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Water Requirement for Coal Slurry Transportation

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WATER REQUIREMENT FOR COAL SLURRY TRANSPORTATION

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ABSTRACT

The amount of water required for coal slurry transportation is a function of the coal properties and the magnitude of coal movement. The pipeline system chacteristics and the method of slurry preparation also affects the overall water requirement of the system. In the present study methodologies are developed based on reported and modified coal slurry flow correlation equations to determine the quantity of water needed under various coal transport and flow conditions. Auxiliary water requirements including start-up and flushing water storage; related evaporation and seepage losses are also included. A computer program and several monographs are presented to provide a quantitative estimation of water requirements for fine to coarse coal slurry transport. The results are useful to the slurry pipeline design engineers in providing essential information for state and local water allocation policy determination.

DESCRIPTORS: Water Demand*, Water Allocation*, Slurries*, Pipe Flow, Pipelines, Coal, Water Requirements*

IDENTIFIERS: Coal Slurry Pipelines, Coal Slurry Transportation, Coal Slurry Pipeline Design

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INTRODUCTION

The outlook of our nation's energy picture has been a topic of discussion since the early 1970's when the Arab oil embargo took place. The embargo lead us to realize the serious security vulnerability a nation too dependent upon imported oil as a major source of energy. The vast coal reserves in the United States are once again being considered as available energy source for domestic needs as well as for export. The availability of transportation systems that can economically serve the coal movement needs was therefore, investigated by many researchers in order to determine the feasibility of extended use of these vast coal reserves.

1.1 National Coal Utilization Outlook

It is estimated that the United States could operate on known coal reserves until the year 2280. Even with an increase in consumption the supply of coal from these reserves could last 200 years. Usage of these coal reserves would allow the United States to become less dependent upon imported oil. Based on the Federal Energy Administration (1976) scenarios, and extrapolation from the existing data, Decker (1978) presented an energy supply and demand projection to the year 2000 as shown in Table 1.1.

In Table 1.1, it can be seen that by the turn of the century the predicted use of coal as an energy source will increase from the current level by a factor of three plus. Coal will become a primary energy source which will supply 37% of the nation's energy needs by the year 2000. This represents an increase from today's figure of nineteen percent.

The intervention by the Federal Government gives another reason for increased coal utilization. Requirements were imposed on electric power plants to convert their boiler fuels from gas and oil to coal. The "United States requires that low sulfur fuels be used to the maximum extent practical where necessary to minimize adverse impacts on public health" (Reed,1976). These electric power plants are not always located where the coal is deposited or produced. This creates a complex transportation problem.

There are currently five transportation methods by which coal, or the energy derived from coal, can be transported. These methods include barge, rail, truck, pipeline, and electric power transmission. Each of these transportation methods has its advantages and application limits.

Barging, for example, is considered to be an energy efficient way of coal transportation but must have an adequate network of waterways and available facilities. Trucking is more suitable for short hauls and is not a very

Table 1.1 Energy Supply and Demand Project
in quads* per year (Decker, 1978)

FEA 1976 reference
scenario basis-imported oil price-
projection, to, $13/barrell, in 1975 dollars

Energy (1)	1974 (2)	1980 (3)	1985 (4)	1990 (5)	2000 (6)
(a) Energy Source					
Coal	13.2	15.7	20.6	25.9	50
Petroleum	33.5	35.6	41.5	50.0	40
Natural Gas	22.0	22.7	24.2	22.8	10
Nuclear	1.2	3.9	8.7	13.3	20
Geothermal/hydro-electric/solar	3.3	3.7	3.9	4.2	15
Total	73.2	81.6	98.9	116.2	135
(b) Energy Use					
Residential/commercial	13.9	12.7	14.8	16.6	19
Industrial	20.9	23.1	27.1	31.1	34
Transport.	18.4	20.1	23.2	25.3	26
Electrical gener.	20.0	25.7	33.7	42.9	53
Synthetics	-	-	0.1	0.2	3
Total	73.2	81.6	98.9	116.2	135

*quad = 10^{15} BTU

energy efficient system. Energy transportation by transmission of electric power generated at the coal source will require large quantities of cooling water at the coal mine where once-through open or recirculating water based systems are used. Besides, the power losses for long transmission systems can be extensive.

The limitations in rail transport capacity was analyzed by Buck(1978). By 1985, an estimated 18.6 million carloads of coal will be moved each year over an average distance of 430 miles. This increased coal transport traffic plus the railways usual commerce is projected to exceed the capacity of the system. The Vice President of Burlingtion Northern Railways estimated that this increase in rail traffic would triple their current car inventory. Rail tracks and facilities, reportedly, would be overloaded resulting in a circuitous routing of coal unit trains. Such a consequence could lead to additional costs in time and tariff.

1.2 Kentucky Coal Movement

Kentucky is the nation's largest coal producing state. A recent Geological Survey report indicated the State as having an estimated 40 billion ton coal reserve, which is equivalent to approximately 8 percent of the total coal reserves in the United States. In terms of coal production, in 1981 Kentucky provided 19.1 percent of the nation's output.

Since Kentucky retains, for its own use approximately 3.0 percent of the Eastern coal and 30 percent of the Western coal (Kentucky Department of Transportation, K.D.O.T.,1974), the utilization of various coal transport systems is extensive. Presently coal is transported out of state by rail, river or highway. However the state's coal transit systems in many areas of Kentucky's coal fields is approaching or has reportedly reached capacity.

A potential alternative for coal transport is by pipeline this includes pneumatic and coal slurry transportation. Applications for pneumatic pipelines in the coal industry to transport coal from the mine or deliver refuse to the mine for backfill have been tried out recently in England by the British Coal Board. For relatively short distances pneumatic transport systems appear to be an economical alternative to belt conveyor and trucking transportation (Oversight Hearings, U.S. Congress, 1976). More extensive studies concerning the technological aspect, economic analysis and general safety of this system has been conducted and reported by Soo & et al. (1975).

1.3 Development of Slurry Pipelines

A coal slurry pipeline transports coal particles by a carrying medium, usually water, through a pipeline. A schematic drawing depicting the various processes involved in and potential long and short distance applications of the coal slurry pipeline is shown in Fig.1.1. This concept was first patented in the late 19th century but was not put into industrial use until 1914 in London, England. A short slurry pipeline was then used to unload coal from barges on

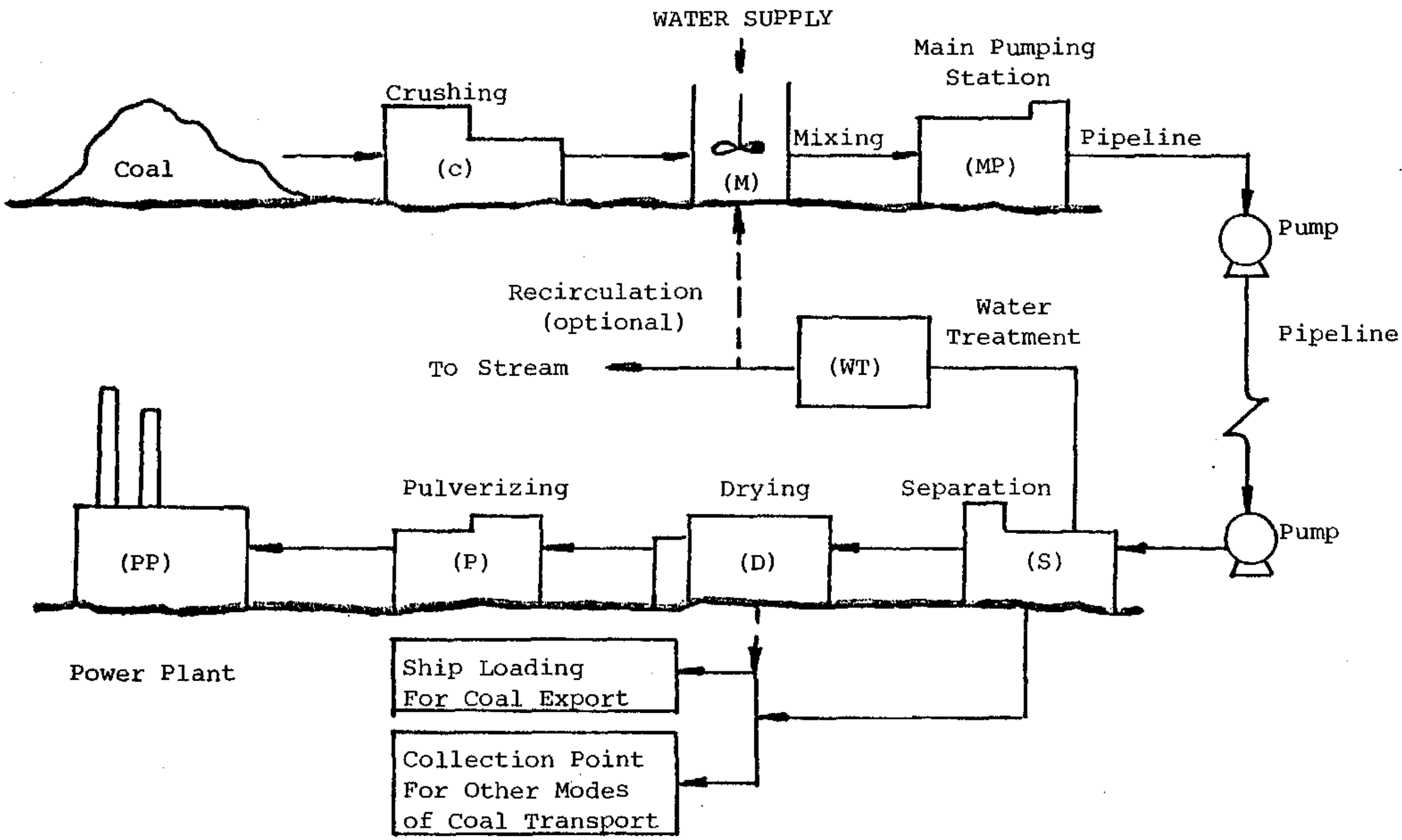

Figure 1.1 Schematic Drawing of a Coal Slurry Pipeline System

the Thames River for use in a nearby electric power generation plant.

This technology was utilized in the United States for long distance coal transport by the Consolidation Coal Company in 1957. A 10 inch diameter pipeline originating in Cadiz, Ohio and terminating at a power plant, near Cleveland Ohio, conveys coal 108 miles (Godwin,1979). After 6 years of successful operation and delivering 1.3 million tons of coal annually, the slurry pipeline was shut down due to the development of the rail unit-train, which lowered rail tariffs from $3.47 per ton of coal to $1.88 per ton of coal, making the operation of the slurry pipeline uneconomical. Since that time there have been only a few slurry transport lines built in the United States with only one long distance coal slurry pipeline in operation today.

The 273-mile Black Mesa pipeline is the only coal slurry pipeline operating in the United States at the present time (1983). This line runs from the Black Mesa mine in northeastern Arizona to the Mohave Power Plant in Nevada. It carries approximately 4.8 million tons of coal each year and has been under continuous operation since 1970 (Godwin,1979). Successful operation of this line sparked development of other coal slurry pipelines including the planned 1003 mile ETSI (Energy Transport Systems Inc.) pipeline to deliver 25 million tons of coal annually from Wyoming to Arkansas.

Florida Gas Company and Fluor Corporation proposed a 1,500 mile pipeline to transport 40 to 50 million tons of coal annually. This line is to carry coal from Eastern Kentucky-West Virginia and Western Kentucky-Illinois regions to the Georgia and Florida markets (Fig 1.2). These markets currently import some coal from South Africa and Poland because of reported high delivery cost of Kentucky coal.

Other potential coal slurry pipelines from Kentucky were studied by the Appalachain Regional Commission (Mathtech,1978). Developed in the ARC report are computerized economic evaluations of these potential slurry pipelines for the region. Based on the results of the economic analysis these pipelines were classified into categories of highly probable, possible and unlikely. Of the initial 573 coal links in the region twenty were categorized as highly probable, from which nine pipelines for Kentucky were included as shown also in Figure 1.2. These nine pipelines will transport an estimated 53.0 million tons of coal from Kentucky annually. These systems if established will require large quantities of water for their operation.

1.4 Water Usage and Energy Industry

Water is required for nearly every imaginable major energy producing system. The amount of water withdrawal and consumed varies from system to system. Water withdrawal is defined as water removed from the source of supply but not necessarily consumed. On the other hand, water consumption indicates the amount of water rendered unavailable for further use. Thus, water discharged from a coal

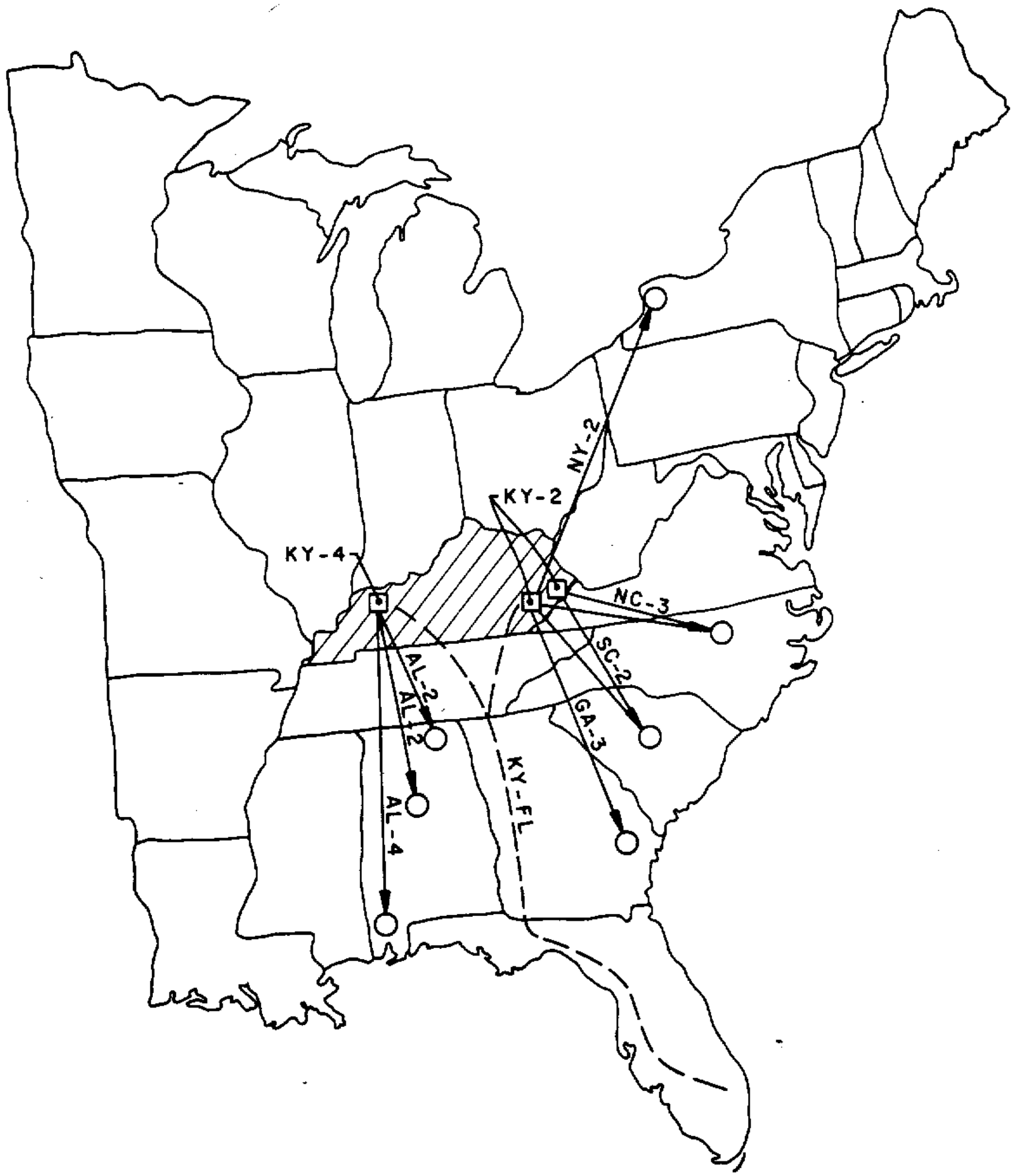

Figure 1.2 Potential Slurry Pipelines From Kentucky

gasification plant, if heavily polluted, is considered consumed water for many competing uses. Water evaporated from a wet cooling tower or man made lake is unlikely to be precipitated as rain in the same region and is therefore consumed water. Water used as a source of hydrogen for synthetic fuel production is also consumed water (Harte,1978).

Water consumed per million BTU output for various energy systems is shown in Figure 1.3 (Davis,Cir.703). This comparison indicates coal slurry pipelines consume the least amount of water from a local source.

It has been suggested that coal slurry pipelines utilize a third to a fifth of the water required for coal gasification and onsite generation respectively (Palmer,1978). As indicated in the Huston Law Review the water required for mine mouth power plants, synthetic gas, and coal slurry pipelines is respectively, 100, 30, and 12 gallons per million BTU delivered (Reed,1976). This estimate is slightly modified by the Office of Technology Assessment (McDaniel,1979). OTA estimated, that for exporting one ton of coal equivalent energy, electric power generation requires five to seven times as much water and coal gasification requires twice as much water, from the coal producing state, as a slurry pipeline.

Another study was conducted using the Yampa River Basin in Northwestern Colorado as a setting (McDaniel,1979). Four energy transportation systems were analyzed to determine the water requirement for transporting 12.5 million tons of coal 1000 miles to Houston, Texas. The four energy transportation

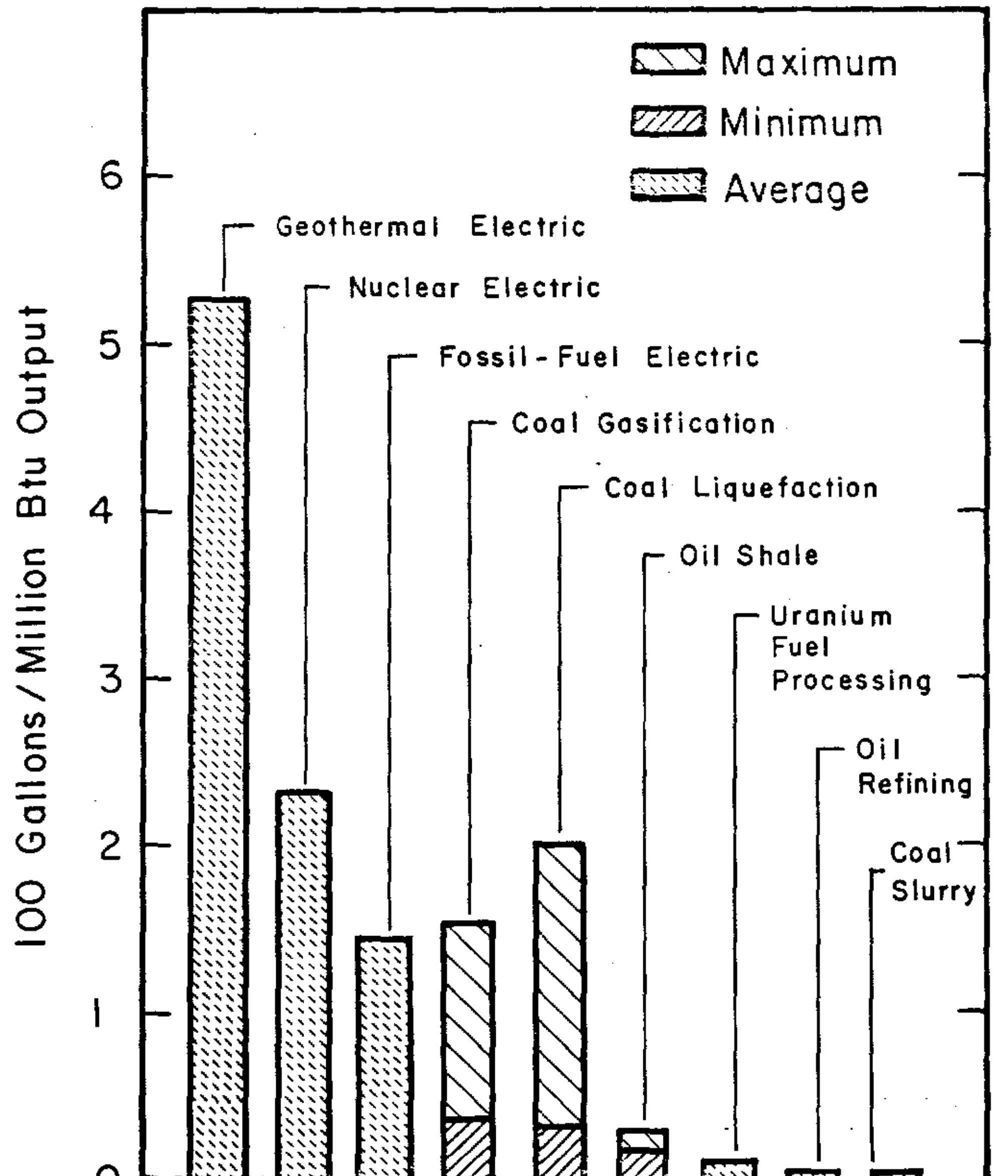

Figure 1.3 Water Consumption of Various Energy Producing Systems

systems investigated were; onsite power generation with high voltage lines to deliver the electricity; onsite coal gasification coupled with gas pipelines; coal slurry transport; and unit trains. It was found that on site generation would require 4.8 times as much water as coal slurry pipelines having a 50/50 coal to water ratio. On the other hand coal gasification needs about 3 times as much water as coal slurry pipelines with a similar coal-to- water ratio. The water required for rail was considered negligible in comparison (Figure 1.4).

The Office of Technology Assessment (O.T.A.) of the United States Congress (1978) compared the water usage of the Jim Bridger Power Plant to two proposed Wyoming coal slurry pipelines. This power plant, which is located in Southwestern Wyoming and uses 5 million tons of coal, requires 25,000 acre-ft of water per year. While the two proposed Wyoming pipelines would each move 25 million tons of coal using 15,000 acre-ft of water.

The major proposed pipelines in the West have plans to develop their own water sources. For example, the proposed Colorado-Texas line would utilize brackish, mineralized water which would not be suitable for human or agricultural use. The Wyoming-Arkansas pipeline would utilize water from deep wells in East Wyoming, that would be drilled by the pipeline company (Committees on Interior and Insular Affairs, C.I.I.A.,1981).

Water for the Black Mesa pipeline is pumped from a deep extensive sandstone aquifer that underlies the Black Mesa

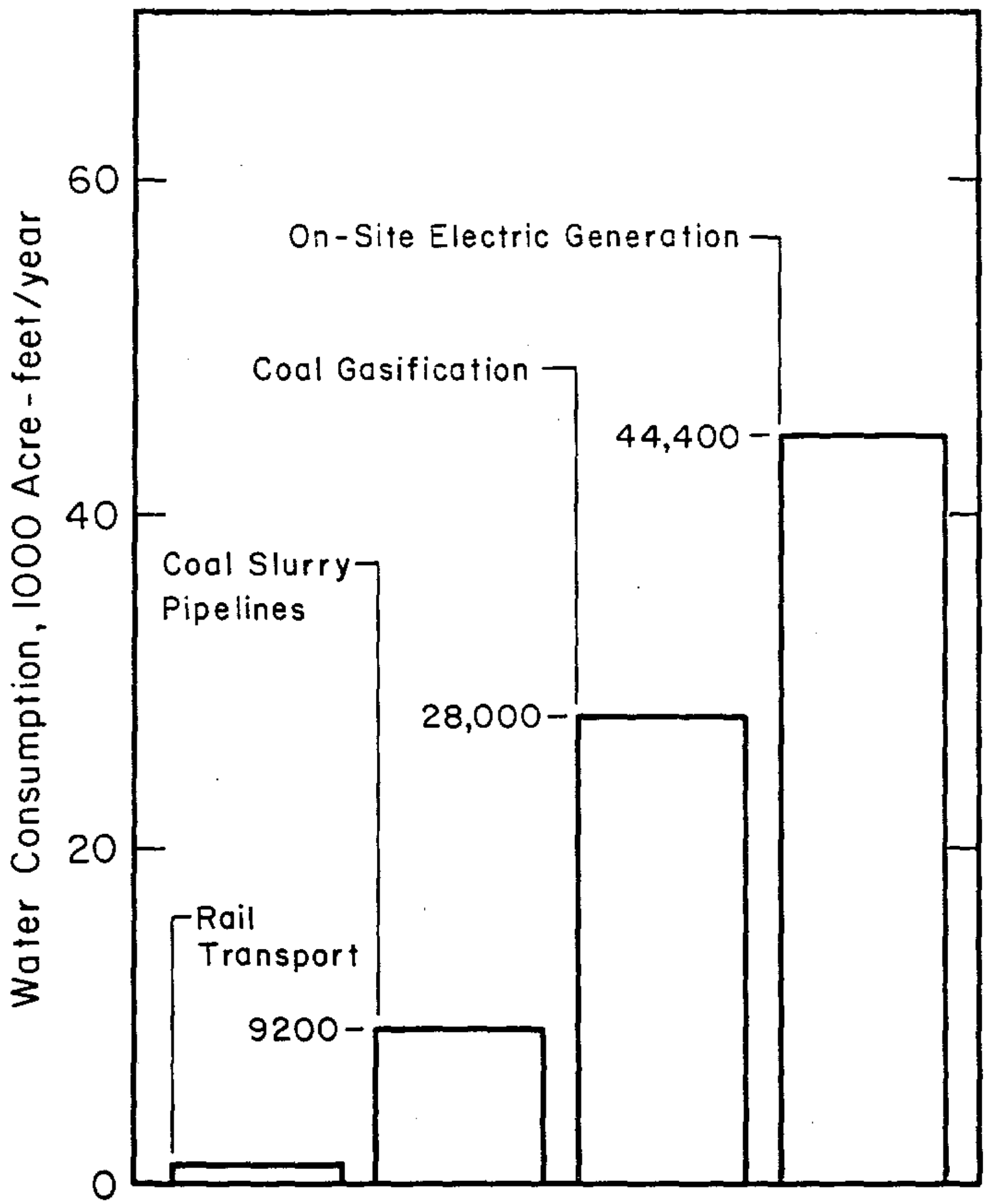

Figure 1.4 Water Consumption of Four Different Energy Transportation Systems

area. Approximately 3,200 acre-ft of water per year are withdrawn from this storage area. Since the recharge of these storage areas by precipitation is negligibly small eventual depletion of the water may be anticipated (Davis,Cir.703).

Other water sources for coal slurry pipelines include surface waters, primary effluent from treatment plants, irrigation return flows, reutilization of water from coal mining, and recovered slurry water (O.T.A.,1978).

The suggested potential intermediate distance pipelines from Kentucky and the proposed long distance Kentucky-Florida Coal slurry transport system will need an estimated 50,000 to 80,000 acre-ft (46 to 73 million gallons/day) of water, if fully implemented.

To further analyze this water requirement the Appalachian Regional Commission (Mathtech,1978) estimated the water required for each of the nine intermediate distance pipelines for Kentucky. It based this estimate on the projected demand of coal from the potential supply zones in Kentucky. The breakdown of this projected 53.8×10^4 acre-ft/year of water is shown in Table 1.2.

Table 1.2 Appalachian Regional Commissions Projection of Water Required for Slurry Transportation. (Mathtech,1978)

Slurry Zone	Demand Zone	Annual Coal Flow (MMTY)	Water Required 1000acre-ft/yr
KY-2	NY-2	7.73	5.93
KY-4	AL-2	17.71	13.57
KY-4	AL-2	22.32	17.10
	AL-4		
KY-2	NC-3	9.92	7.60
	SC-2		
KY-3	NC-3	12.63	9.68
	SC-2		
	GA-3		

Each slurry pipeline requires a pumping station every 50 to 100 miles, each pumping station would require power and water stored for emergency use. These pumping stations may be three to four acres in size and adjacent acreage of four to ten acres must be available for water storage (Buck,1978). Therefore consideration must also be given to the availability of this additional water requirement.

1.5 <u>Water Availability</u>

The 1975 aggregate water demand in the United States is outlined in Table 1.3 (Harte,1978). When comparing the averaged annual freshwater runoff of about 1,700km^3/yr (1.377x10^9 acre-ft/yr.) with the annual consumption of 150km^3/yr,(0.125x10^9 acre-ft/yr.), water availability does not appear to be a problem. One may find such a conclusion to be erroneous because the actual supply and demand of water are highly variable with respect to time and location. Precipitation and river flow can vary broadly from season to season and from year to year.

Table 1.3 Regional Runoff, 1975 Consumption, Per Capita Runoff, and Consumption Per Unit Runoff. (Harte,1978)

Region	Mean Runoff Km^3/yr	Consum. Km^3/yr	PerCapita Runoff 10^3m^3 person/yr	Consum./Mean Ann. Runoff
New England	93.0	0.61	7.9	0.0066
Mid-Atlantic	120.0	2.20	3.0	0.0180
S. Atl. Gulf	270.0	5.10	10.2	0.0190
Great Lakes	100.0	1.50	4.5	0.0150
Ohio	170.0	1.70	8.0	0.0100
Tennessee	57.0	0.39	17.0	0.0068
Upper Miss.	90.0	1.30	4.6	0.0140
Lower Miss.	100.0	7.60	17.0	0.0690
Souris-Red-Rainy	8.6	0.17	12.0	0.0160
Missour	75.0	24.00	8.4	0.3200
Arkansas	100.0	16.00	16.0	0.1600
Texas Gulf	44.0	13.00	4.2	0.3000
Rio Grande	6.9	6.00	3.5	0.8700
Upper Colorado	18.0	3.40	40.0	0.1900
Lower Colorado	4.4	10.00	1.7	2.3000
Great Basin	10.0	5.50	7.0	0.5500
Pacific Northwest	290.0	18.00	44.0	0.0620
California	86.0	34.00	4.1	0.4000
Alaska	800.0	0.0077	2000.0	$9.6*10^{-6}$
Hawaii	18.0	0.77	22.0	0.0430
United States	2471.0	151.0	11.0	0.0600
U.S. (excluding Alaska & Hawaii)	1653.0	150.0	7.8	0.0910

These variations in Table 1.3 demonstrate the importance of determining the fractional runoff which can be safely consumed.

It is, therefore essential to recognize that the x-day, y-year low flow criterion would best account for supply limitations and ecological impacts intrinsic to the hydrological characteristics of a geographic region. Harte (1978) defined the terms x-day, y-year as is the lowest flow rate averaged over x consecutive days of the year expected, on the average, every y consecutive years. This flow is denoted by the symbol $_xQ_y$. He determined that an allowed percentage of the x-day, y-year low flow criterion should be formulated, to account for these limitations and impacts, where $y>1$ and $x<365$.

Actual figures showing the allowable consumptive and withdrawal rates for the nation's water basin areas were unattainable. According to Freezer (1982) these rates are controlled by preemptive Federal Regulations such as: flows reserved for navigation, flows reserved for water quality control, and flow related to the operation of Federal projects.

The availability of water to substantiate the operation of a coal slurry line is a determining factor in its utilization. The potential expansion of the originating area of the pipeline and the restrictive development of new resources due to the water commitment must be considered. This is characterized in the O.T.A.(1978) report on coal slurry pipelines. In its analysis four hypothetical coal slurry lines were proposed including a Wyoming to Texas and a Tennessee to Florida pipeline. These two slurry pipelines were estimated to use an average depleted flow of 3% of the Bighorn River and 0.1% of the Tennessee River respectively. When projected water demands for the 1985-2000 period were obtained, water requirements for three of the four lines were in excess of the legally available water supply, including the Wyoming-Texas pipeline (Freezer,1982).

The Appalachain Regional Commission reported that water availability in Kentucky is substantial due to the Kentucky coal field's access to the Ohio River Basin. This was substantiated by the Ohio River Basin Commission's projection indicating that the consumptive demands by all users for the year 2020 would require a fraction of the available water (Mathtech,1978).

However, of the nine proposed Kentucky slurry pipelines, six are from the Eastern Kentucky coal field where coal is plentiful but water is locally scarce. The report from the Commission did not give specific consideration concerning the possible effect of slurry pipelines on local water needs and the state water resources allocation plan as a whole, except to point out that additional conservation measures may be needed. It did indicate however, that additional reservoirs may be required to supplement the amount of water presently available (Mathtech,1978). Accompanying the establishment of these new reservoirs and pumping station water storage ponds for coal slurry pipelines, one must realize the effect of additional evaporation and infiltration as a part of the overall water consumption that would be attributed to the slurry system.

1.6 <u>Legal and Environmental Aspects of Water Usage</u>

The Federal Government restricts the amount of water each hydrologic area may consume. Legal factors determine these restrictions. These basic legal factors include: Interstate Compacts, Prior Appropriations Doctrine, and Water Rights System (O.T.A.,1978).

Interstate Compacts place a practical limit upon the quantity of water that maybe used in a given river basin or state. This restriction is supplemented by state legislative restrictions on use and possible exercise of reserve rights of water.

The Doctrine of Prior Appropriation was established in 1855. It contains three distinct features. These features include:

1) A right to use the water by diverting the water from a stream for beneficial use.

2) The first to acquire the right has priority over later claimants.

3) The water can be used at any location regardless to the distance the user is from the stream.

Within the jurisdictions governed by the Prior Appropriation Doctrine the water available that is not already in benefical use is very limited (Campbell,1976).

Water rights in the West are administered by the states, usually through a state engineer. Obtaining water rights is often a time-consuming and complicated affair, and the would be appropriator must often stand in line behind a series of prior applications.

Another surface water law is the Riparian System. This restricts water use to areas adjoining the stream or water storage facilities from where the water is taken. Ground water laws vary from surface water laws. Ground water, in some states, is governed by the "English Rule". This rule states that water below the surface is the property of the land owner, who may withdraw it irrespective of the effects on others. In the Western States the "Reasonable Use Rule" and the "Correlative Rights Doctrine" are used. These laws consider, respectively, the adjoining land owners rights must be considered and co-equal rights to adjoining landowners (Campbell,1978).

Because the railroads are reluctant to voluntarily allow coal slurry pipeline crossings, Eminent Domain legislation which gives, the power to condemn private property for public use, may be necessary in order for the development of long distance interstate slurry pipelines. The use of eminent domain legislation to obtain slurry pipeline rights-of-way is a drawback. Such use could impair future developments that depend on water. The Coal Pipeline Act of 1981 restricts the usage of Eminent Domain.

The enviromental disturbances of slurry pipeline systems are concentrated during the period of construction. Because of the linear extension of the system, the enviromental impact during this period is expected to be much greater than that due to construction of a power plant. The environmental disturbances of the construction of power plants is limited to a small geographic area.

Once the system is completed, coal slurry pipelines are dustless, noiseless, (except for pumping station), and independant of weather, traffic and priorities of other shippers. They require approximately 30-50 ft of right of way, which can be revegetated and reused. Godwin (1979) cited that with proper water treatment practice, there will be no major coal slurry by-product water quality problems, leaving a pipeline rupture as the only main environmental hazard.

If a coal slurry pipeline ruptured a spray of suspension fluid would occur. Fine grained coal particles would accumulate in the immediate area. An immediate pressure loss would then be indicated at the following pumping station. This would signal a shut down of the line at the proceeding station terminating any further losses. The line could then be unearthed, repaired, reburied.

1.7 Scope of the Present Study

A more precise estimate of the water requirements for (coal slurry transportation) will help coal slurrification and transportation will help to determine the true effect of such water movement on local water utilization programs. A method of estimating water needs for coal slurry pipelines is presently unavailable. In order to develop a methodology for such applications one must examine the entire system and include all parameters involved in a coal slurry pipeline operation.

The concentration of coal slurry to be transported is usually referred to as 50 percent by weight. This means that the slurry mixture contains 50 weight percent of coal. Industrial practices have indicated that for fine and ultra fine coal particles, up to 75 percent concentration by weight is possible. However, when economic and energy efficiency analysis results dictate the need for a slurry line to deliver coarser coal, the 50 percent weight concentration may be unattainable. Short and medium distance (50 to 200 miles range) coal slurry pipelines for run-of-mine coal, coal collection branch lines or intermode applications are examples for which coarse coal-water mixture may be more energy efficient because of savings in energy when dewatering the slurry coal (Kao,1982). A method for estimating the maximum permissible concentration will be attempted for it directly affects the quantity of water movement via slurry pipelines.

In preparation for slurry transport the coal is crushed to desired particle sizes. Although this process can be controlled to a certain extent, size distribution after power crushing follows closely the relationship suggested by Rosin-Ramler in figure 1.5. This relationship is adopted in this study for illustrating the size distribution effect on the transport phenomena including the possible solids hold-up. This will lead to a more realistic description of the slurry transport system.

To obtain a specified annual throughput of coal, without pipe blockage, a critical transport velocity must be maintained. Determination of this velocity requires taking into account the particle size, the desired concentration, pipe diameter and other related flow properties. Modified slurry flow existing correlation equations will be adopted for use in this analysis. By applying the developed methodology the total water requirement can be estimated for a specific coal slurry pipeline and include all components of concern. Nomographs will be constructed to aid the practical application of the method developed.

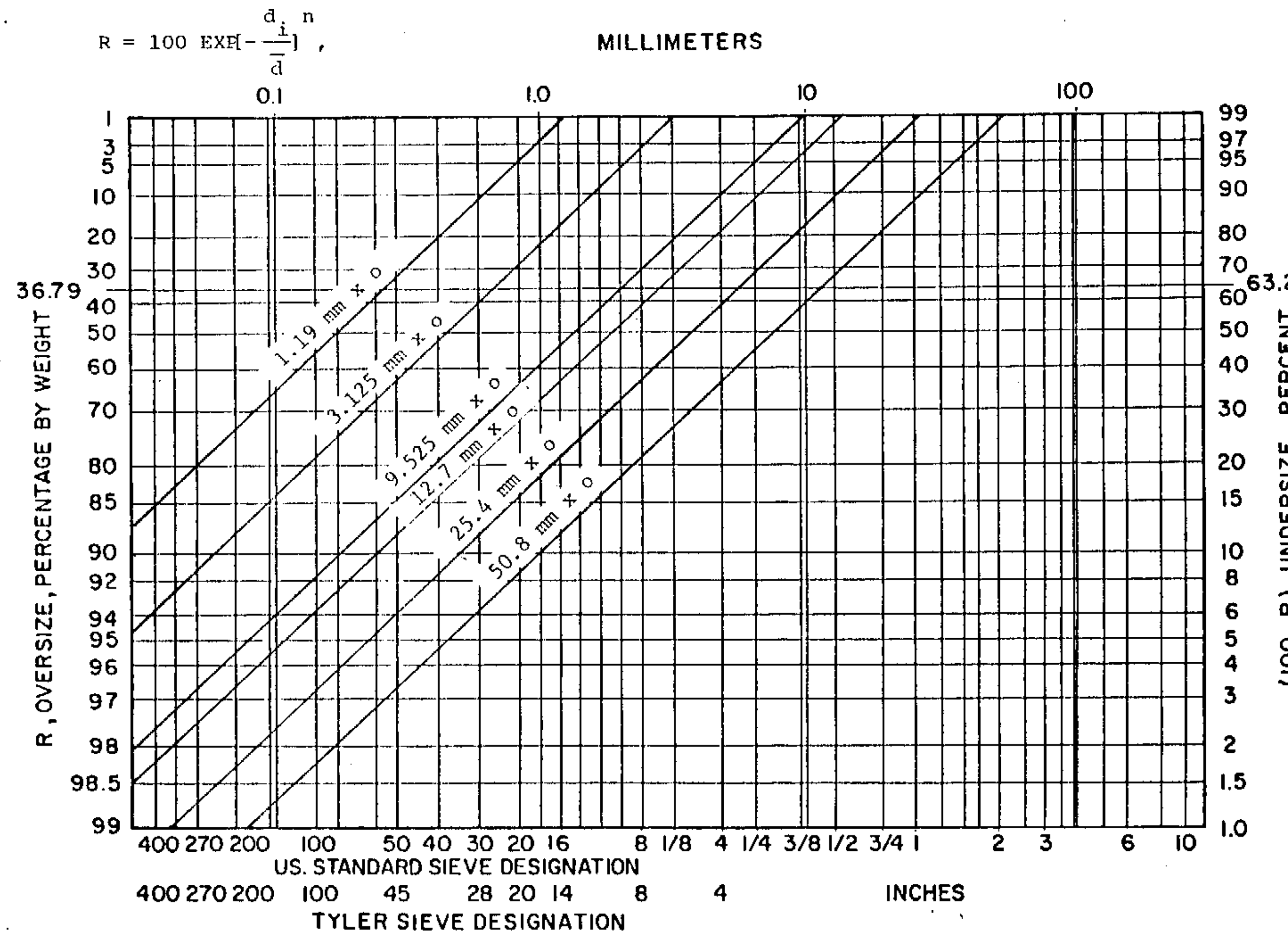

Figure 1.5 Sample Plot of Rosin-Ramler Coal Size Distribution

CHAPTER 2

ANALYSIS

The mechanics of solid-liquid flow is very complex. The trubulent eddies of the flowing liquid provide the primary carrying power to sustain the motion of the solid. Vertical and horizontal drag forces develop whenever a velocity differential exist between the velocity components of the solid particle and the carrying fluid. The vertical fluid drag force helps to maintain solids in suspension while the axial component of the fluid drag helps the solids to move forward along the direction of flow. The unbalanced gravitational force component in the vertical direction becomes apparent for larger particles and manifests itself in heterogeneous solid particle distribution in the pipe with the lower half having higher solid concentration than that in the upper half of the pipe. The horizontal velocity differential between the two phases contributes to the phenomena of "hold-up". Some of these slurry flow properties are briefly reviewed in the following sections.

2.1 Drag Force

In almost all practical coal slurry mixtures the coal particles have a higher density than their carrying fluid. This fluid can be water, methanol, ethanal, oil or liquid CO_2. As a submerged body a coal particle will fall under the net effect of gravitation. This force has a magnitude which can be computed as:

$$F_g = d^3 (\rho_S - \rho_L) g/6 \qquad (2.1)$$

where:

d = particle diameter, L;

ρ_S, ρ_L = mass density of soils and liquid respectively, ML^{-3}; and

g = gravitational acceleration, LT^{-2}

This net gravitational force, will cause the particle to accelerate first until the fluid drag develops due to the relative motion between the fluid and the solid to balance it. The fluid drag force, F_D, can be computed as:

$$F_D = C_D Pa\ \rho_L (V_S - V_L)(V_S - V_L) \qquad (2.2)$$

where:

C_D = coefficient of drag;

Pa = projectional area of the solid on a plane normal to the direction of solid motion, L^2; and

V_S, V_L = velocities of solid and liquid respectively, LT^{-1}

When the two forces become equal in magnitude, $F_g = F_D$, acceleration stops and a constant particle settling velocity is attained . In a resting fluid, $V_L=0$, the solid velocity under the balanced condition is referred to as terminal settling velocity, V_o. Substituting these into Eqs. 2.1 and 2.2 and solving for V_o gives:

$$V_o = \sqrt{\frac{4(s-1)}{3\ C_D}} \qquad (2.3)$$

where, s is the specific gravity of the solid.

The above analysis is derived for a spherical particle with coefficient of drag, C_D, being a function of the particle Reynolds number:

$$Re = V_o d/\nu \qquad (2.4)$$

where, ν is the kinematic viscosity of the fluid with the dimensions in L^2T^{-1}. This functional relationship is well established and is shown in Figure 2.1 by the curve marked ψ = 1.000 indicating that the particle is spherical in shape.

For solid particles having irregular shapes, a shape factor, ψ, will have a value other than unity. The definition of a shape factor can be best expressed by the relationship:

$$\psi = As/Ap \qquad (2.5)$$

where,

As = the surface area of a sphere of the same volume as the particle, L^2; and

Ap = the surface area of the particle, L^2.

The effect of the shape factor on the coefficient of drag is also shown in Figure 2.1 for ψ = 0.9, 0.8, 0.7 and 0.6. The shape factor for a coal particle is commonly recognized as having a value of 0.7. Based on this shape factor the terminal settling velocity, V_o, for coal particles falling in water is shown to follow the relationship as depicted in

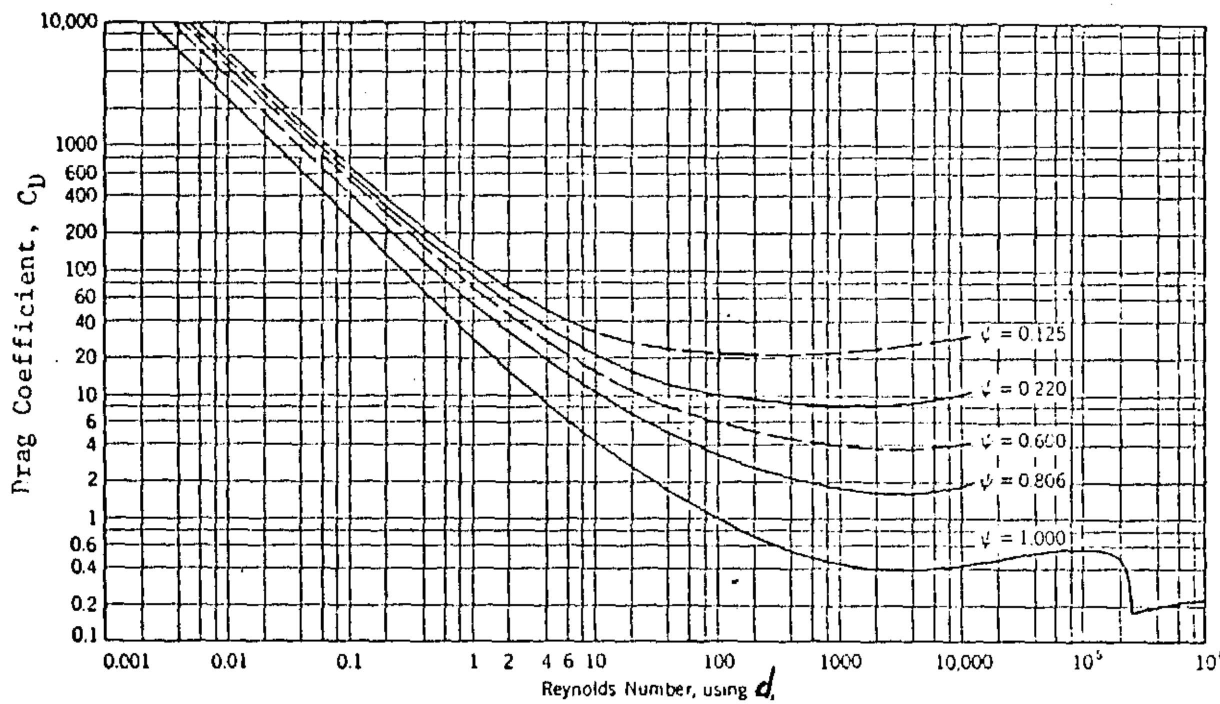

Figure 2.1 Drag Coefficient Versus Reynolds Number for Particles of Different Sphericities

Figure 2.2 for a broad range of particle sizes.

For computer applications, the C_D vs Re curve for coal particle with ψ = 0.7 may be expressed as:

$$C_D = \exp(1.93489-.262589*\mathrm{LOG}(Re)+.0189006*\mathrm{LOG}(Re)^2) \qquad (2.6a)$$

for $Re<100000$

$$C_D = \exp(-9.1019+2.06907*\mathrm{LOG}(Re)-.104981*\mathrm{LOG}(Re)^2) \qquad (2.6b)$$

for $Re<10000$

$$C_D = \exp(1.33574+.0087991*\mathrm{LOG}(Re)-.008345*\mathrm{LOG}(Re)^2) \qquad (2.6c)$$

for $Re<4000$

$$C_D = \exp(4.07581-.81059*\mathrm{LOG}(Re)+.0528908*\mathrm{LOG}(Re)^2) \qquad (2.6d)$$

for $Re<1000$

$$C_D = \exp(6.25354-1.93306*\mathrm{LOG}(Re)+.197017*\mathrm{LOG}(Re)^2) \qquad (2.6e)$$

for $Re<100$

$$C_D = \exp(4.25221-.8569*\mathrm{LOG}(Re)+.0714634*\mathrm{LOG}(Re)^2) \qquad (2.6f)$$

for $Re<10$

$$C_D = 24/Re \qquad (2.6g)$$

for $Re<1$

Similarly, several mathematical expressions are needed to describe the terminal settling velocity vs particle size as:

$$V_o = \exp(-14.803+2.2412*\mathrm{LOG}(d-.0446*(\mathrm{LOG}(d)^2) \qquad (2.7a)$$

for $d<=150$

$$V_o = \exp(-7.4543+.9489*\mathrm{LOG}(d-.0252*\mathrm{LOG}(d)^2) \qquad (2.7b)$$

for $d>3000$

$$V_o = \exp(-19.763+4.261*\mathrm{LOG}(d-.2478*\mathrm{LOG}(d)^2) \qquad (2.7c)$$

for $d<3000$

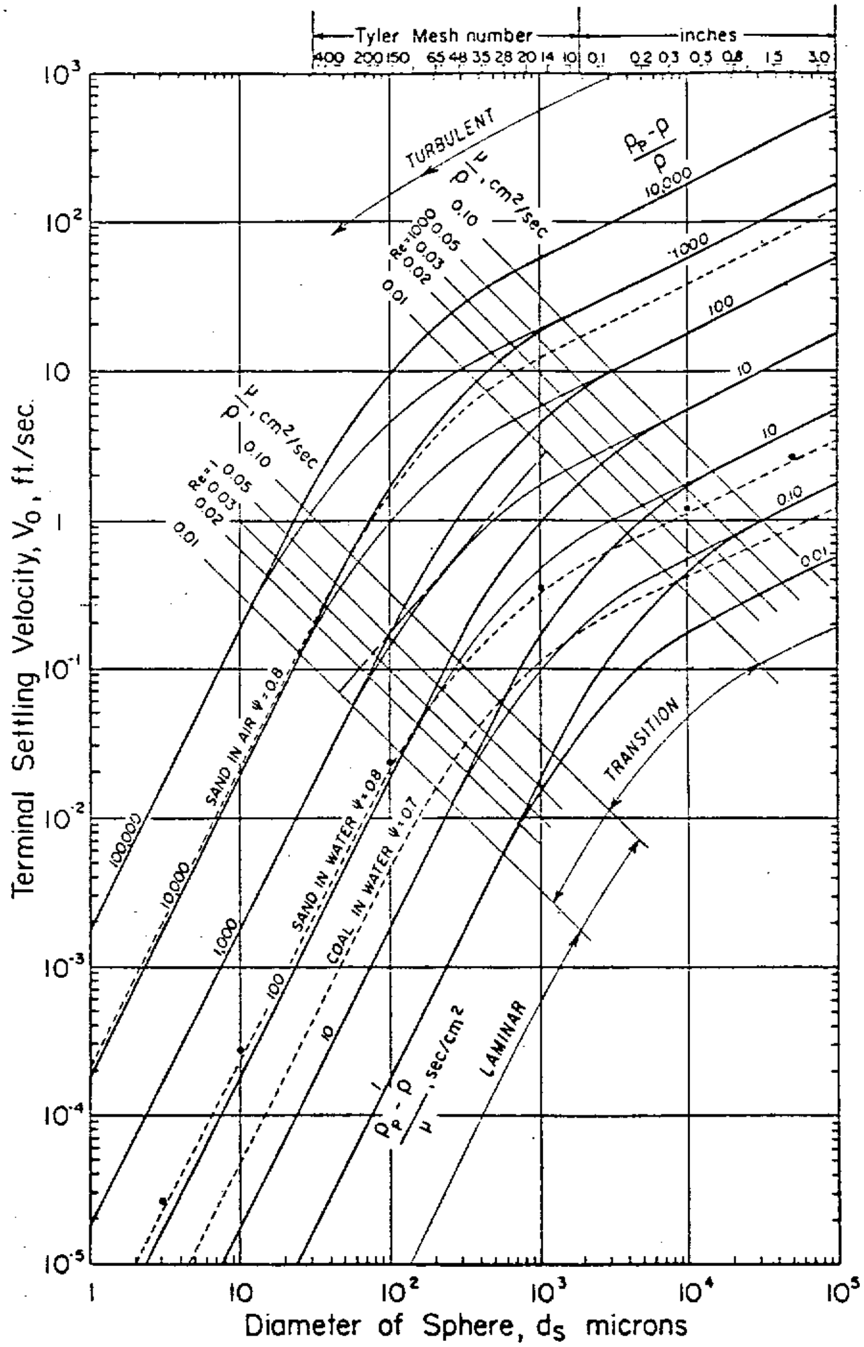

Figure 2.2 Terminal Settling Velocity of Particles (Govier,1972)

2.2 Hold-up Effect

As stated earlier fluid drag in the axial direction provides the actual carrying force to achieve the transport activity. Fluid drag does not exist unless a velocity differential between the solid particle and liquid phase exists with the former having a lower average velocity than the latter. This is generally true except in the case of transporting neutrally buoyant solids.

As a result of the velocity differential, often referred to as slip velocity, the in-situ solid concentration increases. This phenomena is known as "hold-up". The magnitude of hold-up can be expressed in direct proportion to the velocity differential between the phases. Therefore, the hold-up ratio increases with increasing particle size, due to the greater slip velocity between the fluid and large solid particles.

Although, many observations have been made to determine the slip velocity (Newitt and et al, 1962) and hold-up phenomena (Bonnington, 1959; Soo, 1966; and Richardson, 1960) in solid/liquid and solid/gas flows, relatively few reliable measurements of these quantities are available. The observation results obtained by previous investigators are normally limited to the specific conditions employed in their work without presenting a general correlation for future applications.

In the attempt to formulate new prediction equations for flow regime and pressure loss gradient, Gaessler (1967) derived a method which may be used for hold-up ratio evaluation. This method, was confirmed indirectly by the measured pressure loss gradient data for water suspensions of a number of different types of solids, including coal particles. This method is generally considered reliable for medium and coarse particles suspended in water (Govier, 1972).

The importance of the hold-up effect is reflected in of increased in-situ solid concentration. This is also referred to by many as local or transport concentration as opposed to the actual input or delivered solid concentration. This effect becomes more predominant as coarser particles are used in the transport system.

Knowing that the maximum random packing for coal can reach a maximum of 62 to 65 percent by volume (Gaessler,1967; Kao,1981), a criterion can thus be established for the in-situ transport concentration of coal to not exceed a certain value in order to avoid pipe blockage.

Further considerations should be given to the local solid concentration distribution. Because of the effect of the gravitational force, coal particles rarely reach a uniform dispersion throughout the pipe cross-section. Unless ultra-fine particles or extremely high velocities are used in the slurry mixture, the solid particles will be heavily concentrated in the lower portion of the pipe, leaving the upper portion with a solid concentration smaller than average (Durand, 1953; Newitt, 1962). This indicates that the real control for the maximum local concentration should be placed in the lower portion of the pipe, instead of using the average value over the entire pipe cross-section as derived by Gaessler.

To determine the local concentration distribution, a method derived on the bases of turbulent dispersion and momentum transfer will be employed (Kao, 1983). The average concentration of the lower portion of the pipe cross-section can be obtained by a simple integration technique. This concentration, rather than the average in-situ solid concentration over the entire pipe cross-section will be used in determining the maximum permissible solid concentration. The actual water requirement can thus be estimated based on the delivered solid concentration corresponding to the specific maximum permissible value. A major influence on this value is the critical transport velocity of the solids.

2.3 Critical Transport Velocity

The critical transport velocity as mentioned above is defined for a slurry system as a velocity at which no sediment bed formation in the pipe takes place. Because of the complex nature of the slurry transport system, no prediction equation for the critical velocity was derived based strictly on theoretical considerations. None of the existing critical transport velocity correlations are proven to give reliable critical velocity predictions for solid/liquid mixtures containing distributed particle sizes. In an attempt to obtain an average value for the critical transport velocity the following five commonly accepted correlation equations will be used.

Durand (1953)

$$V_C=1.35\sqrt{2gd(s-1)} \quad (2.8a)$$

Jufin (1965)

$$V_C=9.8\ \sqrt[3]{D}\ \sqrt[4]{V_O}(s-0.4) \quad (2.8b)$$

Zandi-Govatos (1966)

$$V_C=\sqrt{40(gd(s-1)C_V)/(\ C_D\ )} \quad (2.8c)$$

Turia-Yuan (1977)

$$V_C=\sqrt{2.411C_V{}^{0.2263}F_L{}^{-0.2334}C_D{}^{-0.3840}Dg(s-1)} \quad (2.8a)$$

Wasp (1977)

$$V_C=F'_L(C_V,d)\sqrt{2gD(s-1)}\ (d_S/D)^{(1/6)} \quad (2.8e)$$

Various notations used in the above Equations are defined as:

C_D = Drag coeff. of particle

C_V = Delivered solid concentration by volume

D = Pipe diameter, L

d = mean solid particle diameter, L

F_L = Fanning friction factor

F'_L = $1.25*C_V{}^{0.19}$

g = Gravity, LT^{-2}

s = Specific gravity of solid

V_O = Particle terminal settling velocity, LT^{-1}

The variation of the results of these correlations is demonstrated by substituting the following set of values into each equation for the corresponding critical velocity predictions.

For:	C_D=9.68	DT=3.125mm	C_w=0.5
	V_o=.0853ft/s (mean)	F_L=3.43^{-3}	C_v=0.427
	D=1.4ft	NS=0.9	S=1.35

the critical velocity given by:

Durand	V_c=7.5805ft/sec
Jufin	V_c=5.6232ft/sec
Zandi-Govato	V_c=9.2864ft/sec
Turai-Yuan	V_c=7.0170ft/sec
Wasp	V_c=4.9343ft/sec

An average of the above is obtained to give V_c = 6.89 ft/sec and is used for the determination of the desired mean slurry flow velocity. To insure steady transport the mean transport velocity of the system is chosen to be 20 percent higher than the critical velocity, or:

$$V_m=1.2*V_c \qquad (2.9)$$

2.4 Effect of Coal Moisture on Water Requirement

The inherent properties of coal can affect the behavior of system. For example, varying the specific gravity of the coal will alter the critical transport velocity. The moisture contents of coal can affect the water requirements for slurry transportation in two different ways: the inherent moisture moves along with the coal as part of the solid which changes the coal particle density; the surface moisture integrates with the carrying medium becoming part of the water supply. When the coal is crushed the inherent moisture is released and air fills the pores that once contained moisture. As a result, coal particle density may drop slightly. The percentage of total and surface moisture content can be obtained by the following:

Total Moisture Content =

$$\frac{\text{(Wet coal weight)} - \text{(Bone dry coal weight)}}{\text{Bone dry coal weight}}$$

Surface Moisture =

$$\frac{\text{(Wet coal weight)} - \text{(Air dry coal Weight)}}{\text{Bone dry coal weight}}$$

These properties are known to vary from point to point even within the same coal seam as seen in Table 2.1 (Kuhn,1982). This prohibits a standard calibration and classification of the property for individual coal beds. Coal samples, therefore, must be analyzed from each mine site to determine the pertinent properties when hydraulic transport is considered.

Table 2.1 Properties of Coal Received (Kuhn,1982)

Location County, Seam	Average Moisture	Average Btu/lb	Specific Gravity
Hopkins, No. 9	8.00	12685	1.34
Mulhenberg, No.9	9.95	13085	1.44
Clay, Fireclay	4.90	14052	1.29
Letcher, Amburgy	3.90	13085	1.40
Harlan, High Splint	4.20	13815	1.30
Letcher, Imboden	2.05	14172	1.32

2.5 Existing Work on Water Requirement Estimation

Many attempts have been made to determine the quantity of water required for a coal slurry pipeline. The technique most commonly used includes a simplified calculation which takes into consideration only coal moisture content or coal-to-water ratio.

The effect of coal moisture can be demonstrated by a linear relationship which relates the water requirement directly to coal throughput. An equation for this relationship can be written as:

$$\frac{MTY2000(1-OMC/100)}{\gamma_L\ 43560} \qquad (2.10)$$

where

WRT = Water required for transport in acre-ft/year;

MTY = Contracted coal in million tons/year;

OMC = Percent original moisture content in coal;

γ_L = specific weight of water in FL^{-3}; and

the constants are for the conversion of tons and cubic feet to pounds of weight and acre-feet.

In the development of this equation, it was implicitly assumed that for coal slurry transportation, a 50/50 coal to water weight ratio always holds true. A corresponding plot demonstrating water requirements in terms of coal throughput for constant moisture content is shown in Figure 2.3.

In the study conducted by the Office of Technology Assessment of the United States Congress (1978), this method was applied in estimating the water for four hypothetical

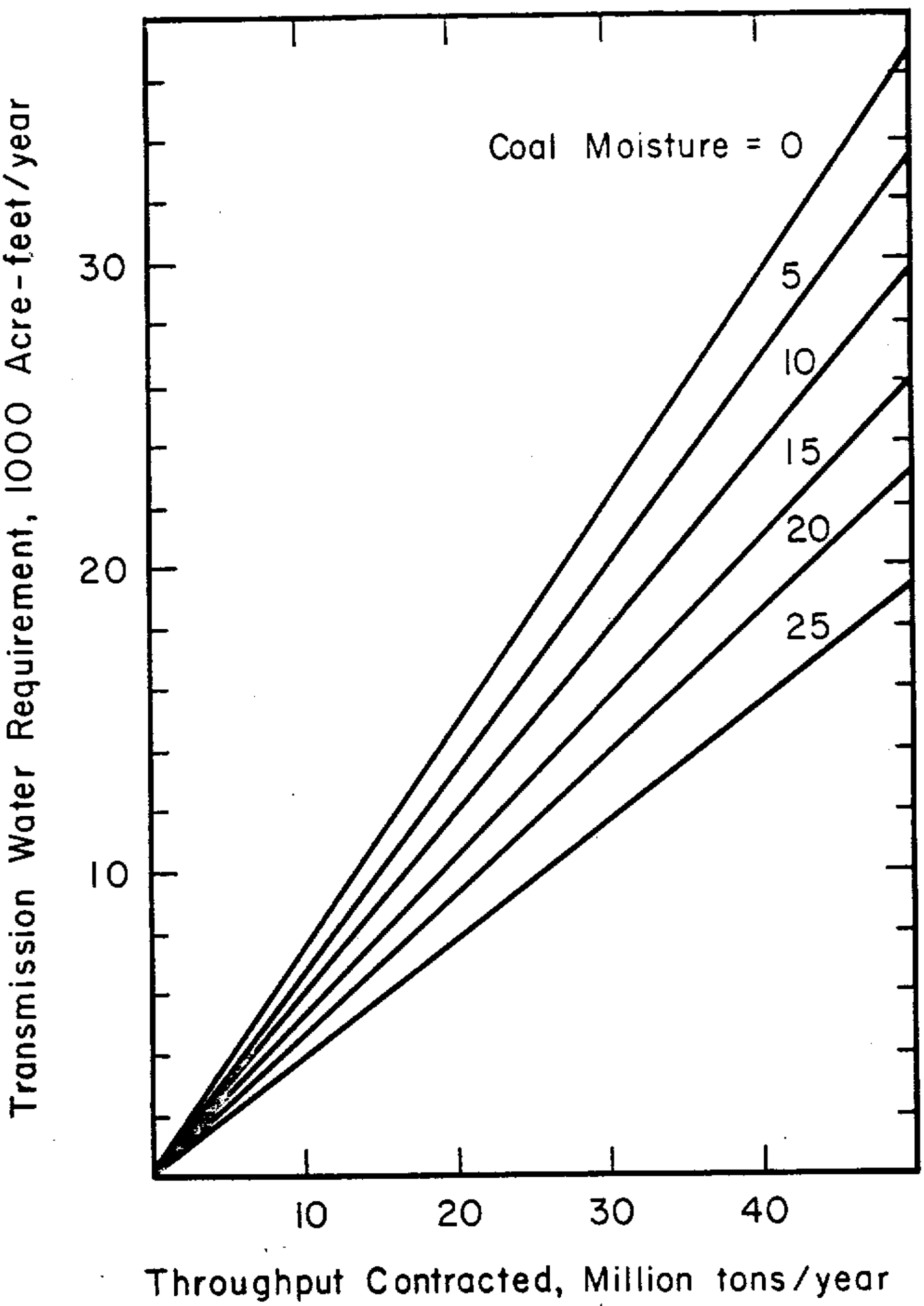

Figure 2.3 Coal Slurry Transmission Water Requirements as a Function of Coal Throughput for Constant Moisture Contents

pipelines of different tonnage capacities and from different coal regions (Table 2.2).

Table 2.2 O.T.A.'s Hypothetical Coal Slurry Pipelines.

PIPELINE	COAL (MTY)	RANGE OF ANNUAL WATER REQUIREMENTS (ACRE-FT/YR)
Wyoming-Texas	35.0	13,000-20,000
Montania-Minnesota/Wisconsin	13.5	6,000-8,000
Tennessee-Florida	16.0	10,000-12,000
Utah-California	10.0	6,000-7,000

This analysis indicates that for each million tons of coal transported each year one must provide a given amount of water regardless what coal particle size distribution is involved and what the size of the pipeline is used. The fact of the matter is that, both particle size distribution and pipeline diameter are important parameters which affect the coal slurry system behavior and water requirement. Without considering these factors one may find the analysis as being a case of over simplification.

When the coal-to-water ratio is taken as the principal factor influencing the quantity of water to be used, a different linear function relating the water requirement to the amount of coal shipped can be established. The United States Geological Survey National Center computed the water requirement for coal slurry pipeline systems (Palmer,1978) with varying coal to water mixture ratio ranging from a 40/60 to 60/40. Simple straightline relationships are obtained for water requirement as a function of coal throughput as shown in figure 2.4. A cost analysis was also conducted over the same range of operating conditions to determine the feasible coal-to-water ratio. Figure 2.5 is a plot of the results of this analysis showing a decrease in pipeline cost as solid concentrations increase at first but pipeline cuts will increase when the coal content exceeds approximately 50 percent of the weight ratio.

Such cost behavior of the system was attributed to the fact that as the solid concentration in the slurry increases, the total volume of slurry mixture decreases for the given weight of coal to be delivered resulting in using smaller pipe diameters. This accounts for some of the system cost savings. However, more and/ or larger pumps would be needed to overcome the greater friction energy loss resulted from transporting high concentration slurries. This, in turn, causes an increase in the overall system cost.

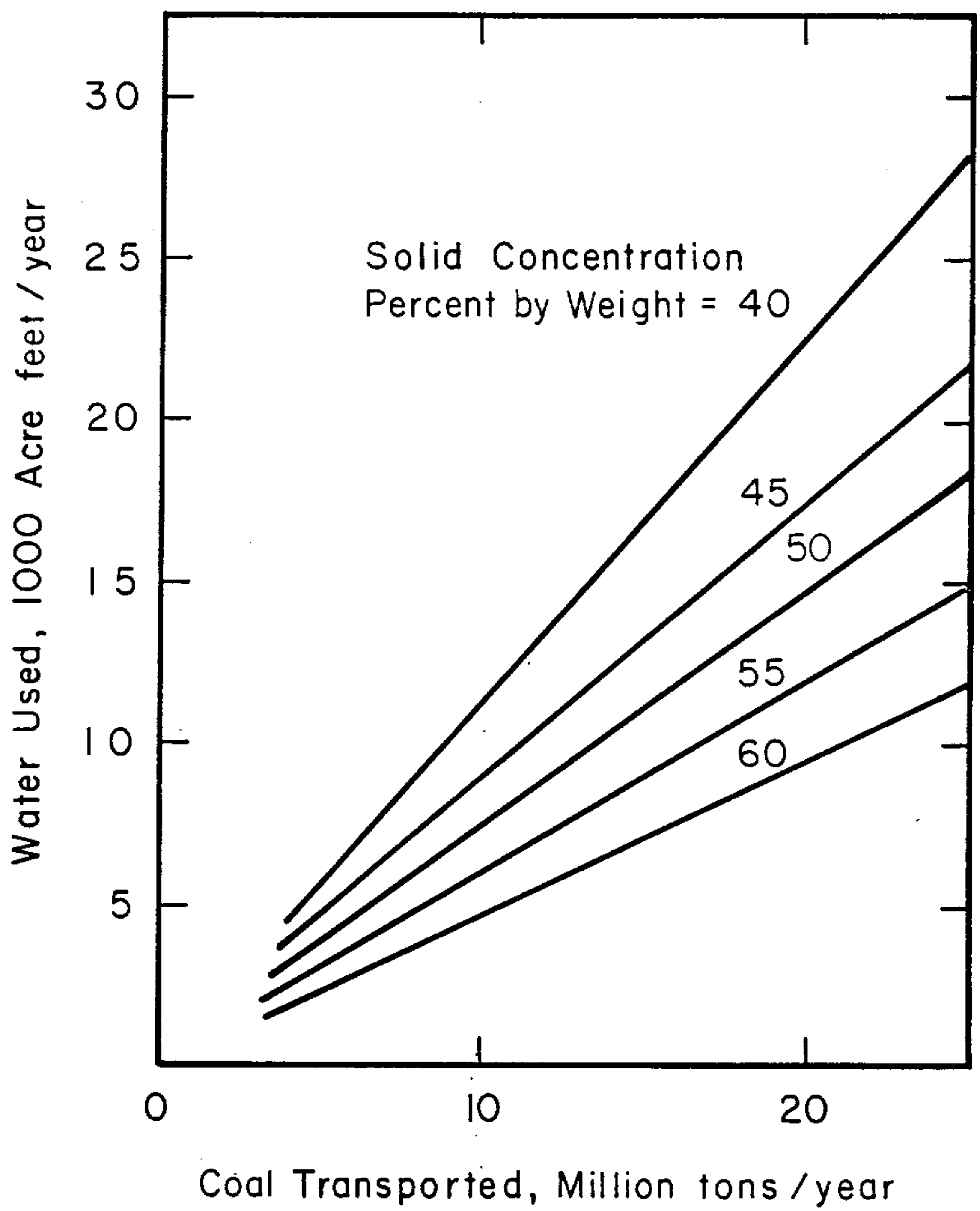

Figure 2.4 Coal Slurry Transmission Water Requirements as a Function of Coal-to-Water Ratio

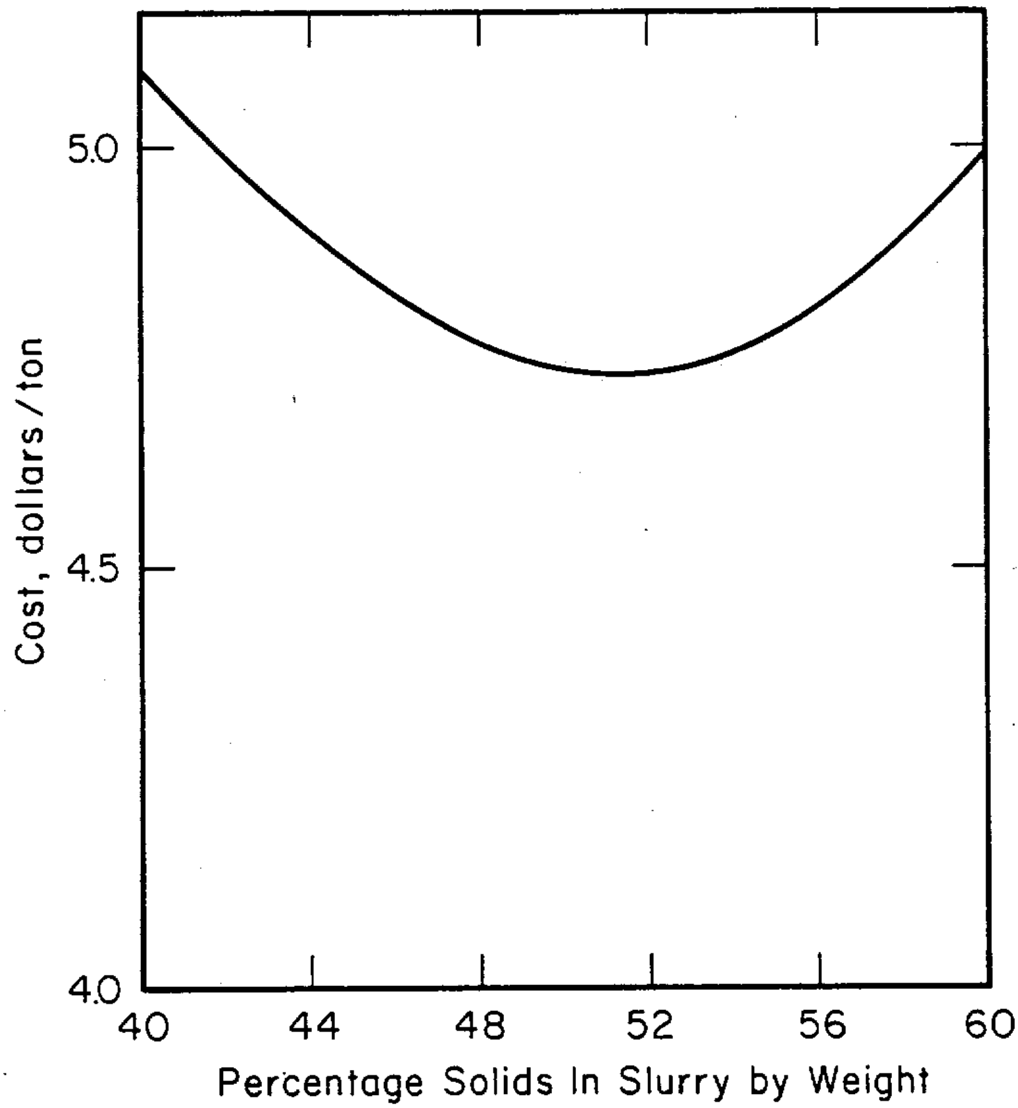

Figure 2.5 Cost Analysis as a Function of Coal-to-Water Ratio

CHAPTER 3

METHODOLOGY

3.1 Water Required for Fine Coal Slurry Transportation

Fine coal particles are assumed to behave as a pseudo-homogeneous substance when transported as a slurry. Because of such behavior, the water required is a function of both the original moisture content of the coal and the coal-to-water ratio.

If the coal is crushed in water during the slurry preparation both the inherent moisture contained within the coal and the surface moisture become a part of the slurry components. In many cases this moisture may make up a significant part of the water required. Therefore, this source of water is taken into account when calculating the total water required for slurry transport.

The concentration of the slurry mixture is the major determining factor in obtaining the water requirement for the coal. Low coal-to-water ratios would require relatively high quantities of water, whereas higher ratios would require lower quantities of water. The concentration of the slurry is expressed in terms of weight or volume fraction and is related to the coal-to-water ratio equally in those respective terms. If the concentration is 30 percent coal by weight the coal-to-water ratio would be 30/70 by weight. The same applies if the concentration is given in terms of volume.

The effect of water moisture and slurry concentration have been used individually to calculate the water required for coal slurry transport as discussed earlier. Combining the two aspects would give a more useful general relationship for determining the slurry transport water requirement. This relationship is expressed in Eq 3.1.

$$WRT=((MTY*2000)/(\gamma_L*43560))*((1-CW)-(OMC/100)) \qquad (3.1)$$

where

WRT = Water requirement, acre-ft;

MTY = Coal throughput, million short tons/year;

OMC = Original moisture content of coal; and

CW = Coal-to-water ratio by weight.

Dividing each side of Eq 3.1 by MTY, million tons of coal per year, the WRT may now be expressed in terms of the MTY as a water requirement coefficient. This relationship can be expressed graphically in terms of the orginal percent coal moisture and the coal-to-water ratio as shown in Figure 3.1. Multiplying the obtained coefficient, RWRT, by the tons of coal per year, the total water required for fine coal slurry transport is obtained in acre-ft/year.

3.2 Water Required for Coarse Coal Slurry Transportation

Because of hold-up and gravitational effects, as discussed in the previous chapter, coarse coal particles do not behave as pseudo-homogeneous substances when transported.

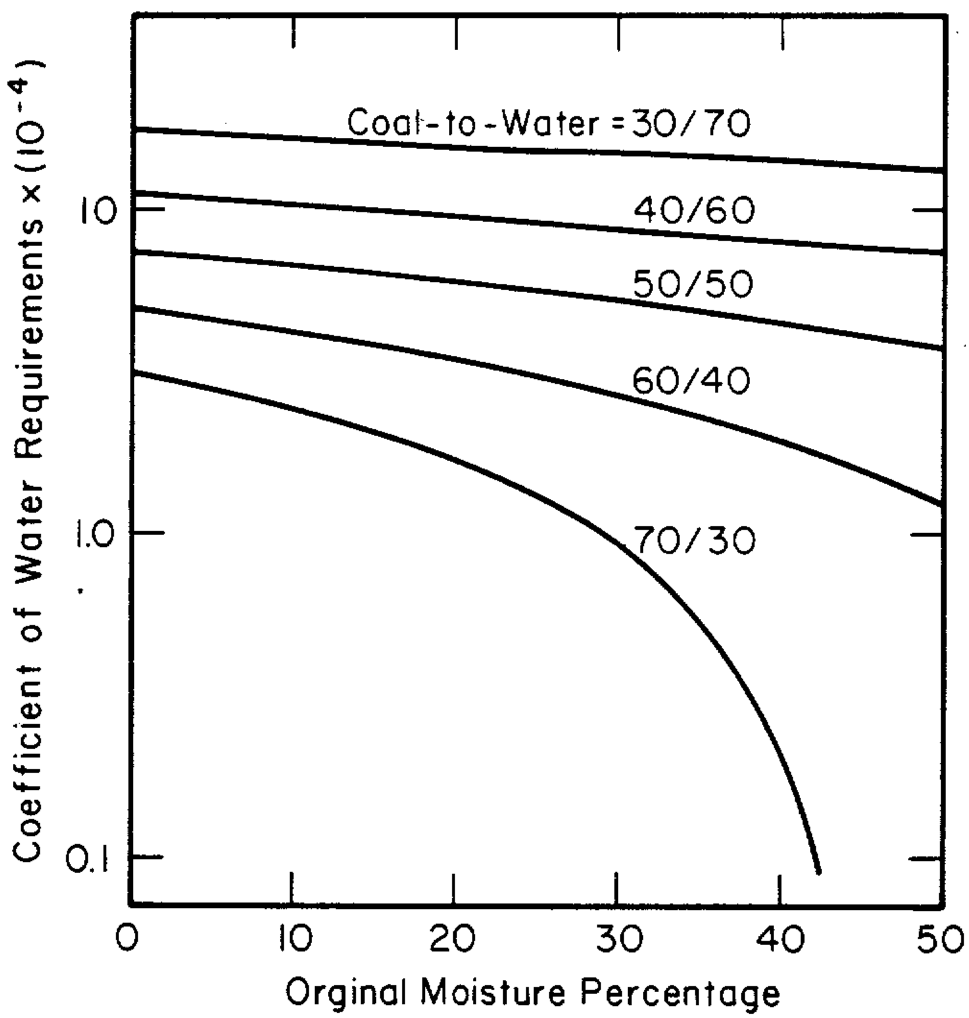

Figure 3.1 Transmission Water Requirement for Fine Coal

in-situ concentration, which is often greater than the delivered concentration, develops within the pipe as a result of hold-up. It is this concentration that will limit the maximum quantity of coal the pipeline can transport. Therefore,in this study, a modified form of the Gaessler empirical correlation is needed to determine the maximum permissible volume of coal that can be safely transported in a horizontal slurry pipeline. The water requirement will then be computed for the pipeline system based on this coal to water ratio.

3.3 Gaessler Correlations For Evaluating Hold-up Effect on In-situ Solid Concentration

Gaessler (1967) developed empirical relationships for estimating suspension and saltating bed load concentrations based on particle size, input concentrations and properties of the particles and fluid. He further proposed a flow pattern criteria based on the ratio of the fully suspended solids, C_{w1}, to input weight concentration of coal, C_w, as shown in Table 3.1.

Table 3.1 Flow pattern Criteria by Gaessler (1967)

Flow Pattern	C_{w1}/C_w
Symmetric Suspension	1.0
Asymmetric Suspension	0.7- 1.0
Moving Bed with Asymm. Suspen.	0.2-0.7
Stationary Bed with Asymm. Suspen.	0-0.2
Pipe Blocked	0

By applying the principle of the conservation of momentum the development of a correlation for predicting the ratio of the solid to mixture velocity was completed. From the results of these correlations the in-situ concentration due to the effect of hold-up can be estimated. The development of these relationships is briefly outlined below.

Estimation of the suspending and saltating solids begins with a simple mass balance equation. The sum of the two concentrations must equal the total input solid fraction:

$$C_w = C_{w1} + C_{w2} \tag{3.2}$$

where

C_w=input weight fraction of solids

$= (Q_s \rho_s)/(Q_m \rho_m)$

C_{w1}=weight solid fraction in suspension

$= (Q_{s1} \rho_s)/(Q_m \rho_m)$

C_{w2}=weight solid fraction in saltation

$= (Q_{s2} \rho_s)/(Q_m \rho_m)$

From the input weight fraction of solids the input volume fraction of solids can be obtained as:

$$C_v = (C_w/\rho_s)/(C_w/\rho_s + (1-C_w)/\rho_L)$$

where:

C_v=input volume fraction of solids

$$= Q_s/Q_m = V_{ss}/V_m \tag{3.3}$$

where Q = volume flow rate

V_m = average velocity of the mixture

V_{ss} = superficial velocity of solids

and subscripts:

S,L,M = for Solid, Liquid and Mixture respectively

1,2 = for Suspension & saltation respectively

Gaessler's experimental analysis on water-solid flow mixtures through horizontal pipes lead to the development of a pressure drop relation. In the process of developing this relationship, he derived a correlation, as shown in Eq 3.4, to determine C_{w2} in terms of C_v and an estimated initial value of C_{w1}.

$$\frac{C_{w2}}{C_w} = \frac{F_{ro}}{0.1\phi_s\sqrt{\frac{3}{4}C_D\left(\frac{C_v}{\phi_s}\right)^{z_1}}} \quad (3.4)$$

where

$$z_1 = \frac{1}{\phi_s}\sqrt{\frac{3}{4}\left(\frac{\rho_t}{\rho_s-\rho_t}\right)\frac{F_{rm}}{3.7}}^{\,z_2} \quad (3.5)$$

$$z_2 = \left(F_{ro}\right)^{(-1/3)}$$

$$\rho_t = C_{s1}(\rho_s-\rho_L)+\rho_L = \text{bulk fluid density} \quad (3.6)$$

C_{s1} = the volume fraction of solids in full suspension

$F_{ro} = V_o/\sqrt{gD}$ = Froude number based on the settling velocity, V_o, of the average particle size

$F_{rm} = V_m/\sqrt{gD}$ = Froude number based on the mixture velocity, V_m

ϕ_s = the volume fraction occupied by the solids if packed in a tube; for coal ϕ_s= 0.60-0.65

After C_{w2} is initially determined the values may be check by Eq 3.2. If Eq 3.2 is not upheld a new value for C_{w1} will be entered until the fundamental of mass conservation principle as expressed in Eq. 3.2 is satisfied.

With C_{w1} determined, the flow pattern of the slurry may be predicted by using Gaessler's flow pattern criteria. The velocity of the solids must now be determined for the evaluation of the in-situ solids concentration.

The velocity ratio of the saltating solids to the total solids is determined using:

$$\frac{V_{s2}}{V_s} = \left(\frac{C_{w2}}{C_v}\right)\left(\frac{0.1\ \theta_s \theta}{F_{ro}\ \ 3C_D/4}\right)\left(\frac{C_v}{\theta_s}\right)^{-z^3} \tag{3.7}$$

where

$$z^3 = \left(\frac{\phi}{\phi_s}\right)\sqrt{\frac{3}{4}\ \frac{\rho_t}{\rho_s - \rho_t}}\left(\frac{F_{rm}}{3.7}\right)^{z_4} \tag{3.8}$$

$$z_4 = 2(F_{ro})^{1/3} - (1/\phi_s)$$

$$\phi = (1 - \phi_s)/\phi_s$$

Gaessler then correlated Eqs 3.4 and 3.7 to obtain a factor of proportionality;

$$\beta = \beta_* \ (C_{w2}/C_w)(V_s/V_{s2}) \tag{3.9a}$$

or

$$\beta = \beta_* \frac{F_{ro}}{0.1(1 - \phi_s)}\sqrt{\frac{3}{4}\ C_D}\left(\frac{C_v}{\phi_s}\right)^{z_3} \tag{3.9b}$$

β = factor of proportionality, which is dependant upon the fraction of altating solids and their velocity, and the coefficient of sliding friction.

β_* = coefficient of sliding friction, which was found to be essentially constant for any solid material, liquid and pipe-wall combination. 0.25-0.28 for coal

Based upon his experimental data, Gaessler prepared nomographs, as shown in Figures 3.2 and 3.3, to simplify the iterative solution of Eqs 3.4, 3.9a and 3.9b. These nomographs are based upon ϕ_S=0.65 and C_D=0.44. If C_D deviates from 0.44 the obtained value may be multiplied by $\sqrt{C_D/0.44}$ for an approximation of C_{w2}/C_w and β / β_*.

Using the above correlations the ratio of the solids to mixture velocity can be determined by Equation 3.10 using an interactive process.

$$\left(1-\frac{V_s}{V_m}\right)^2 = \left(\frac{F_{ro}}{F_{rm}}\right)^2 \left(\frac{V_s - V_m C_v}{V_s}\right) \{\beta + \left(\frac{V_s}{V_m}\right)^2 \left(\frac{F_{rm}}{2}\right)$$

$$[f_s{}^*\left(\frac{\rho_s}{\rho_s - \rho_L}\right) - f_L \left(\frac{\rho_L}{\rho_s - \rho_L}\right) \left(\frac{(1 - C_s)^2}{(V_s/V_m) - C_s}\right)]\} \qquad (3.10)$$

where:

$$f^*_s = f^o_s \quad (1-(C_{w2}/C_w)*(V_{s2}/V_s))$$

f^o_s = material constant that accounts for the properties of the solid particles and the pipe surface.
For coal: (3 to 5mm) in hardened steel $f_s{}^o$=0.0046 and in non-hardened steel $f_s{}^o$=0.0038

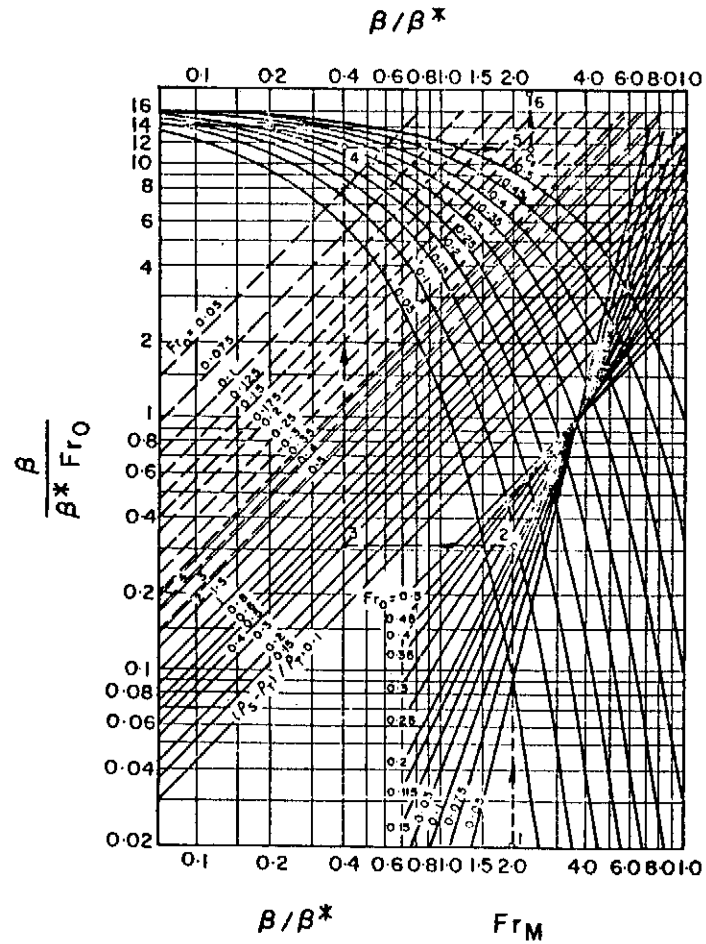

Figure 3.3 Gaessler Nomograph for β/β_*

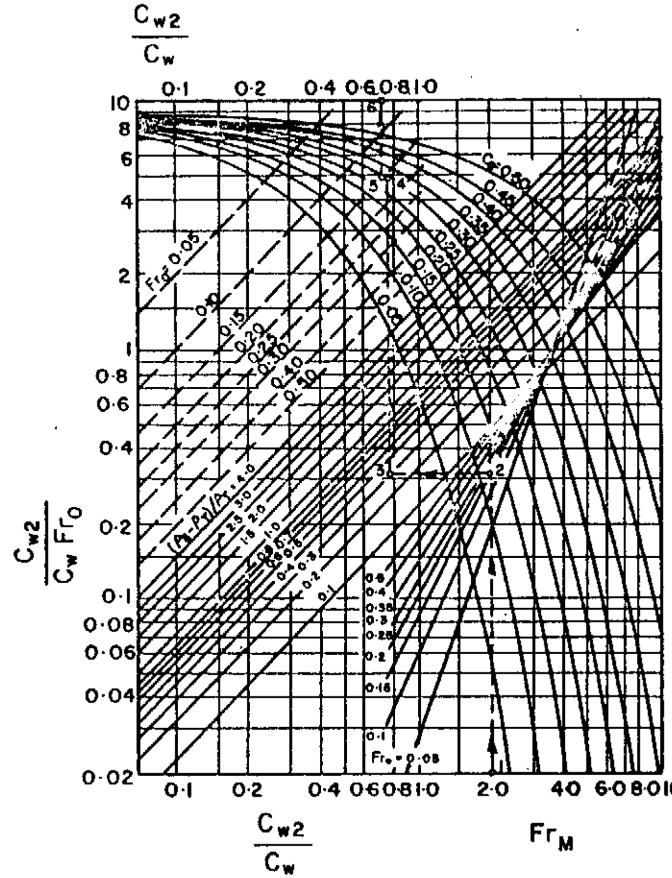

Figure 3.2 Gaessler Nomograph for C_{w2}/C_w

The Velocity for solid, V_s can be obtained by multiplying the resultant value for (V_s/V_m) from Eq. 3.10 by the mean mixture flow velocity, V_m/as:

$$V_s = (V_s/V_m)^* V_m \text{ from Eq. 3.10} \qquad (3.11)$$

The superficial velocity of solids is given as:

$$V_{ss} = C_v V_m \qquad (3.12)$$

and the mean velocity of solids in the saltating bed is:

$$V_{s2} = (V_{s2}/V_s)^* V_s \qquad (3.13)$$

in which, the value of (V_{s2}/V_s) is obtained from Eq.3.7. Equation of continuity, when applied, gives:

$$V_s C_w = V_{s1} C_{w1} + V_{s2} C_{w2} \qquad (3.14)$$

The in-situ transport concentration, CVT, can be evaluated to be:

$$CVT = (V_m/V_s)^* C_v \qquad (3.15)$$

Gaessler demonstrated the sensitivity of this ratio as a function of F_{rm} and F_{ro} in Figure 3.4. This ratio is relatively insensitive to the change of C_v and $\rho_L/(\rho_s-\rho_L)$ (Govier,1972). These computations will allow the determination of the average velocity of solids, V_s, in the slurry transport system. The in-situ solid concentration can be obtained, by applying Eq. 3.15 with the input solid concentration, C_V given.

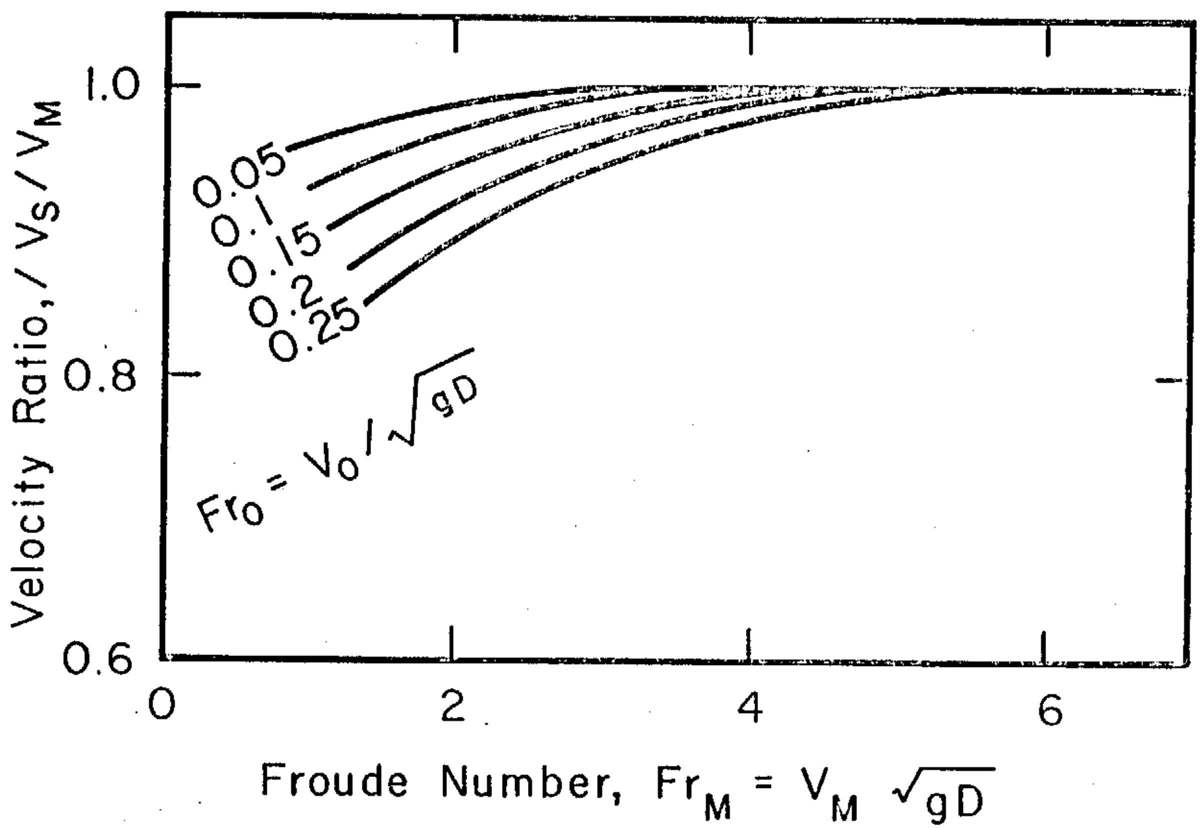

Figure 3.4 Gaessler Velocity Ratio Correlations Vs/Vm

3.4 Modified Gaessler Correlation for Slurries with Distributed Particles Size

Gaessler's analysis was confirmed indirectly by experimental results of pressure loss data collected from small and medium size pipe lines (46 to 160 mm diameter) using narrowly distributed coal particle sizes. To expand the application of these correlation to larger pipelines and transporting slurries composed of solids with broad particle size ranges, a particle size distribution subdivision technique is needed. The development of this technique is briefly outlined in this section.

Three basic assumptions were made in the development of this technique. These assumptions are:

1. The fraction of particles having size d_i behaves the same way in a mixture of water and solids of distributed sizes as in a mixture of near uniform sizes.

2. Suspended solids of size, d_i, contributes its effect on C_{w2} computation only to those particles having size greater than d_i, in the manner of increasing the mass density of the carrying fluid.

3. The size distribution of coal after crushing and grinding is to follow the Rosin-Ramler function expressed mathematically as:

$$R = 100 \exp\left[- (d_i/d)\right]^{NS} \qquad (3.19)$$

where

R = cumulative oversize particles in percent by weight

d_i = specific particle size

d = characteristic particle size

NS = coal character index, representing the slope of the size distribution function.

The particle size distribution particle size is subdivided into n sub-sections with each section having an average particle size, d_i. For each d_i a particle settling velocity is obtained from Eq 2.7a, 2.7b or 2.7c . A corresponding drag coefficient, C_D was determined using one of the equations Eqs 2.6a through 2.6g. These values were then used to determine C_{w2} and V_s. This process is initiated with the smallest d_i and continued until the entire range of the particles is accounted for.

The effect of the suspended solids accumulated from particles smaller in size than that of the particle under consideration is accounted for in the determination of the bulk fluid density, $T^{(i)}$. The percentage of suspended solids for each sub-section having particle size smaller than d_i, is added to the percentage of assumed suspended solids in the sub-section of particle size d_i. This increases the density of the carrying fluid and help to enhance its power to suspend more solids. Equation 3.20 represents the mathematical expression of this relationship.

$$\rho_t(i) = [C_{s1t} + C_{s1}(i)*(1-\Delta P(i))(\rho_s - \rho_L) + \rho_L \qquad (3.20)$$

where C_{s1t} is the accummulated fraction of solids in suspension and;

$$C_{s1t} = \sum_{j=1}^{j=i-1} C_{s1}(j) * P(j) \tag{3.21}$$

$\Delta P(j)$ = percent fraction of j^{th} sub-section

The process of determining the magnitude of other solid fractions; such as $C_{s2}(i)$, $C_{v1}(i)$ and $C_{v2}(i)$ of size d_i and corresponding velocities is as previously described (Sec. 3.3). Each of the solid concentrations and velocities are weighted by their respective percentages in the computation process. Mathematically they are:

$$V_{s1t} = V_{s1}(C_{v1}/(C_{v1}+C_{v2}))\ \Delta P(i) \tag{3.22}$$

$$V_{s2t} = V_{s2}(C_{v2}/(C_{v1}+C_{v2}))\ \Delta P(i) \tag{3.23}$$

where, V_{S1T} and V_{S2T} is the mean velocity of solids in suspension and in bed motion respectively.

The summation of the resulting concentrations, Cv1T and Cv2T, gives the in-situ transport concentration of solids in the pipe. By summing up the weighted solids component velocities as given in Eqs. 3.22 and 3.23, the average velocity of the solids are obtained.

$$C_v = \Sigma\ C_{v1t} + \Sigma C_{v2t} \tag{3.24}$$

$$V_s = \Sigma V_s(i) * \Delta P(i) \tag{3.25}$$

The equations presented in the previous section for computing the supperficial velocity of solids, V_{ss}; mean velocity of solids in the saltating bed, V_{s2}; and the in-situ transport concentration, C_{vt} (Eqs. 3.12 through 3.15) are all applicable. The throughput of coal and its water requirement for transportation is then derived to give:

$$V_L = (V_m - C_{vt} * V_s)/(1 - C_{vt}) \quad (3.26)$$

$$Q_L = V_L(1 - C_{vt}) \bullet (\pi D^2/4) \quad (3.27)$$

$$Q_s = V_s * C_{vt} * (\pi D^2/4) \quad (3.28)$$

This leads to:

$$TSC = Q_s \frac{(3600*24*365OP)}{2200} \gamma_s \quad (3.29)$$

$$WRT = Q_L \frac{(3600*24*365OP)}{2200} \gamma_L \quad (3.30)$$

where

TSC = Total coal transported in metric tons per year; and

OP = Operation Factor, less than or equal to unity.

3.5 Determination of Local Coal Concentration Distribution

The in-situ solids concentration, C_{VT} obtained above represent the volume fraction occupied by solids in a given section of pipe. The value of C_{VT} is greater than the delivered solid concentration C_V as a result of hold-up in the system. The difference between C_{VT} and C_V become more obvious as the solid particle size and/or mass density increases.

The coal concentration distribution profile can be determined using an equation derived based on the theory of turbulent dispersion. Intergration of the in-situ concentration the lower portion of the pipe gives the critical value of the local coal concentration, C_L. This value is then compared with the maximum packing factor, O_s, and used to prescribe the maximum permissible input (or detivered) solid concentration.

The gravitational effect will cause the solids to distribute unevenly over the pipe cross-section with more particle moving along the bottom portion of the pipe. The degree of heterogeniety increases by increasing particle size and/or the specific gravity of the solids. To determine the critical condition for plugging of the pipeline, it is essential that the phenonenon of heterogeneous solids distribution be considered and that the bottom portion of the pipe be taken as the control section.

This process is initiated by determining a reference concentration at 1/3 of the coal particle diameter from the pipe's bottom. The solid concentration C_a, at this reference point can be expressed as (Utterback, 1977):

$$C_a = C_{vt}(A_\rho)/2r^2\left(\frac{a}{2r - a}\right)^z \int_a^\pi \left(\frac{1 + \cos\theta}{1 - \cos\theta}\right)^z \sin^2\theta \, d\theta \qquad (3.33)$$

where

C_a = reference concentration;

A_p = area of pipe; L^2;

r = radius of pipe, L;

a = 1/3 mean particle diameter, L;

z = $V'_o/(B*K\ (F_L V_m^2)/2)$;

B = coefficient of proportionality = 0.92;

K = Karman's constant, for water = 0.4; and

V'_o = mean particle settling velocity adjusted for heavy medium, LT^{-1}

= $V_o\ (\rho_s/\rho_t - 1)/(\rho_s/\rho_L) - 1)$

From the reference point the concentration at any depth, y, can thus be determined to give:

$$C_y = C_a\left(\frac{D-Y}{y}\ \frac{a}{D-a}\right)^z \qquad (3.34)$$

where Cy is the concentration at y distance from the bottom of the pipe. Intergrating Cy from a to /2 the concentration for the lower portion of the pipe is evaluated as:

$$C_L = \frac{2r^2}{A_p/z}\int_a^{\pi/2} C_y \sin^2\theta\ d\theta \qquad (3.35)$$

If C_L greater than CVF* θ_s, where CVF is the concentration factor, a smaller input concentration value must be used for the system so that the danger of plugging can be avoided.

The originally calculated mixture velocity for a 50 percent solid concentration by weight, is maintained during this process. This is done to help maintain a higher solid velocity which in turn reduces C_L.

This computation procedure is continued until C_L reaches a value that is smaller than $CVF*O_S$. The input solid concentration corresponding to the final C_L value is the one used in the water requirement computation.

3.6 Water Required for Start-up

Prior to the transport of a coal slurry mixture the pipeline must be primed. The water required for priming is directly related to the pipe diameter given by (assuming 98% operation time):

$$D = \sqrt{(MMT*10^6)/(11033*C_V*V_m*\ \gamma_L)} \qquad (3.36)$$

where:

MMT=Million metric tons of coal contracted, MLT^{-2}

Each of these variables, except the mean velocity, V_m can be determined by the quantity and type of coal to be transported and the calculated coal-to-water ratio. Thus the water required for startup, priming, is given by:

$$SWR = (1/4)*3.14*D^2*L \qquad (3.37)$$

where:

SWR is the Start-up water required,in L^3T^{-1}; and

L is the Pipe length.

3.7 Storage Reservoir Requirements

To maintain a constant flow, slurry pumping stations will be required at a maximum of 100 miles apart depending upon the system characteristics. These stations will have water storage facilities to insure accessible water for start-up and flushing. The quantity of water stored should be greater or equal to that needed for start-up operation water with adjustments made for evaporation and seepage losses.

Evaporation losses per each square foot can be determined by an empirical equation developed by Meyer (Viessman,1972). This equation is expressed as:

$$E=[C(e_o-e_a)(1+W/10)]365(1/12) \qquad (3.38)$$

where

E = annual evaporation in foot depth/yr, LT^{-1};

C = empirical constant, 0.36 for ordinary lakes;

e_o = saturation vapor pressure at the water surface temperature.(Hg) Table 3.2

e_a = vapor pressure of air, (Hg), must be multiplied by the relative humidity Table 3.2

W = wind velocity in mph at 25 ft above the water surface, L^3T^{-1}

Multiplying the evaporation loss by the reservoir surface area the annual volume of water lost due to evaporation can be determined.

Table 3.2 Water Vapor Pressure at Various Temperatures (Viessman,1972)

TEMP F	(IN. Hg)
32	0.18
40	0.25
50	0.36
60	0.52
70	0.74
80	1.03
90	1.42
100	1.94

The seepage of the storage area is estimated using Dacry's Law (A Water Resources Technical Publication, A.W.R.T.P.,1977)

$$Q=KiA(3.2181*10^{-2}ft/cm)(3.15*10^{7}sec/yr) \qquad (3.39)$$

where:

K = coefficient of permeability for the foundation (table 3.3 , Harr,1962)

A = gross area of foundation through which flow takes place, L^2

Q = discharge per unit of time, L^3T^{-1};

i = hydralic gradient ; L/L_s

with

h = difference in head, (difference in head would be depth of water), L and;

L_s = length of seepage path, L;

If the seepage rate is high, control measures such as; an impermeable lining may be used to inhibit the rate of seepage.

Table 3.3 Typical Values of Coefficient of Permeability (Harr,1962)

Soil Type	Coefficient of Permeability cm/sec
Clean Gravel	1.0 and greater
Clean Sand (coarse)	1.0 - 0.01
Sand (mixture)	0.01 - 0.005
Fine Sand	0.05 - 0.001
Silty Sand	0.002 - 0.0001
Silt	0.0005 - 0.00001
Clay	0.000001 and smaller

The annual water commitment for each pumping station is:

$$WPS = F_c \quad \frac{\underline{SWR(\Delta L)}}{L} + A_e E + Q(A_s Q) \qquad (3.40)$$

where

WPS = Water/pumping station, L^4;

F_c = Factor estimating storage water utilization: depending upon the frequency of pipeline start-up/shut down, FC can be greater or less than unity.

A_e = Water surface area, L^2;

AS = Area subject to seepage, L^2; and

L = Pipe length between pumping stations, L

Therefore the total water required for coal slurry system is the summation of the water needed for coal delivery and that utilized at the pumping stations . This is expressed as:

$$WR = WRT + N*(WPS) \qquad (3.41)$$

where

N = Number of pumping stations

CHAPTER 4

RESULTS AND APPLICATIONS

The methodology developed in this study can be used for determining the maximum permissible solid concentration for coal slurry pipelines and for estimating the slurry transport system water requirements. Although the former represents an important design component by itself for slurry pipelines carrying coarse coal-water mixtures, it is also an essential step in order to make an accurate estimation of the actual amount of water required to deliver a given amoung of coal.

The maximum permissible solid concentration that can be transported through a coal slurry pipeline is determined by taking into account the slip velocity between solids, liquid hold-up phenomena and the heterogeneous solid distribution in the pipe.

Because of the large number of computations involved it is necessary to utilize a computer. A computer program written in Basic language for a microcomputer with c/pm operating system has been prepared and is listed as shown in Appendix B.

To illustrate the proposed method and test the computer program a specific type of coal is selected for use in the assumed slurry transport system and is presented in Section 4.1. Some of the coal properties and the system parameters used in this analysis are similar to that of the Black Mesa coal slurry pipeline system. For a full range sample analysis the following parameters were used:

Rosin-Ramler size dist. index = 0.9 (Ref. Fig. 1.5)

Max. allowable conc. = 0.9*$_{s}$ = 0.585

Pipe roughness = 0.064 mm (0.00015 ft)

Top coal particle size = 1.19 to 50.8 mm

Water Temp. = 70 degree F

Spec. Grav. coal = 1.35

A sample computation was also prepared and presented in section 4.2 to demonstrate the total coal slurry system water requirement estimation method.

4.1 Results Presentation

The computation results are presented in Tables 4.1 through 4.6 in the order of increasing top or largest coal particle size. The different top sizes used are:

1.19mm (1/16")

3.125mm (1/8")

9.525mm (3/8")

12.7mm (1/2")

25.4mm (1")

50.8mm (2")

The top coal particle size used in Table 4.1 is 1.19mm which is the same as that used in Black Mesa pipeline. Five different computations were performed for this top coal particle size and each of the other particle sizes. This is done by varying the pipe diameter from D = 1ft. to 3ft. by 0.5 ft. increments.

Notations used for the computer output is defined as follows:

Nomenclature for Computer Output

CL - Solid concentration in lower half of pipe by volume

CVT - In-situ solid concentration by volume

CW - Delivered solid concentration by weight

D - Pipe diameter, ft.

DT - Top size of coal particle, MM

TC - Tonnage of coal delivered, Metric Tons

TW - Tonnage of water delivered, Metric Tons

TW/TC - Water-coal ratio

VL - Velocity of liquid, ft. Sec^{-1}

VM - Velocity of mixture, ft. Sec^{-1}

VS - Velocity of solids, ft. Sec^{-1}

VP - Terminal Settling velocity of solid, ft. Sec^{-1}

As shown in Table 4.1 that, although the slip velocity does exist between the two phases, it did not produce significant hold-up in the pipe. This is because both the difference between the solid Velocity V_S and liquid velocity, V_L and the degree of local concentration heterogeneity are small. As a result, the water and coal can remain at a one to one ratio even for the largest pipe diameter used in the computation.

For coarser coal particles, however, both the magnitude of the slip velocity and the degree of solid distribution

TABLE 4.1 Computation Results for 1.19 mm x 0 Coal

```
*****************************************************
     WATER REQUIREMENTS FOR COAL SLURRY TRANSPORT
*****************************************************


DT,D,CVT,CL=      1.19        1             .426406       .534902
VP,VM,VS,VL=      .0204096    5.75788       5.74608       5.76665
CW,TC,TW,TW/TC=   .5          2.27748E+06   2.27748E+06   1


DT,D,CVT,CL=      1.19        1.5           .426206       .517216
VP,VM,VS,VL=      .0199762    6.92193       6.91098       6.93007
CW,TC,TW,TW/TC=   .5          6.16029E+06   6.16029E+06   1


DT,D,CVT,CL=      1.19        2             .426091       .506237
VP,VM,VS,VL=      .019717     7.89254       7.88218       7.90023
CW,TC,TW,TW/TC=   .5          1.24873E+07   1.24873E+07   1


DT,D,CVT,CL=      1.19        2.5           .426017       .498551
VP,VM,VS,VL=      .0195464    8.74104       8.73109       8.74842
CW,TC,TW,TW/TC=   .5          2.1609E+07    2.1609E+07    1


DT,D,CVT,CL=      1.19        3             .425964       .492744
VP,VM,VS,VL=      .0194196    9.50357       9.49394       9.51072
CW,TC,TW,TW/TC=   .5          3.38315E+07   3.38315E+07   1


---------------------------------------------

WATER TEMP.        =   70
SPEC. FRA. COAL    =   1.35
SIZE DEST. INDEX   =   .9
MAX. PERM. CONC.   =   .585
```

Table 4.2 Computation Results for 3.125 mm x 0 Coal

```
*****************************************************
     WATER REQUIREMENTS FOR COAL SLURRY TRANSPORT
*****************************************************

DT,D,CVT,CL=      3.125       1             .398403       .564024
VP,VM,VS,VL=      .0450964    7.10092       7.06624       7.12389
CW,TC,TW,TW/TC=   .47         2.6168E+06    2.95086E+06   1.12766


DT,D,CVT,CL=      3.125       1.5           .407617       .576767
VP,VM,VS,VL=      .0479221    8.5327        8.50077       8.55467
CW,TC,TW,TW/TC=   .48         7.2469E+06    7.85081E+06   1.08333


DT,D,CVT,CL=      3.125       2             .417041       .594919
VP,VM,VS,VL=      .0556613    9.72622       9.69687       9.74721
CW,TC,TW,TW/TC=   .49         1.50359E+07   1.56496E+07   1.04082


DT,D,CVT,CL=      3.125       2.5           .416861       .577502
VP,VM,VS,VL=      .0542398    10.7694       10.7415       10.7893
CW,TC,TW,TW/TC=   .49         2.60134E+07   2.70752E+07   1.04082


DT,D,CVT,CL=      3.125       3             .416737       .564426
VP,VM,VS,VL=      .053196     11.7067       11.6799       11.7259
CW,TC,TW,TW/TC=   .49         4.07196E+07   4.23817E+07   1.04082


-----------------------------------------------


WATER TEMP.       =    70
SPEC. FRA. COAL   =    1.35
SIZE DEST. INDEX  =    .9
MAX. PERM. CONC.  =    .585
```

Table 4.3 Computation Results for 9.525 mm x 0 Coal

```
*****************************************************
      WATER REQUIREMENTS FOR COAL SLURRY TRANSPORT
*****************************************************

DT,D,CVT,CL=     9.525       1             .353181       .590705
VP,VM,VS,VL=     .0920117    8.3685        8.27245       8.42095
CW,TC,TW,TW/TC=  .42         2.71576E+06   3.75033E+06   1.38095


DT,D,CVT,CL=     9.525       1.5           .37105        .59168
VP,VM,VS,VL=     .0869677    10.0472       9.96169       10.0976
CW,TC,TW,TW/TC=  .44         7.73049E+06   9.83881E+06   1.27273


DT,D,CVT,CL=     9.525       2             .380018       .580809
VP,VM,VS,VL=     .084692     11.4457       11.3656       11.4948
CW,TC,TW,TW/TC=  .45         1.60589E+07   1.96275E+07   1.22222


DT,D,CVT,CL=     9.525       2.5           .389201       .58637
VP,VM,VS,VL=     .0885381    12.6675       12.592        12.7157
CW,TC,TW,TW/TC=  .46         2.84713E+07   3.34228E+07   1.17391


DT,D,CVT,CL=     9.525       3             .388919       .56237
VP,VM,VS,VL=     .0827345    13.7651       13.6929       13.811
CW,TC,TW,TW/TC=  .46         4.45509E+07   5.22988E+07   1.17391


---------------------------------------------


WATER TEMP.       =   70
SPEC. FRA. COAL   =   1.35
SIZE DEST. INDEX  =   .9
MAX. PERM. CONC.  =   .585
```

Table 4.4 Computation Results for 12.7 mm x 0 Coal

****
WATER REQUIREMENTS FOR COAL SLURRY TRANSPORT
****

DT,D,CVT,CL=	12.7	1	.335149	.570106
VP,VM,VS,VL=	.0976557	8.53507	8.41867	8.59374
CW,TC,TW,TW/TC=	.4	2.62265E+06	3.93398E+06	1.5
DT,D,CVT,CL=	12.7	1.5	.362133	.580571
VP,VM,VS,VL=	.094534	10.2446	10.1414	10.3033
CW,TC,TW,TW/TC=	.43	7.68081E+06	1.01815E+07	1.32558
DT,D,CVT,CL=	12.7	2	.370962	.575215
VP,VM,VS,VL=	.0890457	11.6687	11.5721	11.7256
CW,TC,TW,TW/TC=	.44	1.59611E+07	2.03141E+07	1.27273
DT,D,CVT,CL=	12.7	2.5	.380038	.575567
VP,VM,VS,VL=	.0902089	12.9127	12.8216	12.9685
CW,TC,TW,TW/TC=	.45	2.8308E+07	3.45987E+07	1.22222
DT,D,CVT,CL=	12.7	3	.389288	.58746
VP,VM,VS,VL=	.096329	14.03	13.9432	14.0853
CW,TC,TW,TW/TC=	.46	4.54083E+07	5.33054E+07	1.17391

WATER TEMP.	=	70
SPEC. FRA. COAL	=	1.35
SIZE DEST. INDEX	=	.9
MAX. PERM. CONC.	=	.585

Table 4.5 Computation Results for 25.4 mm x 0 Coal

****
WATER REQUIREMENTS FOR COAL SLURRY TRANSPORT
****

DT,D,CVT,CL=	25.4	1	.300622	.574581
VP,VM,VS,VL=	.173691	9.0901	8.89344	9.17463
CW,TC,TW,TW/TC=	.36	2.48513E+06	4.41801E+06	1.77778
DT,D,CVT,CL=	25.4	1.5	.326701	.589915
VP,VM,VS,VL=	.151226	10.8975	10.7201	10.9835
CW,TC,TW,TW/TC=	.39	7.32473E+06	1.14566E+07	1.5641
DT,D,CVT,CL=	25.4	2	.335044	.571293
VP,VM,VS,VL=	.131951	12.4017	12.2364	12.4849
CW,TC,TW,TW/TC=	.4	1.52431E+07	2.28647E+07	1.5
DT,D,CVT,CL=	25.4	2.5	.35305	.587885
VP,VM,VS,VL=	.133579	13.7149	13.5625	13.798
CW,TC,TW,TW/TC=	.42	2.78173E+07	3.84144E+07	1.38095
DT,D,CVT,CL=	25.4	3	.362104	.586844
VP,VM,VS,VL=	.131875	14.8938	14.7449	14.9784
CW,TC,TW,TW/TC=	.43	4.46659E+07	5.92083E+07	1.32558

WATER TEMP. = 70
SPEC. FRA. COAL = 1.35
SIZE DEST. INDEX = .9
MAX. PERM. CONC. = .585

Table 4.6 Computation Results for 50.8 mm x 0 Coal

```
****************************************************
     WATER REQUIREMENTS FOR COAL SLURRY TRANSPORT
****************************************************

DT,D,CVT,CL=       50.8       1              .295319       .589285
VP,VM,VS,VL=       .32109     9.58311        9.25257       9.72163
CW,TC,TW,TW/TC=    .35        2.53988E+06    4.71691E+06   1.85714

DT,D,CVT,CL=       50.8       1.5            .302094       .594951
VP,VM,VS,VL=       .269071    11.472         11.1691       11.6031
CW,TC,TW,TW/TC=    .36        7.05672E+06    1.25453E+07   1.77778

DT,D,CVT,CL=       50.8       2              .309886       .594639
VP,VM,VS,VL=       .235396    13.0425        12.7592       13.1697
CW,TC,TW,TW/TC=    .37        1.47009E+07    2.50313E+07   1.7027

DT,D,CVT,CL=       50.8       2.5            .318128       .592949
VP,VM,VS,VL=       .213322    14.4126        14.146        14.537
CW,TC,TW,TW/TC=    .38        2.61442E+07    4.26563E+07   1.63158

DT,D,CVT,CL=       50.8       3              .326763       .589337
VP,VM,VS,VL=       .19987     15.642         15.3845       15.7669
CW,TC,TW,TW/TC=    .39        4.2055E+07     6.57784E+07   1.5641

----------------------------------------------

WATER TEMP.        =   70
SPEC. FRA. COAL    =   1.35
SIZE DEST. INDEX   =   .9
MAX. PERM. CONC.   =   .585
```

heterogeneity increases. This causes the lower half of the pipe to approach critical condition at high solid concentrations. When this happens, the computer is programmed to reduce the input (or delivered) solid concentration by one percent and repeat the analysis again until the danger of plugging in the lower portion of the pipe diminishes. This process was carried out with the mean flow velocity, V_m, being kept at the same level as initially determined for $C_w = 0.5$.

The results of these repeated analyses are shown in Tables 4.2 through 4.7 in which the final permissible solid concentration, C_w, is printed. The values of this concentration are somewhat smaller than the initial value of 0.5. As a result, more water is required to deliver a given amount of coal in this case than what is required for a system capable of transporting a coal slurry at a 50/50 coal to water ratio.

With the mean slurry flow velocity selected to equal a value twenty percent higher than the cirtical velocity, $V_M = 1.2\ V_C$, a relationship between the pipe diameter, coal particle size and the throughput of coal exists. This is because the critical velocity, V_C, is computed as a function of pipe diameter, solid concentration and particle size as shown in Eqs. 2.8a through 2.8e. A plot of this relationship is shown in Fig. 4.1.

The water to coal ratio is plotted in Fig. 4.2 for different coal particle sizes. Based on this water/coal ratio, the annual water requirement for coal delivery can be

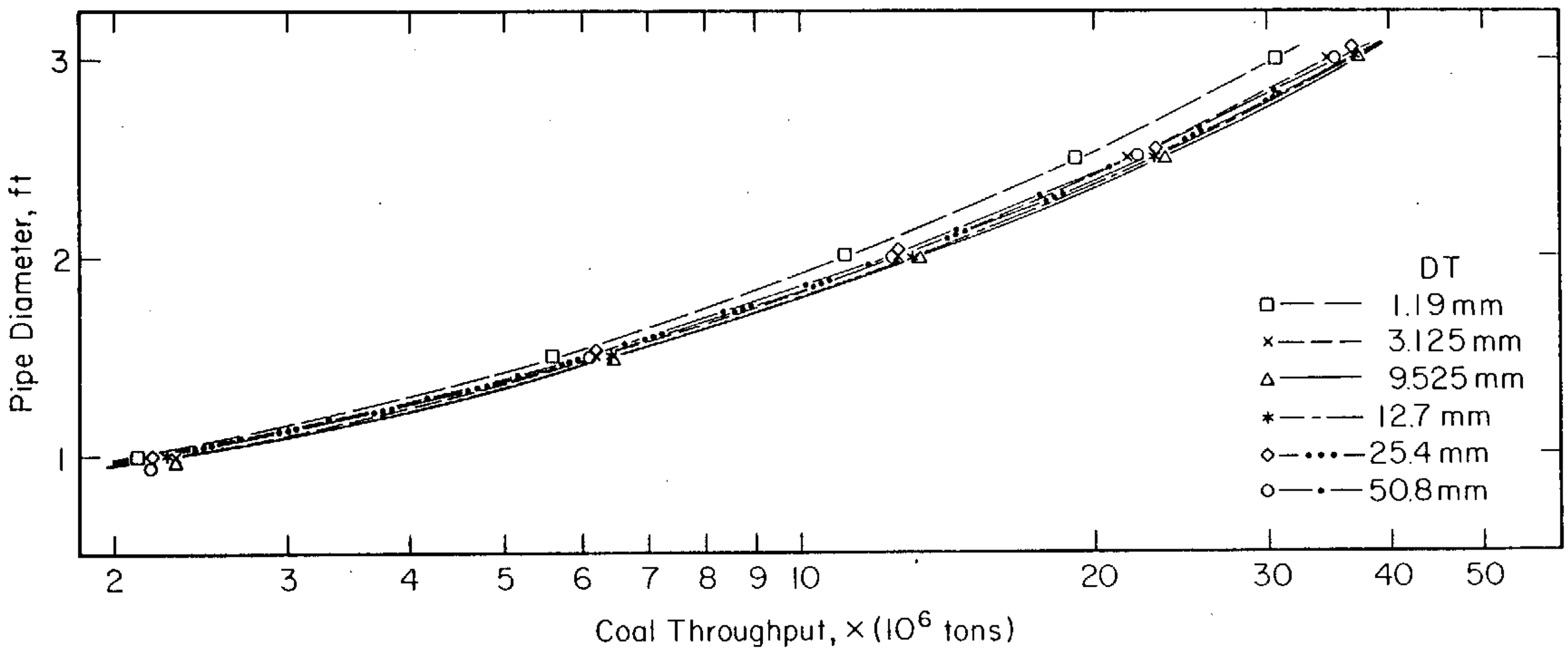

Figure 4.1 Pipe Diameter Required for Coal Slurry Transportation at Various Predicted No-Blockage Mean Flow Velocity

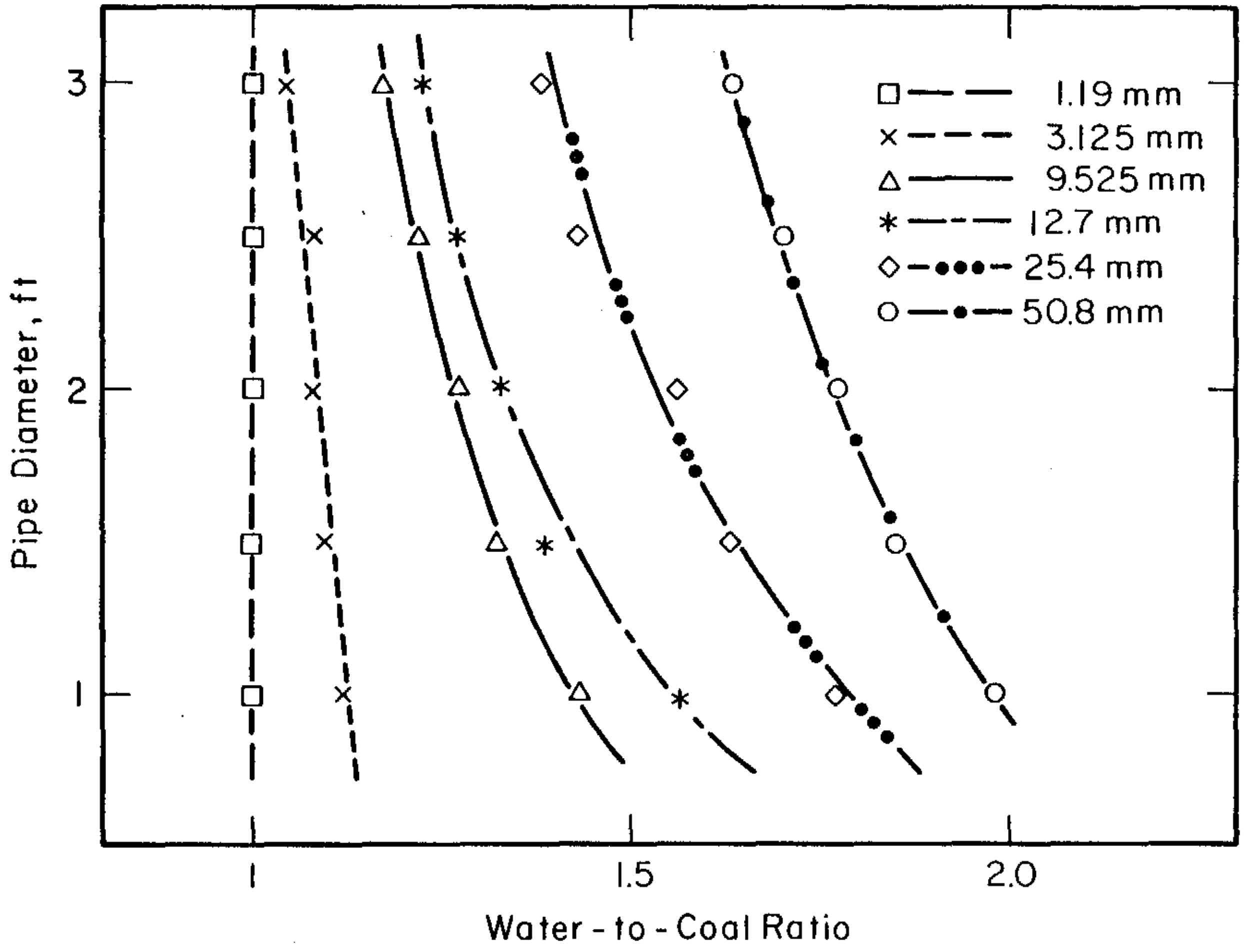

Figure 4.2 Coal-to-Water Ratio vs Predicted Pipe Diameter

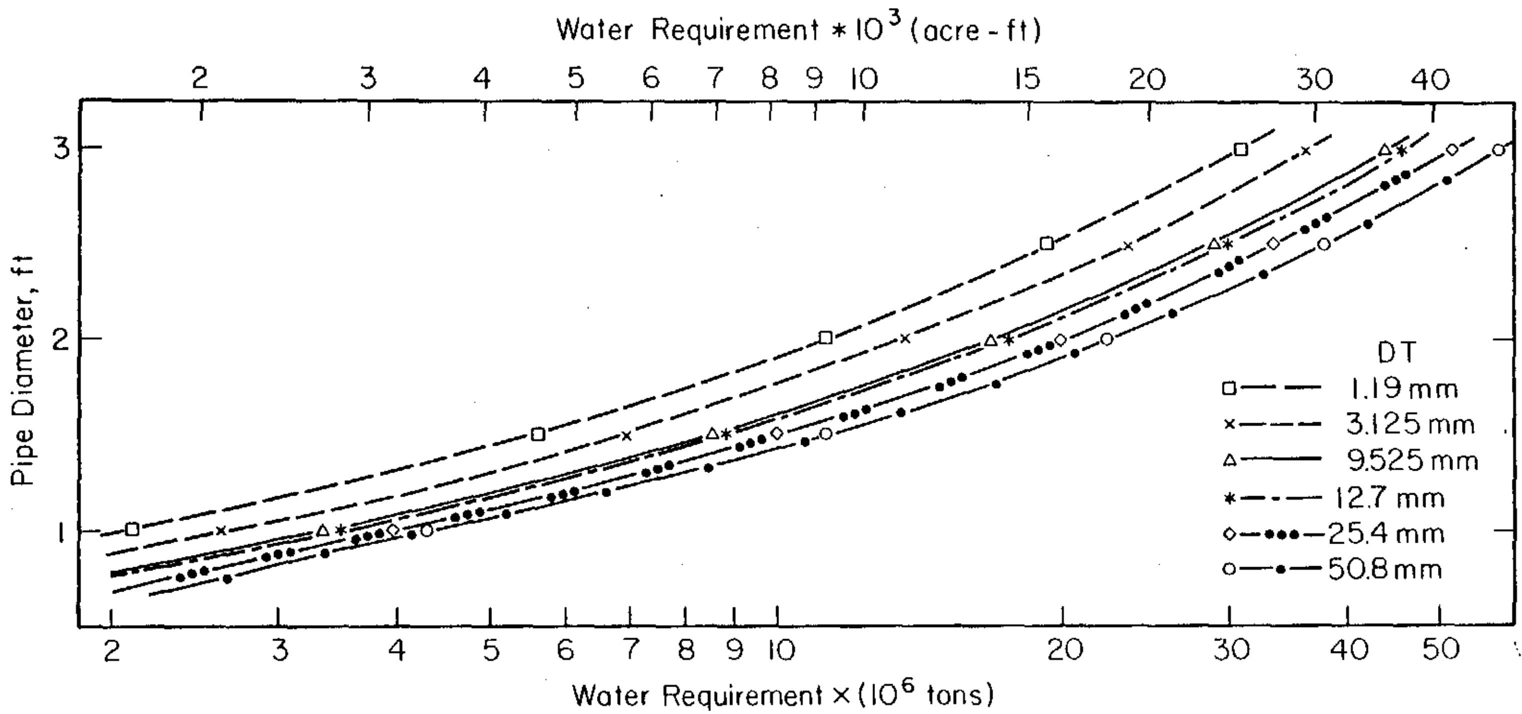

Figure 4.3 Water Requirement for Coal Slurry Transport

computed and is again plotted in terms of pipe diameter as depicted in Fig. 4.3.

In actual application and for preliminary estimation of the slurry transport water requirement, one may use Fig. 4.1 to select a pipe diameter based on the designed coal throughput and desired particle size. Using the selected pipe diameter, in connection with Figs. 4.2 and 4.3, the corresponding water-to-coal ratio and estimated transport water requirement can be determined.

It should be noted, however, that these plots are constructed for a specific type of coal that has a Rosin-Ramler size distributio index n = 0.9. For coal having a substantially different basic property, the given plots may yield erroneous results. In such instances, a separate computer analysis is needed.

4.2 Example Problem for Slurry Water Determination

If a coal slurry transportation system is to deliver 8.0 million tons of coal with a top size of 12.7mm, distribution index 0.9 and sphericity of 0.7 a distance of 1000 miles, the specific parameters for the slurry system are:

γ = 1.35	L = 1000 miles	K = .00005 cm/sec
ψ = 0.7	foundation depth = 70ft	W = 15 mph
NS = 0.9	water temp. = 50°F	L_s = 165 ft
dt = 12.7mm	air temp. = 60°F	humidity = 40 %

From Figures 4.1, 4.2 and 4.3 or by direct computation the water-to-coal ratio is obtained to determine the transport water based on the tonnage of coal and particle top size.

$$TW/TC = 1.39$$

$$D = 1.65 \text{ ft (use 20" pipe)}$$

$$WRT = 11*10^6 \text{ tons/yr} * 8.087*10^{-4} \text{ acre-ft/ton}$$

$$WRT = 8,895.7 \text{ acre-ft/yr}$$

The water requirement for the assumed 50/50 water-to-coal ratio system is 5,886 acre-fr/yr. This value differs from the computed total slurry system water requirement by 3,010 acre-ft/yr. For a pipe diameter of 1.65ft the startup water is determined from Equation 3.38 to be $1.128*10^7$ ft^3 or 259 acre-ft for the entire coal slurry transport system. Dividing the SWR by the total pipe length, L, and multiplying by the pipe length between pumping stations, DL, the water/start-up for each station is obtained.

$$SWR/station/startup = 1.128*10^7 \, DL/L$$

For L = 1,000 miles and DL = 100 miles:

$$SWR/station/startup = 25.91 \text{ acre-ft/each start up}$$

The evaporation loss due to additional storage can now be estimated from Eq 3.39 and Table 3.2 for a water depth of 35ft.

$$E = (0.36*(.25-(.52)(.40))(1+15/10))365(1/12)$$
$$= 1.149 \text{ ft/yr}$$

Assuming a water depth of 35' in the reservior, the water surface area may be computed. The total evaporation of the impounded water is:

$$E = 1.149 * 1.128*10^6/35 = 3.70*10^5 ft^3/yr$$

$$E = 8.501 \text{ acre-ft/yr}$$

The estimated seepage loss for an unlined water pond is evaluated from Eq 50, for an assumed depth of 35ft containing the necessary start-up water as:

$$K = 51.73 \text{ ft/yr}$$

$$A = 70ft * 1 ft$$

$$Q = 51.73ft/yr * 70ft^2 * 35ft/165ft$$

$$Q = 76.81 ft^3/yr * 179.5 \text{ (berm width)}$$

$$Q = 0.3165 \text{ acre-ft/yr}$$

The total water for a coal slurry system from Eqs 3.41 and 3.42 is :

Transport water = 8895.7 acre-ft/yr

Startup water = 25.91 acre-ft/yr

Evaportation = 8.501 acre-ft/yr

Seepage = 0.3165 acre-ft/yr

Number of pumping stations = 10

$$WR = 8895.7 + 10(25.91 + 0.8501 + 0.3165)$$

$$WR = 9166.47 \text{ acre-ft/yr}$$

If evaportation and seepage water requirements were not included the total water requirement would then be 9,154.8 acre-ft/yr.

CHAPTER 5

CONCLUSION

For industrial applications of long distance coal slurry pipelines, fine coal-water mixtures at a 50 percent concentration by weight is presently considered. However, in many instances, when factors involving economics and overall system energy efficiency are taken into account, use of coarse coal could be more advantageous than pulverized fine coal particles. This is true especially for short and medium distance pipelines. If a coarse coal slurry pipeline is adopted, a 50 percent by weight concentration may not always be attainable.

In a coarse coal slurry transport system, the phenomenon of the velocity differential between the suspended and suspending phases becomes more apparent and causes a significant increase in the in-situ transport solid concentration in the pipe. This concentration, instead of input or delivered concentration should be used in the pipeline limiting concentraton determination process if pipeline blockage is to be avoided. Based on this criterion, the maximum permissible delivered concentration, often less than 50 percent weight concentration, can be estimated. As a result, more water will be required through such a pipeline to deliver the same amount of coal.

In the present study, an attempt was made to develop a more comprehensive methodology for estimating the amount of required water to be used in the coal slurry transport pipeline design process. The computed results provide the total water requirement information for the entire system including water for start-up, flushing, evaporation and seepage losses. The total water requirement for a coal slurry pipeline should serve state and local water resources allocation and policy determination needs.

The use of the modified Gaessler correlation appear to provide reasonable results for the hold-up velocity and in-situ transport concentration. By intergrating along the solid concentration distribution curve over the lower half of the pipe cross section, the average in-situ concentraton for this portion of the pipe can be evaluated. A criterion was recommended in which a maximum possible concentration by volume in the lower half of the pipe is not to exceed a value equal to "0.9 x 0.65". The latter quantity represents the maximum attainable volume fraction under random packing conditions.

Although this criterion is considered a rather stringent one the computational results appear to be in close agreement with the experience values. The assumed factor of 0.9 still needs to be verified. Further study along this line is recommended.

APPENDIX A

NOMENCLATURE

A - Storage foundation area, L^2

AP - Area of pipe, L^2

A_p - Surface area of particle, L^2

AS - Water surface area, L^2

A_s - Surface area of a spherical particle, L^2

a - 1/3 mean particle diameter, L

B - Coefficient of proportionality

C - Empirical constant

C_a - Reference solid concentration in pipe

C_D - Coefficient of drag

C_L - Solid concentration in lower half of pipe

C_v, C_w - Volume and weight fraction of solids input, res.

C_{v1}, C_{v2} - Volume and weight fraction of solids in suspension and saltation respectively.
C_{w1}, C_{w2}

CVF - Concentration volume factor

CVT - Actual Transport Concentration

C_{v1t}, C_{v2t} - Total volume of solid concentration suspension and saltation respectively

Cy - Solid concentration at y distance from pipe's bottom

D - Pipe diameter, L

d - Particle diameter, L

d - Characteristic particle size, L

E - Annual Evaporation, LT^{-1}

e_a - Vapor pressure of air, FL^{-2}

e_o - Saturation vapor pressure, FL^{-2}

F_D - Force of Drag, $MLT^{-2} = F$

F_g - Force of gravity, $MLT^{-2} = F$

F_{rm} - Froude Number, V_m/ gD

F_{ro} - Froude Number, V_o/ gD

f_L - Fanning friction factor

$f^o{}_s$ - Material Constant

f - Water supply factor

g - Gravity, LT^{-2}

H - Hold-up ratio

h - Head of water, L

i - Hydraulic gradient

K - Karman's constant

L - Pipe length, L

L - Pipe length between stations, L

L_s - Length of seepage path, L

MMT - Metric million tons, MLT^{-2}/T

MTY - Contracted million tons/yr, MLT^{-2}/T

N - Number pumping stations

NS - Coal character index

OMC - Original moisture content

OP - Operation factor

P - Percent concentration

Pa - Area of particle projected on a plane, L^2

P - Percent change in solid concentration

Q - Volume flow rate, L^3T^{-1}

R - Cumulative oversize particles retained

Re - Reynolds Number

r - Radius pipe, L

S - Specific gravity

SWR - Start-up water required, L^4T^{-1}

TC - Tonnage of coal, MLT^{-2}

TW - Tonnage of water, MLT^{-2}

TSC - Total solid concentration

V - Velocity, LT^{-1}

V_c - Critical velocity, LT^{-1}

V_o - Particle settling velocity, LT^{-1}

V'_o - Adjusted particle settling velocity for heavy medium, LT^{-1}

V_s - Actual velocity of solids, LT^{-1}

V_{s1t}, V_{s2t} - Total velocity of suspended and saltating solids, LT^{-1}

V_{ss} - Superficial velocity of solids, LT^{-1}

W - Wind velocity, LT^{-1}

WPS - Water/pumping station, L^3T^{-1}

WR - Total water required, L^4T^{-1}

WRT - Water required for transport, L^4T^{-1}

y - Distance from pipe bottom, L

β - Proportionality factor

β_* - Material constant

ϕ_s - Gaessler bed packing factor

γ - Specific Weight, $ML^{-2}T^{-2}$

ρ - Density, ML^{-3}

ρ_t - Bulk fluid density of a mixture, ML^{-3}

ν - Kinematic Viscousity, L^2T^{-1}

ψ - Particle sphericity

<u>Subscripts</u>

1, 2 - Suspension and saltation respectively

L, S, m - Solid, liquid and mixture respectively

APPENDIX B

COMPUTER PROGRAM

```
10 DIM VP2(30),DX(30),P(30),DP(30),VP(30),CD(30),RE(30),CV1(30)
20 DIM CV2(30),CW2(30),CW1(30),VS(30),VS2(30),VS1(30),MDX(30),CVT(30)
30 DIM DT(10),DB(10),D(10),CWF(10)
40 REM
50 REM
60 FOR K=1 TO 6
70 READ DT(K),DB(K)
80 NEXT K
90 FOR J=1 TO 5
100 READ D(J)
110 NEXT J
120 READ TW,NS,FV,SS,N,OP,CVF,B4,K4
130 REM
140 REM *****************
150 REM    CONSTANTS
160 REM *****************
170 REM
180 G=32.174     'GRAVITY, FT/SEC
190 EPS=.00015   'PIPE ROUGHNESS, FT
200 PHI=.65      'VOLUME FRACTION SOLIDS PAKED IN TUBE
210 BETA=.28     'PROPORTIONALITY FACTOR
220 FSO=.0046    'MATERIAL CONSTANT
230 REM
240 REM ***************************
250 REM   COMPUTE BASIC PARAMETERS
260 REM ***************************
```

```
270 REM
280 MU=EXP(-9.566-.0215*TW+5.622*10^(-5)*TW^2)    'FOR TW<100 D-F VISCOSITY
290 NU=EXP(-10.227-.02164*TW+5.781*10^(-5)*TW^2)  'FOR TW<100 D-F KINEMATIC VISCOUSITY
300 IF TW>100 THEN MU=EXP(-9.6924-.01775*TW+3.2175*10^(-5)*TW^2)
310 IF TW>100 THEN NU=EXP(-10.355-.1781*TW+3.3425*10^(-5)*TW^2)
320 ROL=MU/NU      'DENSITY OF WATER
330 ROS = SS*ROL   'DENSITY OF LIQUID
340 GAMA=ROL*G     'SPECIFIC WEIGHT OF WATER
350 REM
360 REM *****************************
370 REM   PARTICLE SIZE DISTRIBUTION
380 REM *****************************
390 REM
400 FOR K=1 TO 6
410 DT=DT(K)
420 DB=DB(K)
430 REM
440 LPRINT "*******************************************************"
450 LPRINT "     WATER REQUIREMENTS FOR COAL SLURRY TRANSORT"
460 LPRINT "*******************************************************"
461 LPRINT
462 LPRINT
470 REM
480 FOR J=1 TO 5
490 D=D(J)
500 OPEN "I",#1,"B:SSF"            'INPUT SELECTED PART. SIZE DESIG. IN FILE
510 FOR I=1 TO N
520 INPUT #1,DX(I)
530 NEXT I
540 CLOSE #1                       'CLOSE SCREEN SIZE FILE
550 FOR I=1 TO N
560 P(I)=0
570 IF DX(I)>DT GOTO 590
580 P(I)=100*EXP(-(DX(I)/DB)^NS)   'PERCENT RETAINING, ROSIN-RAMMLER
590 NEXT I
600 DM=0
```

```
610 P(0)=99.99
620 DX(0)=.001
630 IT=1
640 FOR I=1 TO N
650 IF I>IT GOTO 730
660 IF DX(I)>DT GOTO 690
670 IT=I+1
680 GOTO 700
690 DX(I)=DT
700 MDX(I)=(DX(I-1)+DX(I))/2      'MEAN SECTIONAL SIZE IN MM
710 DP(I)=(P(I-1)-P(I))/(100)     'DELTA PERCENTAGES
720 DM=DM+DP(I)*MDX(I) 'MEAN DISTRIBUTION SIZE
730 NEXT I
740 FOR I=1 TO (N+1)
750 IF I=(N+1) THEN MDX(I)=DM
760 IF I=(N+1) GOTO 780
770 IF I>IT GOTO 840
780 DX(I)=1000*MDX(I)             ' CHANGE TO MICRON FOR SETTLING VEL. COMP.
790 IF DX(I)<=150 THEN VP(I)=EXP(-14.803+2.2412*LOG(DX(I)-.0446*(LOG(DX(I)))^2))
800 IF DX(I)<=150 GOTO  830
810 IF DX(I)>3000 THEN VP(I)=EXP(-7.4543+.9489*LOG(DX(I))-.0252*(LOG(DX(I)))^2)
820 IF DX(I)<3000 THEN VP(I)=EXP(-19.763+4.261*LOG(DX(I))-.2478*(LOG(DX(I)))^2)
830 DX(I)=DX(I)/1000    'CHANGE BACK TO MM
840 NEXT I
850 FOR I=1 TO (N+1)
860 IF I=(N+1) GOTO 880
870 IF I>IT GOTO 980
880 DX(I)=DX(I)/(25.4*12)  'CHANGE TO FEET FOR REYNOLDS NO. & DRAG COEFFICIENT
890 RE(I)=VP(I)*DX(I)/NU
900 IF RE(I)<100000! THEN
           CD(I)=EXP(1.93489-.262589*LOG(RE(I))+.0189006*LOG(RE(I))*LOG(RE(I)))
910 IF RE(I)<10000 THEN
           CD(I)=EXP(9.1019*(-1)+2.06907*LOG(RE(I))-.104981*LOG(RE(I))*LOG(RE(I)))
920 IF RE(I)<4000 THEN
           CD(I)=EXP(1.33574+.0087991*LOG(RE(I))-.008345*LOG(RE(I))*LOG(RE(I)))
```

```
930 IF RE(I)<1000 THEN
          CD(I)=EXP(4.07581-.81059*LOG(RE(I))+.0528908*LOG(RE(I))*LOG(RE(I)))
940 IF RE(I)<100 THEN
          CD(I)=EXP(6.25354-1.93306*LOG(RE(I))+.197017*LOG(RE(I))*LOG(RE(I)))
950 IF RE(I)<10 THEN
          CD(I)=EXP(4.25221-.8569*LOG(RE(I))+.0714634*LOG(RE(I))*LOG(RE(I)))
960 IF RE(I)<1 THEN CD(I)=24/RE(I)
970 DX(I)=DX(I)*25.4*12
980 NEXT I
990 REM
1000 REM ************************************
1010 REM  VELOCITY OF MIXTURE DETERMINTATION
1020 REM ************************************
1030 REM
1040 VM1=25
1050 CW=.5
1060 CV=(CW/ROS)/((CW/ROS)+(1-CW)/ROL)   'CONCENTRATION BY VOLUME DELIVERED
1070 IF CW<.5 GOTO 1240
1080 REP=VM1*D/NU       'PIPE REYNOLDS NO.
1090 FL=.25*(1.325/((LOG(EPS/(3.7*D)+5.74/REP^.9))^2))  'FANNING FRICITON FACTOR
1100 VHW=(1.25*(100*CV)^(.19))*(SQR(2*G*(SS-1)*D))*((DM/(25.4*12)/D)^(1/6))
1110 VHD=1.35*(SQR(2*G*D*(SS-1)))
1120 VHZ=SQR(40*G*D*(SS-1)*CV/(SQR(CD(N+1))))
1130 VHY=9.8*D^(.33)*VP(N+1)^.25*(SS-.4)
1140 VHT=SQR(2.411*(CV^(.2263))*(FL^(-.2334))*(CD(N+1)^(-.384))*D*G*(SS-1))
1150 VH=(VHW+VHD+VHZ+VHY+VHT)/5
1160 VM=FV*VH
1170 IF ABS(VM-VM1)>.1 THEN VM1=VM ELSE GOTO 1190
1180 GOTO 1080
1190 REM
1200 REM ************************************
1210 REM           MAIN PROGRAM
1220 REM ************************************
1230 REM
1240 FRM=VM/(SQR(G*D))  'FROUDE NUMBER
1250 PIT=0              'TOTAL PERCENTAGES
```

```
1260 CV1T=Ø                'TOTAL CONCENTRATION IN SUSPENSION
1270 CV2T=Ø                'TOTAL CONCENTRATION IN SALTATION
1280 VS1T=Ø                'RESULTANT SUSPENSION VELOCITY
1290 VS2T=Ø                'RESULTANT SALTATION VELOCITY
1300 VST=Ø                 'RESULTANT SOLID VELOCITY
1310 MCVT1=Ø               'HOLD-UP CONCENTRATION
1320 FOR I=1 TO N
1330 IF I>IT GOTO 1900
1340 REM
1350 REM
1360 REM *********************************
1370 REM       FLOW PATTERN DELINEATION
1380 REM *********************************
1390 REM
1400 LET CV1(I)=.99*CV
1410 DCV1=CV1(I)
1420 DCV1=.5*DCV1
1430 ROM1=(CV1T+CV1(I)*(1-PIT))*(ROS-ROL)+ROL  'BULK FLUID DENSITY
1440 FRO=VP(I)/(SQR(G*D))
1450 B=FRO^(-1/3)
1460 A=(1/PHI)*(SQR((3/4)*(ROM1/(ROS-ROM1))))*((FRM/3.7)^B)
1470 CW2(I)=CW*((FRO/(.1*PHI))*(SQR((3/4)*CD(I)))*((CV/PHI)^A))
1480 IF CW2(I)>CW GOTO 1570
1490 CV2(I)=(CW2(I)/ROS)/((CW2(I)/ROS)+(1-CW2(I))/ROL)
1500 CW1(I)=(CV1(I)*ROS)/((CV1(I)*ROS)+(1-CV1(I))*ROL)
1510 CV3=CV1(I)+CV2(I)     'CHECK FOR CORRECT ASSUMPTION OF CV1(I)
1520 RATIO=CW2(I)/CW       'CHECK FOR PART SUSPENSION
1530 IF RATIO>.98   GOTO 1570
1540 IF ABS(CV-CV3)<.ØØ1 GOTO 164Ø
1550 IF CV > CV3 THEN CV1(I)=CV1(I)+DCV1 : GOTO 142Ø
1560 IF CV < CV3 THEN CV1(I)=CV1(I)-DCV1 : GOTO 142Ø
1570 CV2(I)=CV*.99
1580 CV1(I)=CV*.Ø1
1590 REM
1600 REM *********************************
```

```
1610 REM        PARTICLE VELOCITY
1620 REM *********************************
1630 REM
1640 PH= (1-PHI)/PHI
1650 CW1(I)=(CV1(I)*ROS)/((CV1(I)*ROS)+(1-CV1(I))*ROL)
1660 CW2(I)=(CV2(I)*ROS)/((CV2(I)*ROS)+(1-CV2(I))*ROL)
1670 ROM1=(CV1T+CV1(I)*(1-PIT))*(ROS-ROL)+ROL
1680 A=(1/PHI)*(SQR((3/4)*(ROM1/(ROS-ROM1))))*((FRM/3.7)^B)
1690 B1=(2*FRO^(-1/3))-1/PHI
1700 A1=(PH/PHI)*(SQR((3/4)*(ROM1/(ROS-ROM1))))*((FRM/3.7)^B1)
1710 VSR=(CW2(I)/CW)*(.1*PHI)/(FRO*(SQR((3/4)*CD(I))))*PH*(CV/PHI)^(-A1)
1720 BETA1=BETA*(CW2(I)/CW)*(1/VSR)  'MATERIAL CONSTANT
1730 FS1=FSO*(1-(CW2(I)/CW)*VSR)
1740 LET  VR=.99   'SOLIDS TO MIXTURE VELOCITY RATIO
1750 Y=((FRO/FRM)^2)*(1-(1/VR)*CV)
1760 Z=FS1*(ROS/(ROS-ROL))-FL*(ROL/(ROS-ROL))*((1-CV)^2)/(VR-CV)
1770 M=Y*(BETA1+(VR^2)*(FRM/2)*Z)
1780 VR1=1-SQR(M)
1790 IF ABS(VR1-VR)>.001 THEN VR=VR1 : GOTO 1750
1800 VS(I)=VR*VM
1810 CVT(I)=1/VR*CV
1820 VS1(I)=VSR*VS(I)
1830 VS1(I)=(VS(I)*CVT(I)-VS2(I)*CW2(I))/CW1(I)
1840 VST=VST+VS(I)*DP(I)
1850 VS1T=VS1T+VS1(I)*DP(I)*(CV1(I)/(CV1(I)+CV2(I)))
1860 VS2T=VS2T+VS2(I)*DP(I)*(CV2(I)/(CV1(I)+CV2(I)))
1870 CV1T=CV1T+CV1(I)*DP(I)
1880 CV2T=CV2T+CV2(I)*DP(I)
1890 PIT=PIT+DP(I)
1900 NEXT I
1910 REM
1920 REM ************************
1930 REM    WATER DETERMINATION
1940 REM ************************
1950 REM
1960 CW1T=(CV1T*ROS)/((CV1T*ROS)+(1-CV1T)*ROL)
```

```
1970 MCVT=VM/VST*CV
1980 SCV=CV1T+CV2T
1990 VSS=CV*VM
2000 AP=3.14*(D^2)/4
2010 QS=VST*MCVT*AP
2020 VL=(VM-MCVT*VST)/(1-MCVT)
2030 QL=VL*(1-MCVT)*AP
2040 TC=QS*(3600*24*365*OP)*GAMA*SS/2200
2050 TCW=QL*(3600*24*365*OP)*GAMA/2200
2060 RTW=TCW/TC
2080 R=D/2
2090 ROM=CV1T*(ROS-ROL)+ROL
2100 VP(N+1)=VP(N+1)*SQR(((ROS/ROM)-1)/((ROS/ROL)-1))
2110 USTAR=SQR(FL*VM^2/2)
2120 Z1=VP(N+1)/(B4*K4*USTAR)
2130 AD=(1/3)*(DM/(25.4*12))
2140 P=0
2150 T=0
2160 X3=(R-AD)/R
2170 DH=-ATN(X3/SQR(-X3*X3+1))+1.5708
2180 FPP=3.14159/90
2190 PP2=(3.14159/2)+FPP/2
2200 FOR H=DH TO (2*PP2) STEP FPP
2210 T1=((1+COS(H))/(1-COS(H)))^Z1*(SIN(H))^2*FPP
2220 T=T+T1
2230 NEXT H
2240 CA=MCVT*AP/(2*R^2*((AD/(2*R-AD))^Z1)*T)
2250 FOR H=DH TO PP2 STEP FPP
2260 Y=R-R*COS(H)
2270 CY=CA*((2*R-Y)/Y*(AD/(2*R-AD)))^Z1
2290 P1=CY*(SIN(H))^2*FPP
2300 P=P+P1
2310 NEXT H
2320 CL=2*R^2/(AP/2)*P
2330 CH=CVF*PHI
2340 IF CL<CH GOTO 2380
```

```
2350 IF ABS(CL-CH)>.01 THEN CW=CW-.01
2360 IF CW<.3 GOTO 2440
2370 IF ABS(CL-CH)>.01 GOTO 1060
2380 LPRINT "DT,D,CVT,CL=      ";DT,D,MCVT,CL
2390 LPRINT "VP,VM,VS,VL=      ";VP(N+1),VM,VST,VL
2400 LPRINT "CW,TC,TW,TW/TC=   ";CW,TC,TCW,RTW
2420 LPRINT
2423 LPRINT
2430 GOTO 2460
2440 LPRINT "TOP SIZE, PIPE DIA, SUSP./CW RATIO";DT,D,CWF
2450 LPRINT "IMPROBABLE PARTICLE SIZE-PIPE DIA. COMBINATION"
2453 LPRINT
2454 LPRINT
2460 NEXT J
2461 LPRINT
2462 LPRINT "---------------------------------------------
2464 LPRINT "WATER TEMP.       =  "; TW
2465 LPRINT "SPEC. GRA. COAL   =  "; SS
2466 LPRINT "SIZE DIST. INDEX =  "; NS
2467 LPRINT "MAX. PERM. CONC. =  "; CH
2470 NEXT K
2480 DATA 1.19,.26,3.125,.68,9.525,2.2,12.7,2.8,25.4,5.8,50.8,12.5
2490 DATA 1,1.5,2,2.5,3
2500 DATA 70,.9,1.2,1.35,20,.98,.90,.92,.4
2510 END
```

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