Annual Fixed Cost-$ [3.]	Annual Fixed Cost $/ton[4.]	Operating & Maintenance Cost $/ton[5.]	Total Cost $/ton
Eastern Coal #1	1,415,471	226,136	0.0952	0.1000	0.1952
Pennsylvania Coal #2	1,517,706	242,469	0.1021	0.1200	0.2221
West Virginia Coal #3	1,720,602	274,883	0.1157	0.1500	0.2657
Pocahontas Seam #4	1,807,982	288,843	0.1216	0.1700	0.2916
Pocahontas Coal #5	3,316,572	529,856	0.2230	0.2300	0.4530
C N Coal #6	3,375,913	539,336	0.2269	0.2500	0.4770
Kaiser Coal #7	3,596,933	574,646	0.2419	0.2500	0.4919

1. Appendix E.

2. From Table 10.

3. Based on capital recovery factor for 20 years at 15% (0.15976)(18).

4. Based on 2.376 million tons per year (300 tph and 330 days per year).

5. Available from manufacturer of equipment.

STATISTICAL ANALYSIS OF COAL-SIZE DISTRIBUTION DATA

The most common method of measuring coal-particle size is sieving (screen analysis). Another method of determining the size of small particles is establishing their settling velocity.

Small spheres settle in accordance with Stokes' Law, which states that the settling velocity varies as the square of the particle diameter.

Two graphic procedures are commonly used in presenting coal-particle-size distribution (screen analysis).

1. Histogram is a block diagram that gives the percentage of grains in an arbitrary number of grade sizes present in the screen analysis. Histograms present a factual picture of the abundance of grains in each grade size in a readily visualized form; however, they cannot be used directly for numerical summaries of the data.
2. Cumulative curve is a curve prepared by adding the percentages in succeeding size grades in a screen analysis and drawing a smooth curve through the points. These curves are used as graphic devices

for determing average particle size.

Coal-particle-size distribution has been a subject of much research, which for many years has focused on determining the most meaningful size measure that represents coal or other minerals' size distribution. The following size measures (diameters) are known to the author.

1. Arithmetic Mean
2. Median
3. Weighted Mean
4. Rosin-Rammler
5. Quartile Mean
6. Moment-Phi Mean

Each of these dismeters will be discussed briefly below.

Arithmetic Mean

The arithmetic mean diameter is a simple representation of particle-size distribution. It is calculated by adding the top (largest) and bottom (smallest) of the screen analysis and dividing the result by two. The result is an average size.

Median

The median diameter of a screen analysis is simply the "middle-most" grain size with an equal percentage of grain on each side. It is the diameter, where 50 percent of the screen analysis is smaller and the other 50 percent is

larger than the median diameter. In other words, it is the screen-size diameter, where 50 percent of the sample weight passes through and the other 50 percent is retained.

Weighted Mean

In a screen analysis the first two screen sizes are converted from mesh opening size to inches or mm and averaged. The average is multiplied by the weight percent of the total sample that is retained on the smaller and passes the larger size. This procedure is followed for each consecutive pair of the screen analysis. These products are then summed, and the result is divided by 100 to get the weighted mean diameter, which is represented mathematically by

$$WMD = \frac{\sum_{i=1}^{n} diWi}{100} \qquad (1)$$

Where, WMD = Weighted mean diameter

di = Average diameter of each of the consecutive pairs of sizes

Wi = Weight in percent corresponding to each pair of sizes

n = Number of pairs of screen sizes in the screen analysis.

Along with the weighted mean diameter, two coefficients are used to represent the relative dispersion of the screen

analysis. These are the coefficients of variation and the Hazen Uniformity Coefficients. These coefficients are discussed by Faddick (20). The coefficient of variation, is the dimensionless term used to measure relative dispersion. It is the standard deviation divided by the weighted mean and is expressed as a percent. The larger the coefficient of variation the wider the range. If the coefficient of variation equals zero percent, the particles have uniform size.

The Hazen Uniformity Coefficient is the ratio of the diameter at the 60 percent finer point and the 10 percent finer point on the cumulative gradation curve. This coefficient ranges from unity for uniform solids to 1000 for a well-graded gravel, sand, silt, and clay.

Rosin-Rammler

The Rosin-Rammler function was originated in 1933 for coal (20,21). This function is represented by

$$Wr = 100\, e^{-\left(\frac{D}{a}\right)^{b}} \qquad (2)$$

Where Wr = Cumulative percent weight retained,

D = Mean diameter

a and b are constants,

a = Size constant, determined by sieve opening on which 36.79 percent of the sample is retained,

b = Distribution constant, measures dispersion of material over the size range.

The constants (a,b) are best determined from the linear curve resulting from the Rosin-Rammler Plot. The Rosin-Rammler plot is determined from the equation above. From equation (2)

$$\frac{100}{Wr} = e^{\left(\frac{D}{a}\right)^b}$$

$$\ln\left(\frac{100}{Wr}\right) = \left(\frac{D}{a}\right)^b \text{ and}$$

$$\ln\left(\ln\left[\frac{100}{Wr}\right]\right) = b(\ln D - \ln a) = b \ln D - b \ln a. \quad (3)$$

Let, $\ln\left(\ln\left[\frac{100}{Wr}\right]\right) = Y$

$\ln D = X$, and

$b \ln a = c$, and substituting these values in equation 3 yields a linear equation of the form

$Y = \underline{b}X - \underline{C}$.

In order to obtain values for $\underline{a}$ and $\underline{b}$ in the above equations, a screen-analysis cumulative curve is plotted on logarithmic graph paper. The value of $\underline{a}$ is the particle size, where the screen-analysis cumulative curve line crosses the horizontal line, at which 36.79 percent of the coal sample in the screen analysis is retained. The value of $\underline{b}$ is the

slope of the cumulative curve line; it measures dispersion of material over the size range. For small values of b, the size curve is close to the size axis, and the material is spread over a wide size range (solids with wide distribution-horizontal).

Quartile Mean

The quartile method is based on quartiles obtained graphically from the cumulative particle-size-distribution-curve determined by following the 25, 50, and 75 percent lines to the right of their intersection with the cumulative curve, then reading the values on the size scale which lies directly below the intersections. The first quartile is associated with the 25 quartile. The second quartile, associated with the 50-percent line, is called the median diameter. The third quartile is associated with the 75 percentile. In order to measure the degree of sorting, the sorting coefficient (So) was developed. The sorting coefficient (So) is a measure of the spread of the distribution. It is defined statistically as the extent to which the grains spread on either side of the average. The wider the spread the poorer the sorting. Yet one distribution may have a much wider range than the other. The sorting coefficient (So), as discussed in Krumbein and Sloss (22), is defined as the square root of the ratio of the larger quartile, the (25%)

value Q_1, to the smaller quartile, the (75%) value Q_3.

$So = \sqrt{Q_1/Q_3}$,

Where So = sorting coefficient

Q_1 and Q_3 represent diameters of 25 and 75 percent quartiles.

The more nearly equal the two quartiles, the more closely the sorting coefficient approaches 1. According to Krumbein and Sloss a well-sorted sediment has So values less than 2.5, moderately sorted sediments have So values in the range of 2.5 - 4.0, and poorly sorted sediments have values larger than 4.0.

Moment-Phi Mean

In addition to the quartile measure, Krumbein and Sloss (22) discuss moment measures. Moment measures are related to the center of gravity of the size frequency curve. They have some advantages over the quartile measures in studies of the dynamic condition of sediment transport. Moment measures are usually expressed in logarithm form because of the need for a geometric grade scale in particle size analysis. The average diameter in the logarithmic moment method is the phi mean; its antilog is the geometric mean diameter. The degree of sorting is expressed as logarithmic standard deviation (sigma phi) or its antilog, the geometric standard

deviation. Krumbein and Sloss (22) discuss Inman's proposed method that permits simultaneous graphic treatment for both quartile and moment measures. The cumulative curve of the screen analysis is plotted on probability paper.

The diameter scale is expressed as its negative logarithm to the base 2, which yields the arithmetic phi scale. The phi mean is then defined as half the sum of the phi values associated with the 84- and 16- percent lines; the sigma phi is half the difference between these two values.

phi median = $d_{50} = \phi_{50}$*

phi mean = $(\phi_{84} + \phi_{16})/2 = \frac{1}{2}(d_{84} + d_{16})$*,
which is the geometric mean diameter.

sigma phi = $\phi = (\phi_{84} - \phi_{16})/2 = \frac{1}{2}(d_{84} - d_{16})$*,
which is the geometric mean standard deviation.

These values are in logarithms. They may be converted to their diameter equivalents by use of charts. The measure of skewness ($\delta\phi$) to be used with this measure is based on the extent to which the mean and the median separated as the cumulative curve becomes asymetrical as shown:

$$\delta\phi = (M\phi - Md\phi) / \sigma\phi$$

where, $M\phi$ = phi mean

$Md\phi$ = phi median

$\sigma\phi$ = sigma phi.

* From the cumulative graph.

Any of above-mentioned size measures can be used to represent screen analyses. The most widely used size measures for coal are the "median"; "Rosin-Rammler", and the "weighted mean" size measures (diameters). The median "diameter" is the easiest to compute but is limited because it is difficult to use in predicting an optimal screen analysis. The Rosin-Rammler "diameter", which was originally developed for coal, is a reasonable "diameter" but it is computed in a complicated manner. The weighted mean "diameter" is a reasonable measure; it takes into consideration averaging each consecutive pairs of screen sizes in the screen analysis.

For the purpose of this study, any of these three size measures (diameters) can be used. However, the weighted mean diameter will be used because it is easily and rationally computed. It will also work well in the trial-and-error approach to predict an optimal particle-size distribution (screen analysis).

DEVELOPMENT OF THE MATHEMATICAL FUNCTIONS

Tables 6, 9, and 11 have shown the preparation, pipelining, and separation costs of coal-slurry transportation for different coal size distributions. In order to develop cost equations, cost curves need to be developed. Cost curves are developed by plotting cost of preparation, pipeline transportation, and separation of coal-slurry against representatives of coal-particle size distribution. Again it is emphasized that for the purpose of this study the weighted mean diameters will be used. Throughput this chapter the weighted mean diameter will be designated by WMD.

Coal-Slurry Preparation

Table 6, earlier, showed the total cost of coal-slurry preparation in dollars per ton for 300 tph capacity, for different coal sizes. These coal sizes are the top size of the screen analysis (95-100 percent passing the screen of the top size). Coal screen analyses are impossible to obtain from coal reduction equipment manufacturers because each coal grinds differently, depending on the specific gravity, moisture content, chemical composition, and the amount of ash and other waste material in the coal.

For the purpose of this study, the top size is used to determine an "estimated" WMD, which is needed to develop the

cost function for slurry preparation. The "estimated" WMD is determined by dividing the top size by two. For example, if the top size of a screen analysis is 1 inch, 95 to 100 percent of the coal-particle-size distribution (screen analysis) passes through a 1-inch screen. Dividing that by 2 gives 1/2 inch, what is referred to as the "estimated" WMD, which means that 50 percent of the coal-size distribution is coarser than 1/2 inch, and 50 percent is finer than 1/2 inch. This assumption is limited, but is a fair and reasonable assumption, since the true particle-size distribution (screen analysis) is not known. In the author's opinion, this assumption is the best that can be used to describe the WMD for the coal-slurry preparation section. Coal-slurry preparation costs and the assumed WMD's are shown in Table 12 and are plotted in the upper part of Figure 3.

In order to get a mathematical function to define this cost curve (top Figure 3), three curve-fitting techniques were considered: minimizing the sum of the squares of the deviation (least squares), minimizing the sum of the absolute deviation, and minimizing the maximum absolute deviation. Since the least-squares method is most commonly used, it is used in this study. The other two methods are discussed by Wagner (23).

The "least squares" method is used for determining a regression equation which is used to predict with reasonable accuracy one of the variables based on the other variable.

Table 12. Coal-Slurry Preparation Costs For 300 tph and 200-Mile Long Pipeline

Coal-Particle Size - mm[1].	Total Cost-Cents/Ton-Mile[2].
12.7000	0.0876
9.5250	0.8910
4.7625	0.0914
3.1750	0.0916
1.6800	0.0920
1.1900	0.1021
0.6985	0.1074
0.5950	0.1115
0.4200	0.1198
0.2945	0.1230
0.2475	0.1362

1. Assumed weighted mean diameter, top size in Table 6 divided by 2.

2. Total cost from Table 6 divided by 200 miles.

The method gives what is commonly referred to as the "best fitting" straight line. This method minimizes the sum of the squares of the vertical deviation about the line. For more details refer to Crow et al. (24)

The selection of the mathematical equation that describes the cost curve best was based on the correlation coefficient. In other words, the closer the correlation coefficient to one (100 %), the better the "straight line (regression) equation." For the coal-slurry preparation cost curve shown in the upper part of Figure 3, the best mathematical cost function that defines the curve was of the

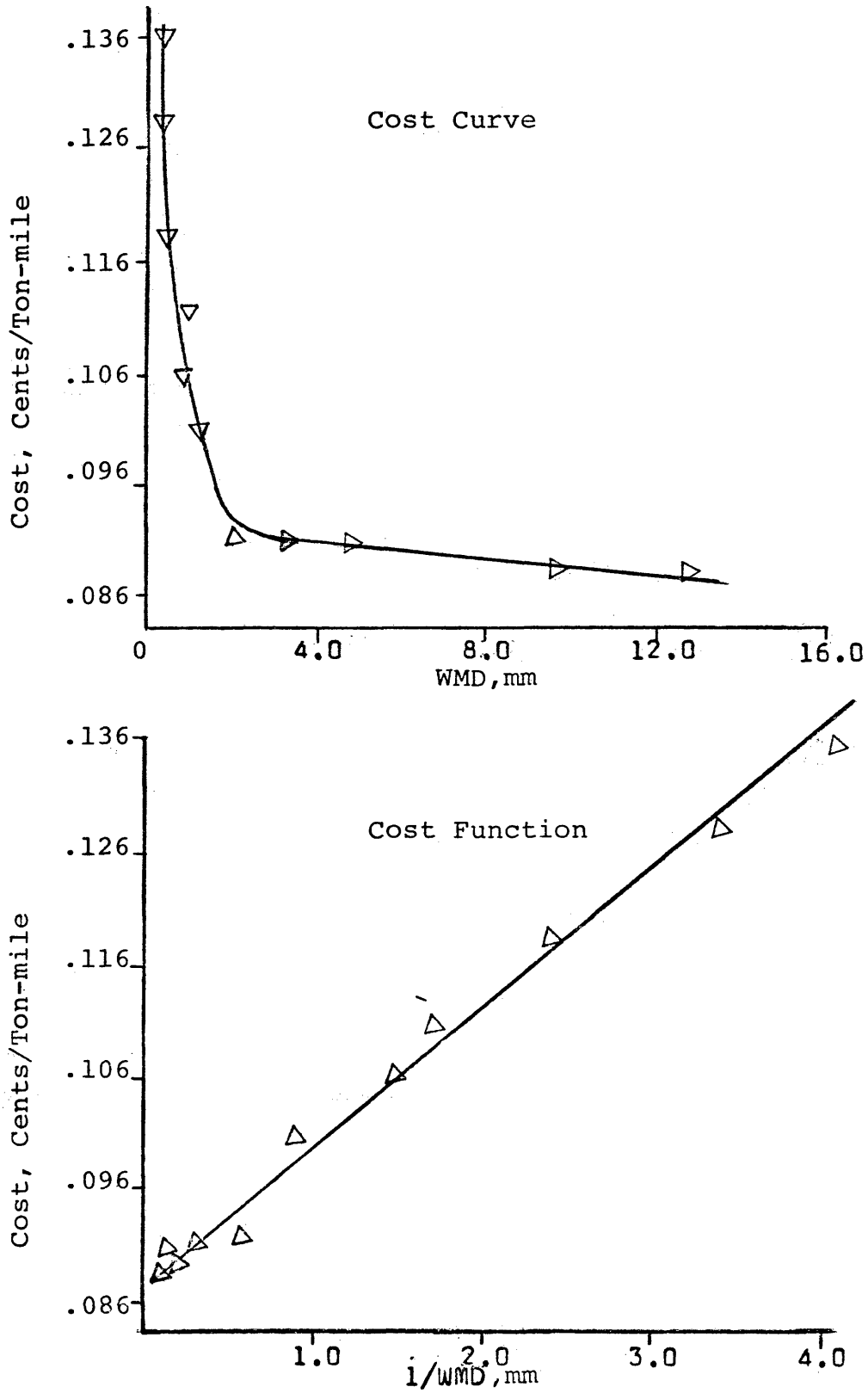


Fig. 3 - Cost Curve and Function for Coal-Slurry Preparation For 200-Mile Line and 300 tph.

form Y = M/X + B, with M = 0.0122592, and B = 0.0884125, with a coefficient of correlation of 0.9917, where X is the coal's WMD and Y is the coal-slurry preparation cost. Note the sudden increase in cost of preparing a coal-size distribution with a WMD smaller than about 2 mm.

Coal-Slurry Pipeline Transportation

The seven WMD's and their corresponding pipeline transportation costs in Table 9 were plotted and are shown in Figure 4. (Note that there are no data points between the last point with a WMD of 12.650 mm and the one before it with a WMD of 2.380 mm). Also, there are no data points between the first two points with a WMD of 0.0607 and 0.330 mm, which means there is no way of knowing if the lowest cost occurs at a WMD of 0.330 mm, to the left of it, or to the right of it. More data are needed between these two points in order to resolve this problem. Since there are only seven data points available for this study, an effort was made to obtain the best mathematical function defined by these points.

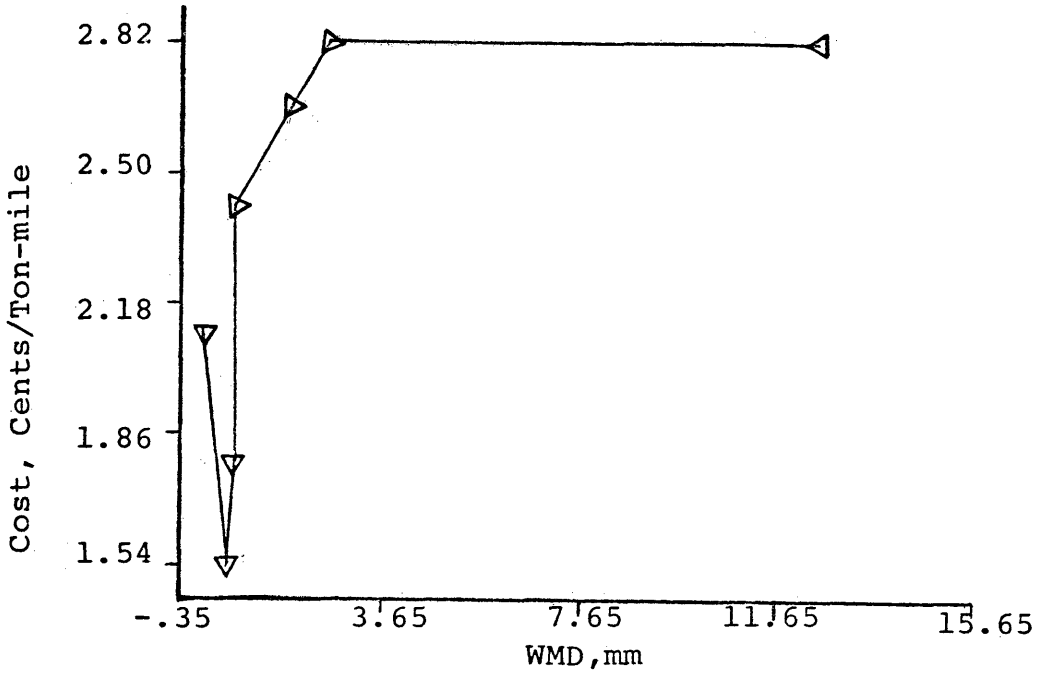
In order to develop a mathematical function defined by the seven points in Figure 4, the first-, second-, third-, fourth-, fifth-, and sixth-order polynomial functions were considered. The results did not yield a very good fit. Therefore, piece-wise curve fitting techniques were investi-

gated. This technique involves dividing the available seven data points into two consecutive sets of data that overlap at a point and fitting a curve through each of these sets. The first set includes WMD's of 0.0607, 0.3300, 0.3610, and 0.5990 mm. The second set includes WMD's of 0.599, 1.479, 2.380, and 12.650 mm. The results were third-order polynomial functions describing each of the sets of points. These two functions have a zero residual, but are meaningless because a third-order mathematical function was forced to fit a curve that goes through a set of four data points. Therefore, these functions will not necessarily describe the true mathematical function for this study.

The only alternative left is to consider linear functions describing the straight line sigment between each pair of adjacent data points in the top curve of Figure 4. The bottom curve shows the top curve, but with an expanded scale and without the last point. The results gave six sifferent linear functions shown below.

Linear Function	Interval of WMD mm
$Y = -2.0052X + 2.2120$	0.0607 - 0.330
$Y = 8.7097X - 1.3242$	0.330 - 0.361
$Y = 2.6470X + 0.8644$	0.361 - 0.599
$Y = 0.1932X + 2.3343$	0.599 - 1.479
$Y = 0.2219X + 2.2920$	1.479 - 2.380
$Y = -0.00097636X + 2.8223173$	2.380 - 12.650

T-1804



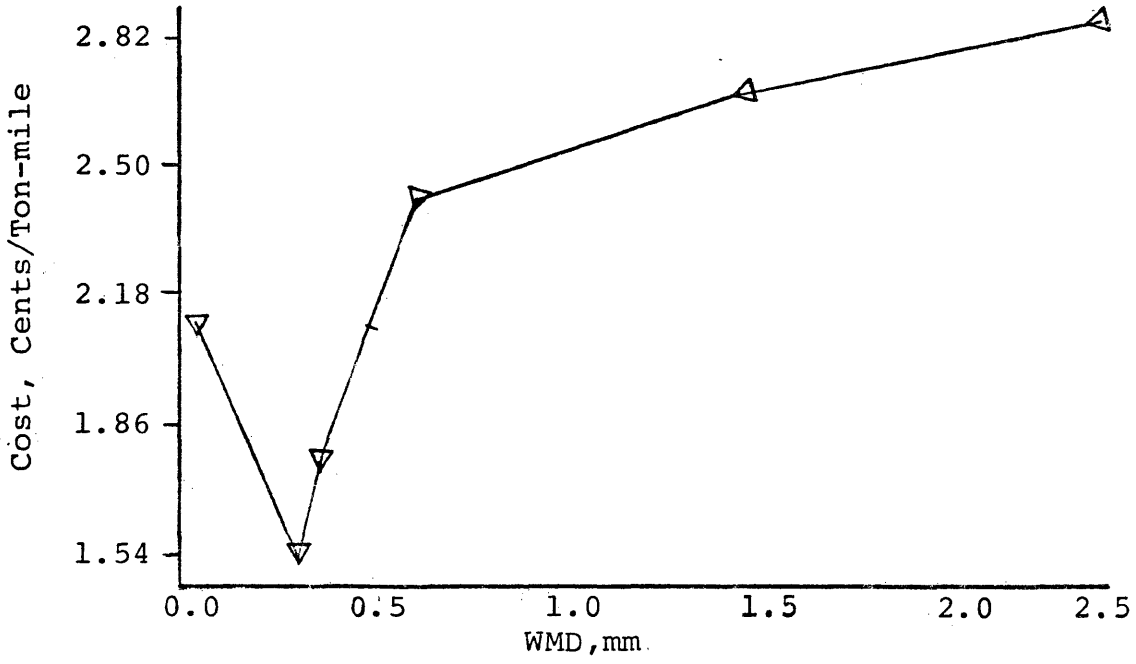


Fig. 4 - Cost Curves for a 200-Mile Coal-Slurry Pipeline Transporting 300 tph.

Since these functions describe the cost curve best, they will be used later to compute the total coal-slurry transportation system's cost.

Coal-Slurry Separation (Dewatering)

Table 11 shows the total cost of separation (dewatering) 300-thp coal slurry for different coals and screen analyses. In order to be consistent with coal-slurry preparation and pipeline transportation costs, the total coal-slurry separation cost (Table 11) has to be in cents per ton mile for the 200-mile pipeline specified for this study. These costs are shown below.

Coal-Particle Size-WMD, mm	Total Cost-Cents/Ton-Mile[1]
12.524	0.0976
5.162	0.1110
2.380	0.1328
1.479	0.1458
0.599	0.2265
0.361	0.2385
0.327	0.2459

The total coal-slurry separation cost for each of these coal slurries was plotted against the WMD of the coal-screen analysis and is shown in the top curve in Figure 5.

From the top curve in Figure 5 the bottom curve was developed to define the cost function. This curve has a least squares equation in the form of $Y = 0.107/\sqrt{X} + 0.06562$, where Y is the coal-slurry separation or dewatering cost, and

1. Total cost from Table 11 divided by 200 miles.

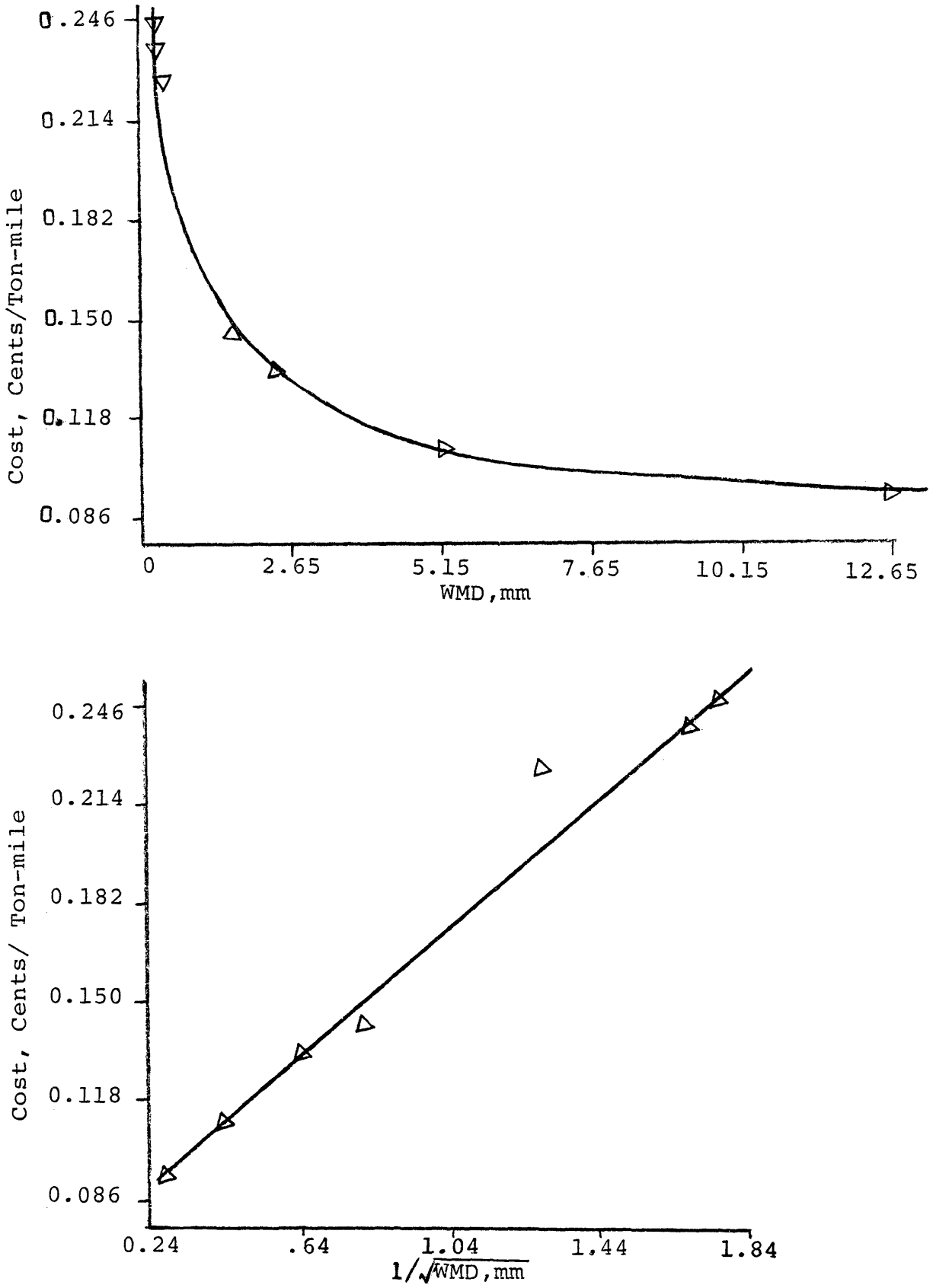


Fig. 5 - Cost Curve and Function for Coal-Slurry Separation for 200-Mile Line and 300 tph.

X is the coal's WMD. This equation has a correlation coefficient of 0.987. Since this function has a good correlation coefficient, it will be used to describe the slurry-separation cost curve. At a WMD above 5 mm, separation costs tend to level out.

Total Coal-Slurry Transportation System

A cost equation for the total slurry transportation system of slurry preparation, pipeline transportation, and slurry separation can now be determined. This equation is simply the addition of the cost equation for each of the slurry system's components (slurry preparation, pipeline transportation, and slurry separation), and is shown below.

For WMD range $0.0607 \leq X \leq 0.330$ mm

$$TC = \frac{0.0122592}{X} - 2.0052 + \sqrt{\frac{0.107}{X}} + 2.366$$

For WMD range $0.330 \leq X \leq 0.361$ mm

$$TC = \frac{0.0122592}{X} + 8.7097X + \sqrt{\frac{0.107}{X}} - 1.17$$

For WMD range $0.361 \leq X \leq 0.599$ mm

$$TC = \frac{0.0122592}{X} + 2.647X + \sqrt{\frac{0.107}{X}} + 1.0184$$

For WMD range $0.599 \leq X \leq 1.479$ mm

$$TC = \frac{0.0122592}{X} + 0.1932X + \sqrt{\frac{0.107}{X}} + 2.4883$$

For WMD range of $1.479 \text{ mm} \leq X \leq 2.380$

$$TC = \frac{0.0122592}{X} + 0.2219755X + \sqrt{\frac{0.107}{X}} + 2.446$$

For WMD range $2.380 \leq X \leq 12.650$ mm

$$TC = \frac{0.0122592}{X} - 0.0009736X + \sqrt{\frac{0.107}{X}} + 2.9763$$

where,

TC = total cost of the slurry transportation system--slurry preparation, pipeline transportation, and slurry separation in cents per ton mile for a 200-mile line and 300-tph capacity,

X = coal-particle size - weighted mean diameter, mm.

RESULTS

The optimal particle-size distribution, WMD, for coal-slurry pipeline, can be determined analytically and/or graphically. Each of these approaches will be discussed briefly. The latter part of the chapter is a comprehensive discussion of these results.

Analytical Solution

The optimal particle-size distribution, WMD, can be determined analytically by the use of calculus. For any mathematical function, f(X), the following steps are followed to determine the minimum and/or maximum points of the function. Find the first derivative (f'(X)) of the function; set it equal to zero, and solve the resulting equation for real roots in order to find the critical values of the variable. Find the second derivative (f"(X)); substitute each critical value for the variable in the second derivative. If the result is negative then the function is a maximum for that critical value; if the result is positive, the function is a minimum for that critical value. When f"(Xo) = 0, or does not exist, the above process does not apply, although a minimum or a maximum may exist, in which case, one critical value should be considered at a time. The first

derivative should be tested first for a value which is a little less and then for a value which is a little greater than the critical value. If the sign of the derivative is first positive and then negative, the function has a maximum value for that particular critical value of the variable; but if the reverse is true, then it has minimum value. If the sign does not change, the function has neither.

From Table 13 the lowest minimum and the highest maximum are then used to define the minimum and maximum cost. The minimum appears to be at a WMD of 0.330 and has a total cost of 1.9215 cents per ton mile; the maximum appears to be at a WMD of 2.380 and has a total cost of 3.04636 cents per ton-mile.

Table 13. The Value of Minimum and Maximum For Different Intervals of WMD

Interval of X, mm	X, mm	Maximum	Minimum
$0.0607 \leq X \leq 0.330$	0.0607	2.827525	-
	0.330	-	1.9215
$0.330 \leq X \leq 0.361$	0.330	-	1.9215
	0.361	2.1808	-
$0.361 \leq X \leq 0.599$	0.361	-	2.1808
	0.599	2.7855	-
$0.599 \leq X \leq 1.479$	0.599	-	2.7855
	1.479	2.8625	-
$1.479 \leq X \leq 2.380$	1.479	-	2.9625
	2.380	3.04636	-
$2.380 \leq X \leq 12.650$	2.380	3.04636	-
	12.650	-	2.9952

Graphical Solution

The graphical solution includes:

1. summation of the three costs of the total coal-slurry pipeline transportation system-preparation, pipeline transportation and separation, for the same particle-size distribution, WMD,
2. plotting the total cost versus the coal-particle-size distribution, WMD, and developing the total cost curve, and
3. determining the optimal coal-particle-size distribution, WMD, from the total cost curve. This is the WMD that corresponds to the lowest cost on the total cost curve.

In order to develop the total cost curve, the total coal-slurry transportation system cost functions shown in the previous chapter were used to predict the costs for different coal-particle-size distributions, WMD. Some of these costs are shown in Table 14. These and some other calculated values are shown in Figure 6. The top curve in Figure 6 shows the range of WMD from 0.0607 to 12.650 mm. The bottom curve shows the WMD range from 0.0607 to 2.380 mm and has a different scale. The bottom curve was constructed to illustrate the optimal WMD more clearly.

Table 14. Total Cost of Coal-Slurry Transportation System of 200 Miles and 300 tph Capacity in Cents/Ton-Mile[1].

Particle Size WMD mm	Preparation	Pipeline Transportation	Separation	Total
12.650	0.089 (0.089)	2.81 (2.81)	0.096 (0.098)	3.00
4.763	0.091 (0.091)	2.82	0.115	3.03
2.380	0.094	2.82 (2.88)	0.135 (0.133)	3.15
1.480	0.097	2.62 (2.62)	0.153 (0.146)	2.86
1.000	0.101	2.53	0.173	2.80
0.599	0.110 (0.111)	2.45 (2.45)	0.210 (0.227)	2.79
0.361	0.122	1.82 (1.82)	0.244 (0.239)	2.18
0.330	0.126	1.55 (1.55)	0.246 (0.246)	1.92
0.248	0.138 (0.136)	1.72	0.280	2.14
0.150	0.170	1.91	0.342	2.42
0.061	0.238	2.09 (2.09)	0.500	2.83

1. Costs in this table are calculated from the total cost equations. Costs in parenthesis are the observed (original) costs.

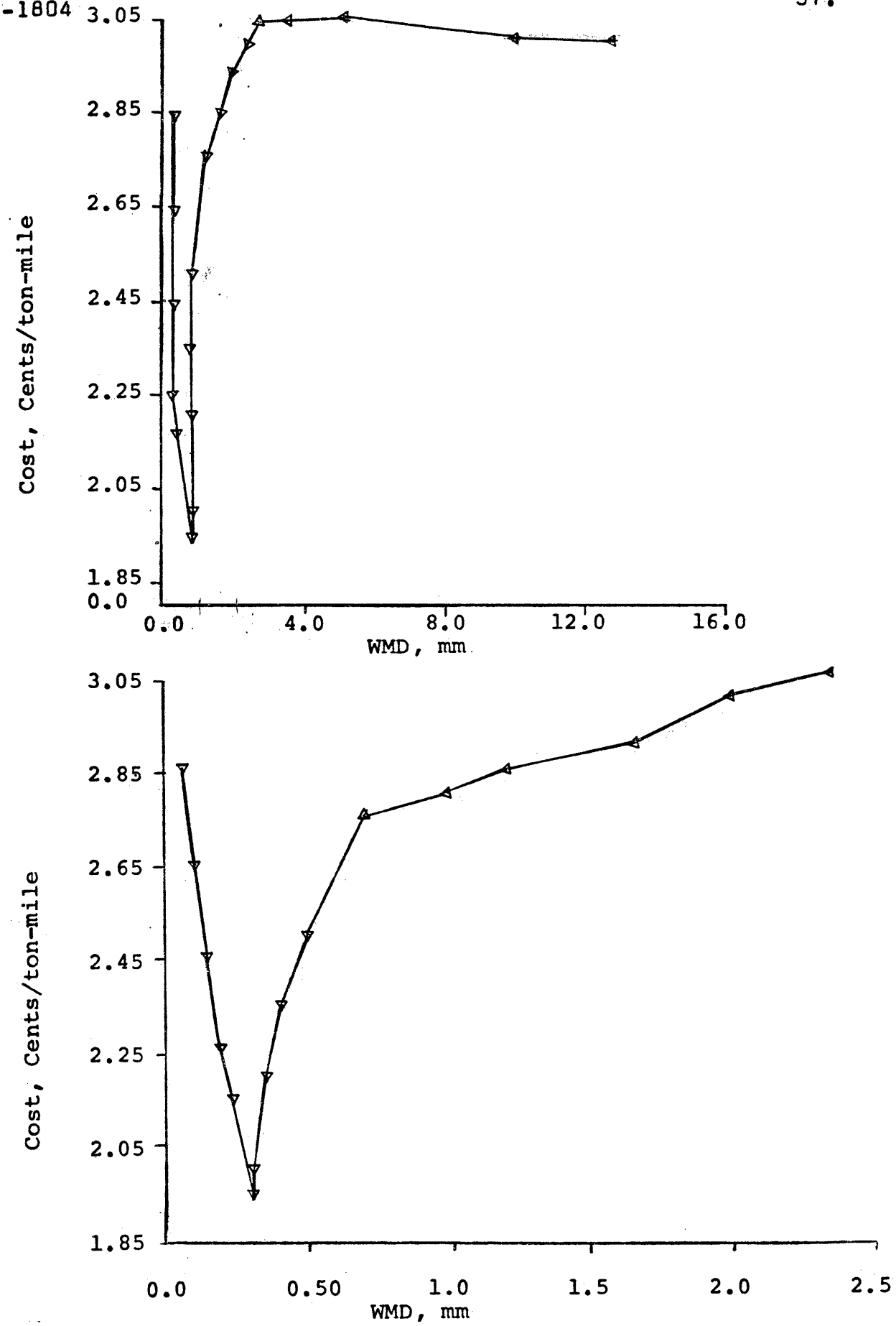


Fig. 6 - Total Cost of Coal-Slurry Pipeline Transportation System for a 200-mile line and 300 tph capacity.

Interpretation

From Figure 6, the high cost shown on the left side of the curve for a WMD smaller than 0.330 mm (between 42 mesh and 48 mesh) is explained by the fact that slurries with excessive fines form a highly viscous slurry which behaves like a mud or paste, making it more difficult to pump and requiring higher pumping costs.

From Table 13 and Figure 6, the optimum particle-size distribution, WMD, occurs at a WMD of 0.330 mm. This is shown by the minimum point in Figure 6, and by the lowest total cost in Table 13--1.9215 cents per ton-mile.

The maximum total coal-slurry transportation cost in Table 13 and Figure 6 occurs at a WMD of 2.380 mm (approximately 8 mesh) with a total cost of 3.05 cents/ton-mile. This cost is higher than the total coal-slurry transportation cost for the coarser screen analysis (with a WMD of 12.650 mm), which is 3.00 cents/ton-mile. This discrepancy can be attributed to the lower slurry concentration used for the coarse screen analysis (with WMD of 12.650 mm), which is 40 percent by weight, while the slurry concentration for the finer screen analysis (with WMD of 2.380 mm) is 45 percent by weight.

The WMD of 0.330 mm was found to be the optimal because the total cost curve, Figure 6, lacks data points between

the 0.330-mm and 0.0607-mm region. There is no way at this time to obtain a screen analysis that has a WMD between the 0.330-mm and 0.0607-mm region. The WMD of 0.330 mm is to be considered the optimal WMD for this case study because of the unavailability of data. The true optimum could be on either side of the chosen WMD of 0.330 mm.

The next value to the right of WMD of 0.330 mm is at a WMD of 0.361, which is about 9.4 percent higher (larger). This means that the optimum generally cannot be greater than 0.361 but could be anywhere in between 1 to 9 percent higher than the optimal WMD of 0.330 mm. Investigating the left side of the chosen optimal WMD of 0.330 mm gives a large range of values since there is no coal-screen analysis with pipeline data available at this time that has a WMD between 0.330 mm and 0.0607 mm. The true optimum could lay anywhere in between that in a range between 1 and 80 percent smaller or to the left of the calculated WMD, 0.330 mm. It is emphasized that more data are needed to investigate this section of the curve. However, the purpose of this study is to show that the technique is viable, that it works. Once the technique is developed, the input data can be modified to handle the details on specific cases.

Moreover, the Black Mesa coal-slurry pipeline (the only operating coal-slurry pipeline in the U.S. which transports

about 5 million tons of coal per year from Kayenta, Arizona, to the Mohave power plant in southwestern Nevada, a distance of 273 miles, has a WMD of 0.283 mm (25), which lies to the only left of the calculated optimal WMD of 0.330 mm and is about 14 percent smaller.

The reason for comparing the results of the study with the Black Mesa pipeline system are twofold: (1) It is the only existing long-distance coal-slurry pipeline and (2) its WMD compares favorably with the results developed in this study. The latter may be only coincidental because the present study uses only half the throughput of the Black Mesa pipeline, and no topographical gradients were assumed in the 200-mile distance.

Whether the optimal particle-size distribution, WMD, will be locked between 0.283 and 0.330 the author does not know. But knowing the Black Mesa's WMD supports the hypothesis that the optimal particle-size distribution is not greater than a WMD of 0.361 mm and is not less than a WMD of 0.0607 mm.

This study brings up the following two questions:

1. Once the optimal WMD is determined, how can the coal-particle-size distribution screen analysis be obtained?
2. After determining the coal-particle-size distribution screen analysis, can this screen analysis

be obtained physically? If yes, how?

Coal-particle-size distribution screen analysis for the optimal WMD can be obtained in two ways, depending on the WMD.

The first is the case where the optimal WMD happens to be at a point where there is a corresponding coal-screen analysis, as in the case study discussed in this thesis, where the optimal WMD happens to be at 0.330 mm, which corresponds to a given coal with a given particle-size distribution (screen analysis). This screen analysis is shown in Table 15. This happened because of the limited input data that forced a linear interpolation between this point and the one preceding, WMD, of 0.0607 mm in the cost curve in Figure 6.

The second is the case where the optimal WMD happens to be at a point where there is no corresponding screen analysis. The procedure then is to develop a screen analysis by trial and error that corresponds closely to the optimal WMD. For example, if the optimal WMD happens to be to the right or the left of the WMD of 0.330 mm (coarser or finer) shown in this study, the trial-and-error method suggests starting with the screen analysis that corresponds to the WMD of 0.330 mm as a basis, and using successive analysis as a guide to develop a screen analysis that corresponds to the optimal WMD. It may not be a very accurate screen analysis,

Table 15. Suggested Optimal[1] Coal Size Distribution Screen Analysis

Inch/Tyler Mesh			Percent
0.1	x	8	0.16
8	x	10	0.56
10	x	14	4.42
14	x	20	3.78
20	x	28	8.56
28	x	35	10.38
35	x	48	11.30
48	x	65	9.52
65	x	100	8.18
100	x	150	7.12
540	x	200	5.54
200	x	325	5.54
325	x	pan	24.94
			100.00

1. This screen analysis has a weighted mean diameter of 0.330 mm (0.01299-inch, between 42- and 48-mesh).

but it would be close. Since there could be more than one screen analysis that had the same WMD, common sense and experience must be used.

In addition, special attention should be paid to the amount (percent) of coal fines (passing through 325-mesh screen) in the assumed screen analysis. One must make sure that the amount of coal fines should be at least consistent with the coarser and finer given screen analyses that correspond to these WMD's, that screen analysis is the optimum one.

Now that an optimum coal-particle-size distribution (screen analysis) is available, can this exact optimal screen analysis be obtained physically? The answer is "No", because the coal-particle-size distribution screen analysis is dependent on (1) the method of crushing and grinding of coal, (2) the type of reduction equipment used, (3) the kind of coal used, and (4) the moisture, chemical, and ash content of the coal. Even the same coal from different seams will grind differently; therefore, there is no way of obtaining the exact screen analysis. However, a close screen analysis may be obtained by experimental work done at pilot plants owned by producers of coal-crushing equipment. Usually the coal operator sends samples of his coal and the optimal screen analysis to these companies. The companies in turn

determine the equipment that gives a close screen analysis to the optimum one. This is as close as is humanly possible to get.

In summary, the technique described is viable, and it works. It may be applied for short and long distance horizontal pipelines, and for vertical coal transportation from underground mining.

It is not limited to coal, it may be applied to any other mineral such as oil shale, copper and nickel ores, sand and gravels, and many other minerals to be transported by pipeline.

The technique could be used for any capacity and pipeline lengths; the optimum particle-size distribution may change, but the technique will not. The technique has only one noticeable limitation: it does not determine the exact particle-size distribution screen analysis, but it is close enough.

The technique will serve as a design tool for future coal-slurry pipelines for any capacity and any pipeline length. A step by step recap of the technique follows.

Step 1. Determine the throughput or capacity of the mineral to be transported by estimating the production and the market requirements.

Step 2. Determine the distance (length) and topography of the land by tracing the route the

pipeline will take from the starting location to destination. Slurry pipelines are sometimes limited to a 15 percent grade (50).

Step 3. Obtain cost of slurry preparation for the above determined capacity for different particle size distributions by

a. contacting slurry-preparation equipment manufacturers, along with cost and engineering texts and journals, or

b. consulting with experts in the field.

Step 4. Determine pipeline transporation costs by consulting Lavingia's thesis (18) and experts in the field of hydraulic transport.

Step 5. Determine mineral-slurry separation or dewatering cost for different particle size distributions by

a. contacting slurry-separation equipment manufacturers, along with cost and engineering texts and journals, or

b. consulting with experts in the field.

Step 6. From the costs obtained for slurry preparation pipeline transportation, and slurry deqatering, construct cost curves versus "particle-size distribution" measures. The "weighted

mean diameter" measure is recommended.

Step 7. From the cost curve, determine cost equations for each component of the slurry transporation system. The least-square method is recommended.

Step 8. Sum the above-mentioned cost equations and call it the total slurry transportation cost equation.

Step 9. Determine the optimum total cost of the slurry pipeline transportation system by the following methods:

a. Analytically by using calculus and determining the minimum cost, and

b. graphically by projecting the total cost of the slurry pipeline system for different particle-size measures (WMD's) and plotting these costs against the WMD's used. From the curve the minimum cost can be seen and determined. This cost corresponds to the optimum particle-size measure, which represents a screen analysis.

Step 10. From the optimum WMD, determine an optimum particle-size distribution (screen analysis) by following these steps.

a. Start with a WMD that corresponds to a

known screen analysis and is close to the optimum WMD. Use that as a base to determine an <u>assumed</u> screen analysis.

b. From the <u>assumed</u> screen analysis determine a WMD by using equation (1),

$$WMD = \frac{\sum_{i=1}^{n} di Wi,}{100}$$

in the text:

c. Check the calculated WMD with the optimum one. If it is the same or reasonably close, stop and go on to Step 11. If it is not close, make adjustment to the <u>assumed</u> screen analysis and repeat part b. of Step 10.

d. Repeat part c until the WMD of the <u>assumed</u> screen analysis is reasonably close or the same as the optimum WMD. This is the <u>assumed optimum</u> screen analysis. Here, special attention should be paid to "weight percent of the fines" (passing through 325-mesh screen size) in the <u>assumed</u> screen analysis. Note that the amount of fines in the <u>assumed optimum</u> screen analysis should

be consistent with the base screen analysis used in part a of this step.

Step 11. Once the optimum particle-size distribution (screen analysis) is determined, samples of the mineral (in this case coal) and copies of the assumed optimum screen analysis should be sent to various manufacturers of material-handling equipment for testing in their pilot plants. The manufacturers then would recommend the optimum equipment (crushers and/or grinders) that would give a close particle-size distribution (screen analysis) to the assumed optimum one.

CONCLUSIONS AND RECOMMENDATIONS

Based on the specific case used in this study a set of conclusions, recommendations, and limitations were developed.

Conclusions

A technique that determines the optimal particle-size distribution for coal-slurry pipelines has been developed and has been proven to be viable and was shown by the case study to work, both analytically and graphically. However, the accuracy of the results is strictly dependent on the quantity and quality of data used to develop the mathematical cost function for each of the pipeline transportation system components.

For the specific case used in this study, a coal-slurry pipeline delivering 2.376 million tons of coal per year a distance of 200 miles, the following conclusions may be drawn.

1. The optimal coal-particle-size distribution (represented by the weighted mean diameter) is 0.330 mm (0.01299-inch) or between 42 and 48 mesh, but closer to 42 mesh. Based on this weighted mean diameter, a suggested coal-particle-size distribution (screen analysis) was shown earlier in Table 15.

2. Based on the above optimal coal-particle-size distribution, the total annual cost of the coal-slurry transportation system in December 1975 was $9,130,787, or 1.9220 cents per ton-mile. $596,670 or 0.126 cents per ton-mile is attributed to coal-slurry preparation; $7,365,600, or 1.55 cents per ton-mile is attributed to pipeline transportation; and $1,168,517 or 0.246 cents per ton-mile is attributed to coal-slurry separation or dewatering.
3. Coal-slurry preparation cost contributed an average of 3.2 percent of the total cost for coarse coal weighted mean diameter range between 1 and 12.650 mm (1/2) inch), and an average of 6 percent of the total cost for fine coal weighted mean diameter range between 0.7 and 0.06 mm.
4. Pipeline transportation cost contributed an average of 92.5 percent of the total cost for coarse coal weighted mean diameter range between 1 and 12.650 mm (1/2 inch), and an average of 81 percent of the total cost for fine coal weighted mean diameter range between 0.7 and 0.06 mm.
5. Coal-slurry separation or dewatering cost contributed an average of 4.3 percent of the total cost for

coarse coal weighted mean diameter range between 1 and 12.650 mm (1/2 inch), and an average of 13 percent of the total cost for fine coal weighted mean diameter range between 0.7 and 0.06 mm.

6. Nonlinear curve fitting of the total pipeline transportation cost curve may result in an optimum particle-size distribution, WMD, either 9 percent higher or 1 to 80 percent lower than the one depicted in this study. Therefore, it is concluded that the optimum particle-size distribution occurs between the weighted mean diameter of 0.061 mm (65 mesh) and 0.361 mm (42 mesh).
7. Coal-slurry preparation costs increase with decreasing coal-particle-size distribution (represented by the weighted mean diameter of the coal screen analysis), and decreases with an increase in the weighted mean diameter. This is true because the power and capital cost requirements for crushing and grinding increase with a decrease in product sizes.
8. Coal-slurry transportation costs decrease with decreasing coal-particle-size distribution (represented by the weighted mean diameter of the coal screen analysis), up to a certain weighted mean diameter, where the slurry has excess fines,

resulting in a high viscosity and higher pumping costs than slurries with fewer fines.

9. Coal-slurry separation or dewatering costs decrease with increasing coal-particle-size distribution (represented by the weighted mean diameter of the coal screen analysis). This inverse relationship is explained by the fact that fine coals require filters and thermal dryers that increase capital and operating costs.

Recommendations

Because of the potential use of the tool outlined earlier in this study, research should be continued in the following areas:

1. For more accurate optimal particle-size distributions for the case study described in this study, more pipeline data are needed between a weighted mean diameter of 0.0607 mm and 0.330 mm, in order to define properly the curve between these two points.
2. Further work can be done to demonstrate the effect of changing the pipeline throughput (capacity) and pipeline length on the optimal particle-size distribution. Such further work would result in a library of optimum-size distributions for any

combination of pipeline throughput (capacity) and length.

Limitations

This study revealed two noticeable limitations. The first is that the author ignored the cost of water for slurry because of the assumption that any time a coal-slurry pipeline is considered, water is available and the water at the terminus of the pipeline is used for cooling in the power plant to which the pipeline is delivering the slurry.

The second is that the author treated an assumed WMD for coal-slurry preparation, (which was calculated by halving the top size of the selected screen analyses), the same as the real or calculated WMD used for the coal-slurry pipeline transportation and separation (dewatering), analyses. This is a fair assumption at this time because the author is concerned with the viability and the workability of the technique. Once the technique has been proved to work, it could be used for better input data which will result in a more accurate answer. The author also assumed a horizontal pipeline and ignored topography.

APPENDIX A

The following is a summary of the current status of the art of synthetic fuels from coal. Table 16 summarizes available coal gasification. Table 17 summarizes available coal liquefaction processes.

Table 16. Coal Gasification Processes

Process	Group	Coal Size	Moisture Content %	Stage
Atgas	Applied Technology Group	(-1/8-in.)	4 %	Continuous small scale test facility
Bigas	Bituminous Coal Research Inc.	(70% through 200-mesh)	dried	Advanced pilot plant stage
CO_2 Acceptor	Consolidation Coal Co.	crushed	NA[1.]	Advanced pilot plant
Hygas	Institute of Gas Technology	crushed	dried	75-ton/day pilot plant in operation-prelim. demonstration plant (80 million cfd) design is complete
Hydiane	U.S. Bur. of Mines	pulverized	NA	Initial pilot plant-planned scale up pilot plant
Lurgi	Lurgi mineral at Technik G.M.B.T.	crushed	dried	14 industrial plants are in operation
Koopers-Totzek	Heinrich Koopers G.M.B.H. of Essen	(70% through 200-mesh)	dried	15 plants in operation since 1952
Molten Salt	M.W. Kellog Co.	12-mesh	dried	Advanced testing stage
Synthane	U.S. Bur. of Mines	crushed	dried	70 ton/day pilot plant has been constructed

Table 16. Continued

U-Gas	Inst. of Gas Technology	crushed	dried	Demonstration size facility is underway
Union	Chemical Construction Corp. (Chemico)	-35-mesh	dried	25-ton/day pilot plant is being constructed
Westinghouse	Westinghouse Research Labs.	(1/8-1/4in)	dried	14.4-ton/day pilot plant is being built
Wellman - Galusha	Wellman Engineering Co.	(3/16-5/16in)	dried	2 units have been operating commercially in the U.S.
Winkler	Davy Powergas Inc.	(0-3/8in)	dried	16 industrial plants are in operation - produce low BTU gas

1. N.A. = Not available

Source: Bodle and Vyas (26)

Table 17. Coal Liquefaction Processes

Process	Group	Coal Size	Moisture & Content	Stage
COED	FMC Corp.	1/8-in.	dried	36-ton/day pilot plant has been operating
Fischer-Tropsh	M S. Kellog Co. & Arge. Arbeit Germeinshoft Lurgi & Ruhrchemis	3/8-in to 1/2-in.	dried	Sasol plant 6600/tons/day has been operating since 1957 in S. Afr.
Consol Synthetic Fuel (CSF)	Consolidation Coal Co.	(-14-mesh)	dried	Pilot plant has operated. Shut down for details.
Garret's Coal Pyrolysis	Garret R & D Co., Inc.	crushed	dried	3.6-ton/day pilot plant is in operation
H-Coal	Hydrocarbon Research Inc.	(-40-mesh)	dried	Operated on 3-ton/day pilot plant scale
Solvent Refined Coal (SRC)	Pittsburgh & Midway Coal Mining Co.	(-200-mesh)	dried	50-ton/day pilot plant is being built
Synthoil	U.S. Bur. of Mines	crushed	dried	Plan to construct a 5-ton/day pilot plant
Toscoal	Oil Shale Corp.	crushed	dried	25-ton/day pilot plant is in operation

Source: Bodle and Vyas (26).

APPENDIX B

The following brief discussion of coal-slurry preparation equipment is divided into two parts; the first briefly discusses each coal-slurry preparation equipment, and the second discusses coal-reduction equipment that is applicable to this study.

Coal-Slurry Preparation Equipment

Coal-slurry preparation equipment includes crushers, grinders, screens, dust collectors, conveyor belts, slurry tanks, meters and gauges, slurry pumps, and pipes. Each of these is discussed below.

Crushers and Grinders: Crushers and grinders are used to reduce coal to the size needed for pipelining.

Screens (dry or wet): Dry screens in a slurry preparation plant usually complement the crushers and grinders. Their purpose is to size the coal for further reduction or for slurry preparation.

Wet screens, or slurry screens in a coal-slurry preparation plant, are used to check the oversize particle size of the coal slurry.

Dust Collectors: The purpose of the dust collectors is to collect the fine particles that are produced from the

crushers, grinders, and conveyor belts during the coal reduction and transportation processes. These collectors eliminate explosions of fine particles and are usually equipped with fans.

Conveyor Belts: In coal-slurry preparation plants, conveyor belts are used to move dry coal from one part of the plant to another. In some plants these belts move coal from the crushers directly to the slurry mixing tank. In others, where wet grinding is available, these belts move coal from the crushers to the wet grinders.

Slurry Tanks: These tanks are used mainly either as mixing tanks or as slurry holding tanks, where the coal slurry is being held before it is pumped to the pipeline. The tanks are usually equipped with agitators to keep the coal particles in suspension.

Meters and Gauges: In coal-slurry preparation plants, the most common meters are weightometers and density meters. Weightometers, which are used to weigh the coal before it is mixed with the liquid carrier, water, are usually located at the conveyor belts before delivery to slurry mixing tanks, or before delivery to the rod mills (in case of wet grinding). Density meters, or gauges, are used to read the density of the coal-slurry and to monitor the coal concentration in the slurry before the slurry is sent to the pipeline. Usually,

these meters are mounted on the pump-discharge line that delivers the coal slurry to the slurry holding tank (see Figure 1).

Automatic Slurry Samplers: The slurry sampler to be used in this study is a self-contained unit designed specifically for secondary sampling of slurries. Samples are sent to the laboratory for immediate analysis of size content and solids concentration of the slurry.

Plant Pumps: In coal-slurry preparation plants, there are usually water pumps and slurry pumps. Water pumps are used to pump the water to be mixed with the dry coal to form the coal slurry. Slurry pumps are used to pump the coal slurry formed from the slurry surge tanks to slurry screens and from the slurry holding tanks to feed the pipeline pumps. Plant pumps are usually centrifugal pumps.

Motors: Motors used on crushers, grinders, agitators, and pumps are usually supplied with the equipment, or purchased separately.

Coal-Reduction Equipment

The following is a description of the reduction process for this case study. In this section when a manufacturer of coal-reduction equipment is mentioned, there is no implication that this specific equipment is recommended; it implies only that the manufacturer was cooperative in giving the cost

of the equipment.

Reduction of Coal to 95 Percent Passing Through a 1-inch Screen Opening: This reduction is accomplished by the use of a Williams reversible impactor size 350 (27). This impactor is able to reduce up to 315 tph of 8-inch feed coal to 95 percent passing through a 1-inch screen opening in one pass. The impactor requires a 200-hp motor.

Reduction of Coal to 95 to 100 Percent Passing Through a 0.75-inch Screen Opening: Run-of-mine coal is fed to a standard-duty Gundlach roll crusher, model 70 DA (28), which can accept coal feed up to 16 by 69 inches. This machine can crush up to 295 tons of coal per hour to 95 to 100 percent passing through a 0.75-inch screen opening in one pass. The machine requires a 150-hp motor.

Reduction of Coal to 95 to 100 Percent Passing Through a 0.375-inch Screen Opening: This reduction is accomplished by use of a Jeffrey Flextooth crusher, size 4266 (29), which is capable of crushing up to 300 tph of run-of-mine coal to 96 percent passing through a 0.375-inch screen opening in one pass. This machine requires a 300-hp motor.

Reduction of Coal to 95 Percent Passing Through a 0.25-inch Screen Opening: This reduction is accomplished by the use of a ring-type Gruendler hammer mill, model 3XE, size 4260 (30), which can reduce 16-inch coal to 95 percent

passing through a 0.25-inch screen opening at a capacity of 300 tph in one pass. This machine requires a 300-hp motor.

Reduction of Coal to 95 Percent Passing Through a 6-Mesh Screen Opening: In order to maintain 95 percent passing through 6-mesh screen, coal is introduced to a 50-inch Gundlach Cage Paktor (28), which will accept coal sizes up to 20 inches and crushes up to 333 tph of this size coal to 95 percent minus 6 mesh and about 80 percent minus 8 mesh. This machine requires a 250-hp motor.

Reduction of Coal to 95 Percent Passing Through 8-Mesh Screen Opening: To accomplish this, run-of-mine coal is first introduced into a standard Gundlach roll crusher, model 56DA (28), which has a capacity up to 400 tph and requires a 75-hp motor. This crusher reduces run-of-mine coal to pass through a 4-inch screen opening. The product is fed into Koppers Hammermill (31), with a capacity of 350 tph. The product of this machine is 95 percent passing through an 8-inch screen opening. This hammermill requires a 400-hp motor.

Reduction of Coal to Top Size of 14-, 16-, 20-, 30-, 35-Mesh: The grinding of coal to the above-mentioned sizes is accomplished first by the use of a Gundlach Cage Paktor, size 50-inch (28), which can crush 12- by 25-inch coal to about 95 percent passing through a 6-mesh screen opening. The Cage Paktor is capable of handling about 333 tph and requires a 250-hp motor. The product of the Cage Paktor is fed into a

Nordberg rod mill (32), which in turn will reduce coal to finer sizes by wet grinding. The Nordberg rod mill has different horsepower requirements for different levels of fineness. For the purpose of this study the above five sizes were used. The mill's horsepower requirements are summarized below.

100 Percent Passing Through	Nordberg Rod Mills Horsepower Requirement
14 mesh	450
16 mesh	600
20 mesh	900
30 mesh	1200
35 mesh	1500

Based on the above description of the size reduction equipment to be used, capital costs were obtained from the manufacturer and are shown in Appendix C.

APPENDIX C

This appendix briefly describes the coal-slurry preparation equipment and costs. Table 18 shows the reduction equipment discussed in Appendix B and corresponding capital costs. Table 19 shows all other miscellaneous coal-slurry preparation equipment and corresponding costs. Table 20 shows the total capital equipment cost. All of these costs are in December 1975 dollars.

Table 18. Capital Equipment Cost For 300 tph Coal Reduction

Reduction to 95 % Passing Through	Reduction Equipment and Cost	Motor & Drive, Plates Etc.	Total Cost
1 inch	Williams Resersible Impactor (27) $22,422	$ 7,500	$ 29,922
0.75 inch	S.D. Gundlach Roll Crusher, Model 70DA(28) $33,000	7,500	40,500
0.375 inch	Jeffrey Flextooth Crusher Size 4266 (29) $37,350	19,000	56,350
0.250 inch	Gruendler Hammer Mill (ring type) Model 5XE Size 4260 (30) $38,075	20,000	58,075
6 mesh	50" Gundlach Cage Paktor (28) $36,000	25,000	61,000
8 mesh	S.D. Gundlach Roll Crusher, Model 56DA, (28) $26,625	(Included)	26,626
	Koppers Hammermill, Model 917, (31) $80,000	25,000	105,000
14 mesh	50" Gundlach Cage Paktor (28) $36,000	25,000	
	Nordberg Rod Mill (32) $180,000	(450 hp motor included)	241,000

Table 18. Continued

16 mesh	50" Gundlach Cage Paktor (28) $36,000	$ 25,000	
	Nordberg Rod Mill (32) $240,000	(600-hp motor included)	$301,000
20 mesh	50" Gundlach Cage Paktor (28) $36,000	25,000	
	Nordberg Rod Mill (32) $360,000	(900-hp motor included)	421,000
30 mesh	50" Gunlach Cage Paktor (28) $36,000	25,000	
	Nordberg Rod Mill (32) $480,000	(1200-hp motor included)	541,000
35 mesh	50" Gundlach Cage Paktor (28) $36,000	25,000	
	Nordberg Rod Mill (32) $600,000	(1500-hp motor included)	661,000

Table 19. Miscellaneous Capital Equipment Cost For Slurry Preparation of 300 tph

Equipment	Remarks	Cost
Conveyor Belts	200 Ft. of 60-inch belt (33) 200 Ft. of 48-inch belt (33)	$ 50,000 48,000
Dust Collectors	2-Type R Roto-clone, American Air Filter (equipped with 400 cfm fan) (34)	24,516
Weightometer	1 - Compudyne (35)	5,000
Water Pump	2 - 6-inch Irrigation Centrifugal Pump (36)	22,328
Slurry Tanks	3 - Tanks 75 Ft-Diameter x 20 Ft. High, Capacity 600,000 Gal. (37)	137,586
Agitators	3 - Propeller Type, Equipped with Superstructure, Shaft and 125-hp Motor[1]. (38)	219,000
Density Meter	1 - Kay Ray Density Meter (39)	5,000
Slurry Pumps	2 - 8-inch, and 2 - 10-inch Wilfey Rubber Lined Centrifugal Pumps Equipped with 100-hp Westinghouse Motors	49,528
Slurry Screens	Syntron Single Deck Rotary Vibrating Screen, Size 5 Ft. Wide x 20 Ft. Long (28)	5,860

Table 19. Continued

Automatic Slurry Sampler	Denver Slurry Samplers (38)	$ 5,860
Plant Pipes	Plant Pipes are Usually Estimated as 10 Percent of the Installed Cost of Equipment	Shown Earlier
Total (Excluding Plant Pipe Cost)		$579,818

1. Only two are needed where Rod Mills are used.

Table 20. Total Capital Equipment Cost for 300-tph Coal-Slurry Preparation Plant

Reduction Size (Inches/Mesh)	Capital Equipment Cost, $ 1.
1 inch	609,740
0.750 inch	620,318
0.375 inch	636,168
0.250 inch	637,893
6 mesh	640,818
8 mesh	710,818
14 mesh	747,818
16 mesh	807,818
20 mesh	927,818
30 mesh	1,047,818
35 mesh	1,167,818

1. Tables 18 and 19.

APPENDIX D

PLANT DESIGN COSTS

Total estimated costs of a typical process plant include cost of equipment, installation, plant pipes, building and site development, engineering and construction, land, and various contingencies. Each of these costs is briefly discussed below.

Process Equipment

This cost includes expenditures for plant-process equipment, handling and storage equipment, gauges, and instruments. It is sometimes shown as f.o.b., or delivered cost.

Installation

The installation cost of equipment involves costs for labor, foundations, supports, platforms, chutes, gates, vents, insulation, installation-erection, and any other costs related to the erection of the purchased equipment.

Plant Piping Installation

The cost for piping covers labor, valves, fittings, pipe supports, and other items involved in the complete erection of all piping used directly in the plant. It includes water, air, sewer, and all other pipes used in the plant.

Buildings and Site Development

This cost includes fencing, grading, roads, sidewalks, landscaping, buildings, and all electrical installation. Building costs include labor, materials, and supplies involved in the erection of all buildings connected with the plant. It includes cost of plumbing, heating, ventilation, and electrical installation. Electrical installation includes power, wiring, lighting, and instrument-control wiring.

Engineering and Construction

This cost includes temporary construction, rental of equipment, field and home office, overhead, engineering design and drafting reproduction, communication, travel, taxes, and insurance.

Land

Land cost, which depends on the location of the property, may vary from one area to another. Land cost for industrial plants amounts to 4 to 8 percent of the purchased equipment cost.

Contingencies

Contingency costs are usually included in an estimate of plant costs to compensate for unpredictable events such as storms, floods, strikes, price changes, small design changes,

errors in estimation, and other unforseen expenses which previous estimates have shown statistically to be likely to occur. Table 21 shows each of these costs as a percent of purchased capital equipment cost.

Table 21. Plant Design Costs As a Percent of Purchased Equipment Cost

Cost Item	Percent of Purchase Equipment Cost
Process Equipment Purchase Cost	100
Installation Cost	43
Plant Piping Installation Cost	10
Building & Site Development Cost	50
Engineering & Construction Cost	57
Land Cost	6
Contingencies	23

Sources: (41, 42, 43)

APPENDIX E

The following is a list of the different coals and their screen analyses to be used in the pipeline transportation section and slurry separation section of this study.

Table 22a. Different Coals and Screen Analyses
Eastern Coarse Coal[1].
Specific Gravity-1.26

Inch & Tyler Mesh	Percent
1 5/8-in. x 1 1/2-in.	1.0
1 1/2-in. x 1-in.	9.2
1-in. x 3/4-in.	12.5
3/4-in. x 1/2-in.	17.3
1/2-in. x 3/4-in.	35.6
1/4-in. x 5M	1.4
5 x 10	8.8
10 x 16	4.0
16 x 20	2.2
20 x 30	1.3
30 x 50	2.1
50 x 100	1.5
100 x 200	1.1
200 x pan	2.0
	100.0

1. Source: U.S. Bureau of Mines (44)

Table 22b. Different Coals and Screen Analyses
Pennsylvania Coal[1].
Specific Gravity-1.30

Inches & Tyler Mesh			Percent
1.5-in.	x	1-in.	0.09
1-in.	x	3/4-in.	0.62
3/4-in.	x	1/2-in.	6.61
1/2-in.	x	3/8-in.	8.81
3/8-in.	x	3M	22.62
3M	x	6M	12.46
6M	x	10M	13.37
10M	x	16M	6.79
16M	x	20M	4.72
20M	x	48M	9.18
48M	x	100M	7.23
100M	x	200M	4.99
200M	x	pan	2.51
			100.00

1. Source: U.S. Bureau of Mines (44)

Note: This coal has no headloss data, it was used only in the Coal-Slurry Separation Section.

Table 22c. Different Coals and Screen Analyses
West Virginia Coal[1].
Specific Gravity-1.306

Inches & Tyler Mesh			Percent
0.525 in.	x	3M	8.41
3	x	6	18.37
6	x	12	16.86
12	x	20	13.75
20	x	42	7.28
42	x	65	9.10
65	x	150	6.85
150	x	200	2.89
200	x	pan	16.49
			100.00

1. Source: U.S. Bureau of Mines (45)

Table 22d. Different Coals and Screen Analyses
Pocahontas Seam Coal[1].
Specific Gravity-1.339

Inches & Tyler Mesh		Percent
3/8 in.	x 3M	0.06
3	x 4	3.44
4	x 6	7.17
6	x 8	12.39
8	x 10	13.85
10	x 14	11.40
14	x 20	8.41
20	x 28	6.78
29	x 35	5.01
35	x 48	4.53
48	x 65	3.41
65	x 100	3.45
100	x 150	2.73
150	x 200	2.15
200	x 270	1.53
270	x 325	0.90
325	x pan	12.79
		100.00

1. Source: U.S. Bureau of Mines (46)

Table 22e. Different Coals and Screen Analyses
Pocahontas Coal[1].
Specific Gravity-1.32

Inches & Tyler Mesh	Percent
0.090 in. x 14M	13.66
14 x 28	27.86
28 x 48	18.92
48 x 65	5.34
65 x 100	4.26
100 x 150	2.85
150 x 200	2.31
200 x 325	2.27
325 x pan	22.42
	100.00

1. Source: U.S. Bureau of Mines (47)

Table 22f. Different Coals and Screen Analyses
Western Canada C.N. Coal[1].
Specific Gravity-1.36

Inches & Tyler Mesh			Percent
0.093	x	10M	0.37
10M	x	14M	4.07
14	x	20	4.03
20	x	28	11.30
28	x	35	13.83
35	x	48	13.47
48	x	65	9.87
65	x	100	7.86
100	x	150	6.10
150	x	200	4.40
200	x	325	4.10
325	x	pan	20.60
			100.00

1. Source: S.R.C. (48)

Table 22g. Different Coals and Screen Analyses
Western Canada (Kaiser) Coal[1].
Specific Gravity-1.385

Inches & Tyler Mesh			Percent
0.1	X	8	0.16
8	x	10	0.56
10	x	14	4.42
14	x	20	3.78
20	x	28	8.56
28	x	35	10.38
35	x	48	11.30
48	x	65	9.52
65	x	100	8.18
100	x	150	7.12
150	x	200	5.54
200	x	325	5.54
325	x	pan	24.94
			100.00

1. Source: S.R.C. (48)

Table 22h. Different Coals and Screen Analyses
Eastern Fine Coal[1].
Specific Gravity-1.381

Inches & Tyler Mesh	Percent
80 x 100	1.50
100 x 200	30.00
200 x pan	68.50
	100.00

1. Source: Faddick (49)

APPENDIX F

HEADLOSS EQUATION(S) FOR HETEROGENEOUS SLURRIES

Since rheology laboratory equipment (viscometers) does not provide precise rheology data for slurries containing particles coarser than about 65 mesh (0.20 mm), pipeline loop studies are used to develop mathematical models for heterogeneous slurries.

For determining slurry friction losses for heterogeneous slurries, the following modified Durand's equation is used (50):

$$\phi = A\psi^{b}$$

where, $\phi = \frac{im-i}{C_v \cdot i}$

$$\psi = V_m^2 \frac{\sqrt{3 \cdot C_D / X}}{4(S-SL)/SL} \Big/ gD(S-SL)/SL$$

- im - the total friction loss of the mixture, ft. of slurry/ft. of pipe,
- i - the friction loss due to the vehicle, ft. of flowing fluid/ft. of pipe,
- C_v - the volumetric concentration of the solids, fraction,
- D - the pipe diameter, ft.,
- S - the specific gravity of the solids,

SL - the specific gravity of the liquid,

V_m - the velocity of the slurry, ft./sec.,

C_D - the drag coefficient of some representative particle size, dimensionless,

g - the acceleration of gravity, ft./sec.^{2},

X - the shape factor that deviates from a sphere, dimensionless,

A and b are, respectively, the intercept and the slope of the logarithmic plot of ϕ versus ψ in the headloss equation formulated by Durand (50).

Headloss Equations for Homogeneous Slurries

For homogeneous slurries, friction-loss calculations may be based on studies of the slurry rheology. According to Faddick (50), rheology is the study of the deformation of pseudo-liquids due to shearing. Several available mathematical models describe this deformation and are well explained by Govier and Ariz (51). According to these authors, many non-Newtonian homogeneous slurries can be defined by the general mathematical model

$$\tau - \tau_y = K\dot{\gamma}^n$$

where τ - the slurry shear stress, dynes/cm^2

τ_y - the slurry yield stress, dynes/cm^2

$\dot{\gamma}$ - the slurry shear rate, sec^{-1},

K - the slurry consistency index, dynes-sec^n/cm^2

n - the slurry flow behaviour index, dimensionless.

The generalized model reduces to simpler expressions for other rheological models as follows.

Newtonian Fluids	$\tau = u\dot{\gamma}$; (n=1.0, K=u)
Bingham Plastic Slurries	$\tau - \tau_y = K\dot{\gamma}$ (n=1.0)
Pseudoplastic Slurries	$\tau = K\dot{\gamma}^n$ (n<1.0)
Yield Pseudoplastic Slurries	$\tau - \tau_y = K\dot{\gamma}^n$ (n<1.0)

These models are shown in Figure 7.

To utilize any of the mathematical models shown above, laboratory measurements must be obtained from the slurry being examined. These measurements will provide data which yield values for τ_y, τ, $\dot{\gamma}$, K, and n. From these data the slurry Reynolds number may be determined; and then by means of a Moody diagram, the friction factor is determined. The friction factor is then used to compute the friction headloss by means of the Fanning equation,

$$H = f\frac{2L}{D}\frac{V^2}{g}$$

where f = friction factor, dimensionless,

H = friction loss, ft. of flowing fluid,

L = pipe length, ft.,

V = fluid velocity, ft/sec.,

D = pipe diameter, ft.,

g = acceleration of gravity, ft/sec^2.

Note: In this study, rheology data are expressed in SI units, whereas pipeline data will be expressed in English units.

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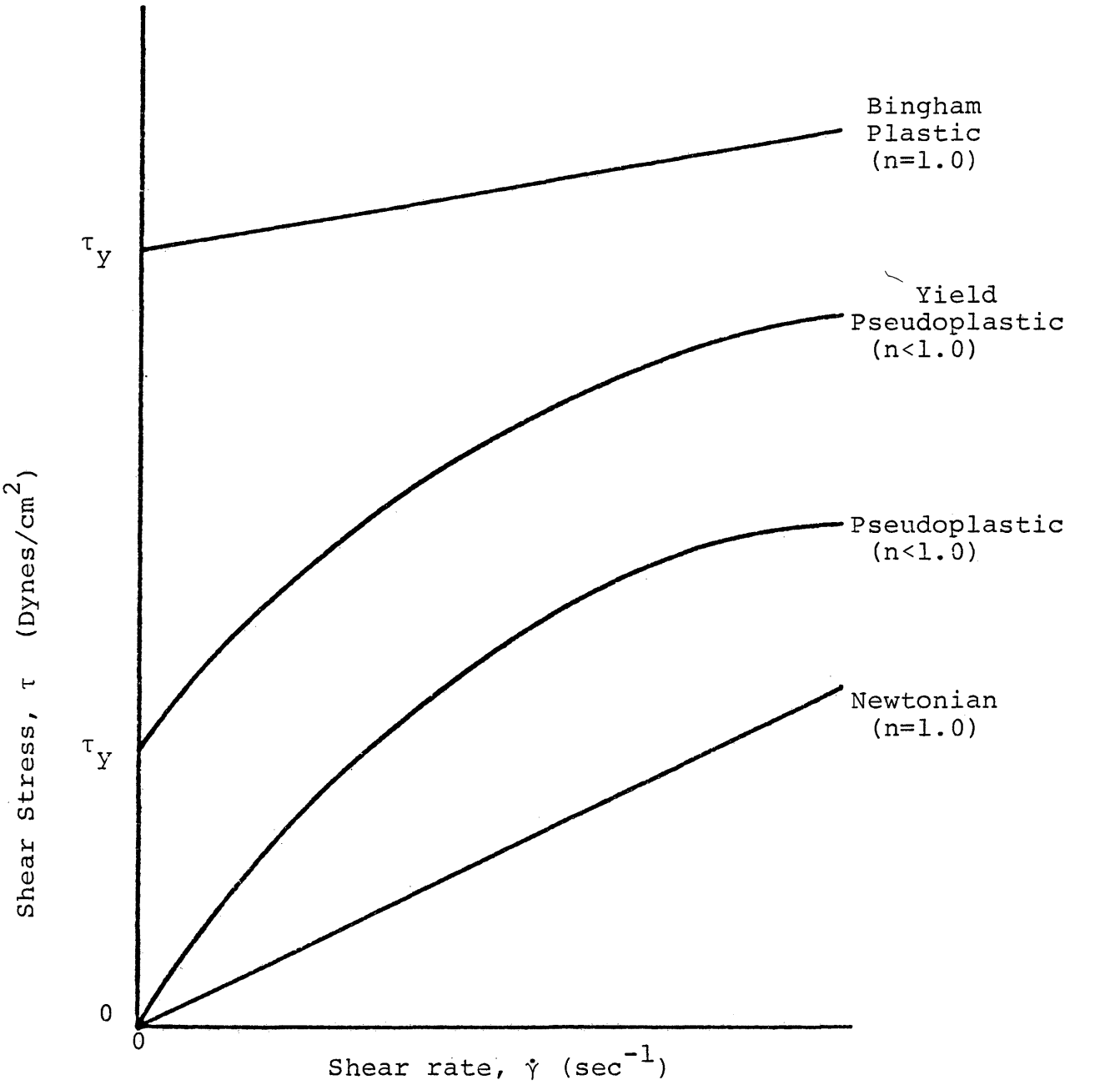

Fig. 7 - Flow curves for various types of time - Independent Fluids.

APPENDIX G

SEPARATION PROCESSES AND EQUIPMENT

The following is a brief description of the coal-slurry separation process and equipment to be used for each of the coals used in this study.

It should be noted that, when a manufacturer of coal-slurry separation equipment is mentioned, there is no implication that this specific equipment is recommended; it implies only that the manufacturer was cooperative in giving the cost of the equipment.

Separation Equipment for Coal No. 1 (Eastern Coal)

Coal-slurry received at 60-percent moisture is thickened by two Tabor vibrating dewatering screens to about 65-percent solids. The thickened slurry is fed into two CMI centrifugal dyrers (Model VC-48)($2). This dryer has a capacity of 170 tons per hour and recovers about 99 percent of this coal with a surface moisture of about 3 percent.

The remaining unrecovered coal, 1 percent (3 tph) of the coal is sent to a 10-ft -diameter thickener. The thickener recovers the remainder of the coal.

Separation Equipment for Coal No. 2 (Pennsylvania Coal)

This screen analysis is slightly finer than the previous one. Coal slurry is received at 60-percent moisture content and thickened as before to 65-percent solids by two Tabor vibrating dewatering screens. Because of the fineness of the coal, more drying capacity is required; therefore, three CMI vibrating centrifugal dryers (Model VC-48)(52) are required for further dewatering. These dryers will recover about 97 percent of this coal at a surface moisture content of 4 percent.

Separation Equipment for Coal No. 3 (West Virginia Coal)

Coal slurry is received at 55-percent moisture content and thickened by three Tabor vibrating dewatering screens to about 65-percent solids. The thickened slurry is introduced to five CMI continuous centrifugal dryers (Model EB-36)(52). This type of dryer develops a greater gravitational force because of its higher rpm. These dryers will recover about 90 percent of this coal at a surface moisture of about 5 percent.

The remaining 10 percent (30 tph) of the coal comes out with the effluent and is discharged into a 45-ft-diameter thickener, where it is thickened and mixed with the dried coal.

Separation Equipment for Coal No. 4 (Pocahontas Seam)

Coal slurry is received at 50-percent moisture content and is delivered to three Tabor vibrating dewatering screens to be thickened to 65-percent solids. Because this coal is finer than the previous ones, more drying capacity is required; therefore, six CMI continuous centrifugal dryers (Model EB-36)(52) are used to dewater the thickened slurry. Because of the fineness of the coal, only 85 percent of this coal will be recovered by these dryers, at a surface moisture of 6 to 7 percent.

The remaining 15 percent (45 tph) of the coal comes out with the effluent and is discharged to a 55-ft-diameter thickener, where it is thickened and mixed with the dry coal.

Separation Equipment for Coal No. 5 (Pocahontas Coal)

This coal is fine--more than 22 percent passes 325 mesh. This coal slurry is received at 50-percent moisture content and thickened by ten Bixby-Zimmer dewatering screens. The thickened slurry is fed into twelve CMI continuous centrifugal dryers (modified Model EB-36)(52), which dry fine coal (28 mesh x 0) and each of which has a capacity of 25 to 30 tph. Because of the fineness of this coal, these centrifugal dryers recover only 80 percent of this coal at a surface moisture of 13 percent.

The remaining 20 percent (60 tph) of the coal comes out with effluent and is discharged into a 60-ft-diameter

thickener. The coal is pumped from the thickener into two Eimco vacuum disc filters (53) for further dewatering. The size of these filters (12' x 6" x 15) means that the filter has 15 discs, each 12.5 ft. in diameter. This size filter has a capacity of 3,300 square feet of filtration area. These disc filters reduce the moisture content of coal and produce a cake containing 20 to 25 percent moisture.

Separation Equipment for Coal No. 6 (C. N. Coal)

This is also a fine coal but is slightly finer than coal No. 5. Coal slurry at 50-percent moisture content is thickened by twelve Bixby-Zimmer dewatering screens, and fed into twelve CMI modified continuous centrifugal dryers (modified Model EB-36)(52). These dryers recover only 78 percent of this coal (due to the fineness of the coal), at a surface moisture of 15 percent.

The remaining 22 percent (66 tph) of the coal is discharged with the effluent to a 70-ft-diameter thickener. The slurry from the thickener is then pumped into two Eimco Vacuum disc filters (size 12' x 6" x 15)(53) for further dewatering, which produces a coal cake having 20 to 25 percent moisture.

Separation Equipment for Coal No. 7 (Kaiser Coal)

This coal is still finer than that described above. The same equipment used for coal No. 6 is used for this coal.

Because this coal has about 25 percent passing 325 mesh, the centrifugal dryers will recover only 75 percent. The remaining 25 percent (75 tph) comes out with the effluent and is discharged into an 80-ft-diameter thickener.

The slurry from this thickener is pumped into three Eimco vacuum filters (12' x 6" x 15) and one (8' x 10" x 10) (53). The third filter is needed to cover for the extra 900 sq ft of filtration area.

A summary of the capital costs of the above-described equipment is shown in Table 23.

Miscellaneous Slurry Separation Equipment

In addition to the slurry separation equipment discussed above, other equipment such as slurry holding tanks and surge tanks, agitators, conveyor belts, pumps, and pipes are needed.

Slurry holding tanks, which are usually located at the terminal of the pipeline, are equipped with agitators to keep the coal particles in suspension. They hold the slurry until it is needed for dewatering. These tanks may vary in capacity, depending on the throughput of the pipeline and the number of hours of surge capacity needed for the tanks to deliver water to the dewatering plant if a problem is developed with the pipeline. In addition to these tanks, there is always an emergency storage pond. For example, the Mohave power plant at the terminal of the Black Mesa pipeline

Table 23. Capital Cost of Slurry Separation Equipment, December 1975

Coal	Screen & Cent. Dryers[1.]	Thickeners[2.]	Filters[2.]	Total
Coal No. 1 Eastern	$100,000	$12,000	$----	$112,000
Coal No. 2 Penn.	126,000	25,000	----	151,000
Coal No. 3 W. Va.	196,000	30,000	----	226,000
Coal No. 4 Poca. Seam	220,000	40,000	----	260,000
Coal No. 5 Poca.	442,000	45,000	350,000	837,000
Coal No. 6 W. Can. CN	460,000	50,000	350,000	860,000
Coal No. 7 W. Can. Kaiser	460,000	55,000	431,000	946,000

1. CMI (52)
2. Eimco (53)

has a 15-day emergency storage with a capacity of 90 million gallons. This emergency storage pond is a part of the power plant, and its cost does not enter into the slurry separation costs.

Slurry surge tanks receive coal slurry from the pipeline or from the holding tank and deliver it to the dewatering equipment. The tanks are equipped with an agitator to keep the coal particles in suspension.

Conveyor belts are used to transport the coal from the centrifugal dryers and filters to a storage area near the power-plant boilers.

Centrifugal slurry pumps, in a coal-slurry dewatering plant, are usually used to pump coal slurry, effluent, and thickened slurry in the following areas of the plant:

1. coal slurry from slurry dump tank to slurry holding tank,
2. coal slurry from the coal-slurry surge tanks to dewatering screens and centrifugal dryers,
3. the effluent from the centrifugal dryers to the thickeners, and
4. the thickened fine slurry from the thickeners either to the disc filters or to the boilers in the power plant.

Based on the specified slurry concentration for this study (50% solids by weight), and the specified capacity (300 tph), centrifugal pumps of various sizes were selected to be used in this section.

Plant pipes include pipes of various sizes, elbows,

valves, and fittings. For this type of plant, pipes, elbows and fittings costs are usually 25 percent of the purchased costs (41).

This miscellaneous equipment and the capital costs are listed in Table 24. Table 25 shows the pump requirements and costs. The total capital investment costs for a coal-slurry separation (dewatering) plant with a 300-tph capacity for different coals were shown earlier in Table 10.

Based on these capital investment costs (Table 10) and the operating and maintenance costs, the total coal-slurry separation cost per ton was found for different coals. These costs were also shown earlier in Table 11.

Table 24. Miscellaneous Coal-Slurry Separation Equipment Cost For Dewatering 300 tph, December 1975

Equipment	Remarks	Cost
Slurry holding tanks	1 - 700,000-gal capacity 81' dia. x 20' ht. (37)	$ 49,783
Slurry supply tanks	1 - 600,000-gal capacity 75' dia. x 20' ht. (37)	45,862
Slurry agitators	2 - propeller-type, includes shaft, superstructure, and 125-hp motor (38)	146,000
Conveyor belts	100-ft 36" belts. For coals #5, 6, and 7, need extra 50' of 24" belts (33)	20,000 10,000
Pumps	Refer to Table 25	
Plant piping	Refer to Table 21	

Table 25. Coal-Slurry Separation Pump Requirements and Cost For Different Coals December 1975

Coal Number	Centrifugal Size (in.)	Pump Requirements Motor(hp)	Number[1].	Pump and Motor Cost
1	10	100	21	$ 77,142
	6	50	2	
	1½	5	2	77,142
2	10	100	4	
	6	50	2	
	2½	20	2	77,922
3	10	100	4	
	6	50	2	
	4	20	2	81,870
4	10	100	4	
	6	50	2	
	4	20	2	81,870
5	10	100	4	
	6	50	2	
	4	20	2	81,870
6	10	100	4	
	6	50	2	
	4	25	2	81,960
7	10	100	4	
	6	50	2	
	4	25	2	81,960

1. The number of pumps is doubled for spares.

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