COMPARATIVE COAL TRANSPORTATION COSTS: AN ECONOMIC AND ENGINEERING ANALYSIS OF TRUCK, BELT, RAIL, BARGE AND COAL SLURRY AND PNEUMATIC PIPELINES

VOLUME 7

PNEUMATIC TRANSPORT

Prepared for

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FINAL REPORT

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FOREWARD

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Subject Inventions

This is to certify that, to the best of my knowledge and belief, there were no Subject Inventions made or have resulted from the performance of this contract.

August 1977

Michael Rieber

Michael Rieber
Principal Investigator

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by

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7. PNEUMATIC TRANSPORT

7.1 INTRODUCTION

A new mode of coal transportation based on the principles of pneumatic conveying has been recently proposed by Soo, et al. [5]. Pneumatic transport is not a novel concept and commercial experience with pneumatic pipelines for short haul distances is plentiful. The list of applications is long and includes transporting ores, chemicals and pharmaceutical products, agricultural products, and domestic and industrial wastes. The study by Soo, et al. [5] updated an earlier one [10] and presented the most recent economic evaluation of pneumatic transportation of coal. Their preliminary study concluded that there are immediate advantages for short-distance transport (less than 100 miles) and that it is both technologically and economically feasible. That study also concludes that pneumatic transport has a higher potential and more promising profitability in long-distance applications than rail if new track and roadbed must be built. Some of the advantages of long and short distance pneumatic pipeline transport of coal compared to rail and slurry transport are:

1) Replacement of diesel fuel consumed by unit trains, as the pipeline can be powered by coal-generated electricity;

2) Reduction of the skilled-labor costs required for upgrading and maintaining railroads;

3) Elimination of signaling, rerouting and overpass costs due to increased rail traffic on mainline trackage;

4) Elimination of wind loss of coal fines which occur with some coals during rail shipping, and its environmental and safety impacts;

5) Elimination of major loading and unloading facilities from mine mouth to plant delivery;

6) Reduction of storage space and facilities needed for continuous supply;

7) Elimination of the high cost of preparation and separation of coal slurry [13];

8) No water requirement and therefore none of the associated handling and environmental problem with which slurry pipelines must be concerned;

9) Power failures, pumping outages and their handling are not a problem when compared to slurry pipelines;

10) Suitability for the complete automation of the entire system by means of programmed remote control; and

11) Provision for flexibility of route design, for example:

    a) shorter and more direct transportation routes,

    b) improved profitability of railroads by serving as feeders from new mines and distributors to new consumers,

    c) distribution from a large production coal mine to several small consumers, or feeding from multi-mine mouths to a large coal consuming gasification or liquefaction facilities can be served by simply branching the conduits using switching locks or rotary distributors,

    d) gathering from mines to a rail head [15].

It appears that the most immediate application of a pneumatic pipeline is that of a conveyor system for coal transport in conjunction with the use of the right of way of a railroad system. Substitution of short distance coal haulage or transfer by pneumatic pipeline would eliminate loading and unloading features which involve both tight scheduling and significant costs. Pipeline augmentation of railroads as feeders and distributors, replacement of abandoned railroads, and short distance haulage all should be more cost competitive than capital and labor intensive railroads.

The U.S. Bureau of Mines has made two feasibility studies (1962, [10] 1967 [16]) of the pneumatic transport of coal. Based on the technical uncertainty of the compression of the coal-gas mixture, the confused state of pressure drop correlations and the unacceptable energy requirements of the system, both studies ruled out the technical as well as the economic feasibility of such application for large tonnages and long distance transport. However, the hypothetical model on which those conclusions were based was less than realistic. Operating an unsteady flow of pulverized coal and compressing the coal-gas mixture to a pressure of 100 atmospheres undoubtedly lead to questions of operability and technical feasibility. High energy requirements resulted from the misused high loading ratio and the extrapolation of the friction factor from small scale laboratory work.

In this study, a conceptual design as well as an economic evaluation of pneumatic pipeline transport is developed and extended to a possible 3.5 mile pilot system. An economic analysis of the coal transport costs of a feeder (1000 ft) and an intermediate distance (100 miles) pneumatic pipeline is included for comparison.

A list of symbols used in this study is presented here for convenience.

NOMENCLATURE

Letter Symbols

A	Pipe cross-sectional area
d	Particle diameter
D	Pipe diameter
g	Gravitational constant
G	Mass flow ($\dot{M}/A$)
K	Pipe roughness
k	Suspension parameter as defined in (7.3.7a)
L	Pipe length
$\dot{M}$	Mass flow rate
P	Static pressure
δp	Pressure drop
$\dot{Q}$	Volumetric flow rate
R	Gas constant
T	Temperature
V_s	Saltation velocity for single particle

V	Nominal velocity ($M/\rho A$)
V_α	Settling velocity of solids in an infinite fluid, as defined in [45]
z	Elevation

Dimensionless Group

A	Correlation constant as defined in (7.4.8)
C_1	Constant as defined in (7.3.4)
C_D	Drag coefficient, $4gd\ (\rho_p - \rho_f)/3\rho_f\ V^2$
f	Friction coefficient
Fr	Fronde number ($\frac{V^2}{gD}$)
$\dot{M}^*$	Mass flow ratio ($\dot{M}_s/\dot{M}_f$)
Re	Pipe Reynolds' number (VD/ν)
S	Exponential correlation constant as defined in (7.3.4)
ρ^*	Density ratio (ρ_s/ρ_f)

Greek Symbols

α	Parameter as defined in (7.3.4)
β	$d/\delta = \left[C_D Re_p{}^2\right]^{1/3}$
	Parameter defines the spread of the sizes of particles
δ	$\left[3\nu^2/4g\ .\ (\rho^*-1)\right]^{1/3}$, feet
ϵ	Shape factor
θ	Pipe inclination

μ	Dynamic viscosity
ω	$\left[\frac{4}{3}g \quad \nu/(\rho^{*}-1)\right]^{1/3}$ ft/sec.
ν	Kinematic viscosity
ρ	Density
ϕ	Correlation constant as defined in (7.4.10)

Subscripts

a	Air
C	Minimum transport condition
f	Fluid
m	Mixture
p	Particle
s	Solid
1	Inlet
2	Outlet

7.2 TECHNICAL BASIS OF PNEUMATIC TRANSPORT

7.2.1 Introduction

> "Design of today's pneumatic conveying systems still hinges around the empirical approach, with particular emphasis on so called 'seat of the pants' engineering. Judgment and experience play a large part in specification and selection. Most know-how is closely held by the relatively few engineers who specialize in the pneumatic field."

This statement appeared in John Fischer's article, "Practical Pneumatic Conveyor Design" "Math Doesn't Tell Whole Story" [18,1958]. It illustrates the state of the art of pneumatic transport systems. The reason why pneumatic conveying has not yet come into general use seems to be traceable to the absence of a well-founded, precise, scientific theory which embraces all problems of detail and has undergone verification in practice. The variety of the physical properties of the materials being conveyed and the multiplicity of design possibilities hamper calculation by specific formulae and make research extremely expensive. The first installations were built mainly on an empirical basis adopting the results of research made by the industry, [19] or by extending and scaling up from current practice.

The details of such empirical methods are presented by Fischer [18] EEUA [19], Hudson [20,21,22], DallaValle [23], Bannister [24], and Gluck [25]. These authors present approximate methods and formulae for calculating the overall pressure drop in the gas-solid system, starting from a recommended superficial air (carrier gas) velocity based on the type of material conveyed. Typical of such tabulated data is that given in reference [19] page 61. Such data are, in fact, the air rate at which blockage occurs plus a margin established by practice and experience for the particular material listed. They can serve only as a rough guide for new situations and are useful only where subsequent adjustments can be readily made in operation and where efficiency is not of prime importance.

7.2.2 Previous Theoretical Analyses

Pneumatic conveying is not a new field of development; experimental investigations on grains and other particulate material were first reported by Gasterstadt [26] as well as Cramp and Priestley [27] in 1924. Further investigations of the fundamental phenomena and design were motivated by the application of transporting coal and grains in pipelines. The bibliographical review compiled by Wendy A. Thornton [28] contains the most comprehensive literature survey of the fundamental research, application, and other related studies of pneumatic transport of solids in pipes. It should also be noted that Dukler, et al. [29] reported that by 1964, over 20,000 experimental data from various sources had been employed for obtaining correlations and generalizations of pressure drop, hold-up and friction factors. However, different approaches have been undertaken by theoretical investigators for their correlations and analyses of results. A representative, rather than an accumulative listing, includes:

1) Empirical correlations are the most commonly employed techniques.

2) Dimensional analysis has been used by Boothroyd [30], Jones and Hitchcock [31], Chowdhury [32], and Rose and Duckworth [33]. The work by Rose and Duckworth provides the most detailed and convincing solution for this type of approach.

3) An approach through the solution of equations of motion was presented in references [34,35].

4) Summation models which make a linear summation of the momentum of the two phases were considered by Soo [36], Peskin [37] and Trezek [38,39].

5) Continuum mechanics has been utilized by McCarthy and Olson [40].

6) A first trial of similarity analysis was claimed by Dukler, et al. [29] and

7) Statistical analyses have recently been employed [41,42].

Much arduous research has been reported, but the published results seem more useful to theoretical investigators whose interest lie in advancing the understanding of suspension flow, than to industrial designers and users whose primary concern is a workable application. Furthermore, the phenomena which occur in pneumatic conveying are too varied and too complex to be expressed in an equation of general form. For example, the solid friction factor, as presented in Rose and Duckworth's analysis, could be a function of thirteen variables or ten non-dimensional groups.

Symbolically:

$$
\begin{aligned}
f_s &= F\left[\rho_f,\ V,\ D,\ \mu,\ g,\ \dot{M}_s,\ \rho_s,\ \epsilon,\ d,\ K,\ z,\ \beta,\ \theta\right] \\
&= F\left[\left(\frac{\rho_s VD}{\mu}\right),\ \left(\frac{V^2}{gD}\right),\ \left(\frac{\dot{M}_s}{\dot{M}_f}\right),\ \left(\frac{\rho_s}{\rho_f}\right),\ (\epsilon),\ \left(\frac{d}{D}\right),\ \left(\frac{K}{D}\right),\ (z),\ (\beta),\ (\theta)\right] \qquad (7.2.1)
\end{aligned}
$$

(Notations are explained in NOMENCLATURE)

Attempts made to generalize the empirical work have not been successful.

A comment of an earlier reviewer [43,1959] illustrates the problem:

> "A good many of the experimental investigations reported had been aware of only a few of the many possible system variables, so that they dealt with a comparatively narrow range of conditions. As a result, most of the published data on gas-solid systems were restricted in scope and frequently conflicting. Also, scarcity of the fundamental information and the lack of uniformity of presentation made a comparative study of the experimental evidence extremely arduous."

In spite of considerable technical effort, the design of systems for the pneumatic transport of solids has not become an exact science. Nevertheless, a theoretical analysis and correlation of friction factor data for dilute gas-solid suspensions has been reviewed by Pfeffer, et al. [44]. While there is no reliable generalized design equation for pneumatic transport, Duckworth [45] has tabulated pressure gradients, and velocity correlations of dilute phase gas-solid flows, and discussed their pertinence to the application of design.

7.2.3 Minimum Transport Velocity

Of all the determinations to be made in designing a dilute gas-solid suspension system, the most fundametal one must be the establishment of the minimum permissible gas flow rate for a given system. This minimum must be high enough to prevent settling of solids, especially in a horizontal transport system, thus maintaining a steady flow condition. If the air flow rate is reduced below this value, it leads to unstable operation and the possibility of solid flow stoppage. On the other hand, operation of a system at a velocity which is too high leads to unnecessarily high power requirements. In either of these two extreme cases, the system operates uneconomically due to the frequent shutdown of the system in the former case, and to excessive power consumption in the latter.

The importance of establishing the minimum air flow as a fundamental design parameter is emphasized by the following:

1) Power requirements for gas-solid transport systems might be higher than those of more conventional conveyors;

2) Blower power requirements increase approximately as the cube of the gas velocity;

3) Pipe erosion increases significantly as gas velocity increases;

4) Particle size attrition.

Successful design depends, therefore, upon first establishing the minimum carrier gas velocity at which the material may be steadily conveyed. The successful prediction of the minimum gas velocity for any given system with a reasonable degree of certainty is a pre-requisite to an economical design.

Although most of the basic studies of the lift force on a particle in a gas-solid suspension treated cases of particle size smaller than the thickness of the laminar sublayer in the turbulant flow [46,47], these do not apply to the case of transport of large particles above millimeter size [5]. Using particles of size greater than the laminar sublayer thickness, Thomas [48] claims that his equation applies to all suspensions of particles which conform to the size criterion. However, the great complexity of his equation, coupled with the fact that it was developed from data obtained in rather small scale model tests, discourages the use of this correlation for design purposes. It is also interesting to note that there is a considerable overlap in the variables used in the correlations developed by Doig and Roper [49] (Equation 7.3.1), Duckworth [45] (Equation 7.3.2) and Matsumoto [50] (Equation 7.3.3) that the minimum transport velocity, V^c, is related to the mass flow ratio, $\dot{M}^*$ and the settling velocity of solids in an infinite fluid, V.

$$\frac{V_c}{(gD)^{\frac{1}{2}}} = Fr_c = \left[\log_e\left(\frac{V_\alpha - 2}{28}\right)\right] \cdot \dot{M}^{*0.25} \qquad (7.3.1)$$

$$V_\alpha = \left[\frac{4gd\,(\rho^* - 1)}{3C_D}\right]^{\frac{1}{2}} \qquad 10 < V_\alpha < 40\,(\mathrm{ft/s}) \qquad (7.3.1a)$$

$$Fr_c = \text{Constant} \times \dot{M}^{*0.2} \times \left(\frac{D}{d}\right)^{0.6} \cdot \left[\frac{V_\alpha}{(gD)^{\frac{1}{2}}}\right]^{0.5}$$

(7.3.2)

$$Fr_c = 10\left(\frac{1}{11.1}\right)^{0.333} \cdot \dot{M}^{*0.333} \cdot \rho^{*-0.1833} \left[\frac{V_\alpha}{10(gD)^{\frac{1}{2}}}\right]^{0.767} \qquad (7.3.3)$$

where ρ^* is the material density ratio $\overline{\rho_p}/\overline{\rho_g}$ of particle to gas, d is the particle diameter, D is the pipe diameter, g is the gravitational constant, and C_D is the drag coefficient of the particle.

Matsumoto, et al., claims that their equation also covers Barth's correlations which are extensively used for designing pneumatic wheat conveyors. However, they do not provide enough information for the formulation of our large scale system.

Zenz [51] who claims his correlation is applicable to large scale coal conveying installations of 8 inch and 12 inch pipe diameters and coal sizes ranging from 200 mesh to less than 3/4 inch, is extended as follows for $\beta > 10$:

$$\alpha = C_1 \beta^S \qquad (7.3.4)$$

where $C_1 \simeq 0.90$ for spherical particles and 0.5 for angular particles; $S \simeq 0.45$, and

$$\beta = \frac{d}{\delta} = \left[C_D \, Re_p{}^2\right]^{1/3} \qquad (7.3.5)$$

where

$$\delta = \left[\frac{3\nu^2}{4g} \,/\, (\rho^*-1)\right]^{1/3} \text{ (ft.)}$$

and

$$\alpha = V_s/\omega \, D_{in}{}^{0.5} \qquad (7.3.6)$$

where

$$\omega = \left[\frac{4g\nu}{3} (\rho^*-1)\right]^{1/3} \text{ (ft/s)} \qquad (7.3.6a)$$

D_{in} is pipe diameter in inches; other groups are dimensionless. Here ρ^* is the material density ratio of solid gas; ν, kinematic viscosity of the gas; g, gravitational constant; and V_s, minimum suspension velocity of a single particle. For the mass flow ratio of particle $\rho_p U_p$, and for minimum transport velocity, V_c in fps, Zenz suggested an approximate relation:

$$\frac{\dot{M}_p}{(\pi/4) D^2 \rho_p} = 0.7\, S^{1.5} \left[\frac{V_c}{V_s} - 1 \right] \qquad (7.3.7)$$

Soo went still further to include a suspension parameter k, in his formulation [5], so that

$$\frac{\dot{M}_p}{(\pi/4)\ D^2 \bar{\rho}_p} = 0.7 k S^{1.5} \left[\frac{V_c}{V_s} - 1 \right] = \dot{M}^* V_c \frac{\bar{\rho}}{\bar{\rho}_p} \qquad (7.3.7a)$$

Correlation of the Konchesky data obtained from a large scale experimental model, with the above relations on suspension velocity shows that the distribution in particle size of coal in his tests is represented by d = 1/16 inch (1.6mm) with flow velocity V above the value of V_c obtained from Equation (7.3.7a). In that equation, the suspension parameter ranges from 1 to 10, and is consistent with the largest capacity data of Konchesky [54]. The calculated values of the parameters in his case are:

$\dot{M}_p$ = 55 tons/hr

$\dot{M}^*$ = 7.32

f_a = 0.0031824

f_m = 0.009385

$k \geq$ 0.81 for 1/16" coal

$k \geq$ 7.084 for 1-1/2" coal

Based on the data of the Radmark Pneumatic Conveying System [55] which represents a current and workable system, further correlation results also fall into this range of suspension parameter values. The calculated values of the parameters in this case are:

$\dot{Q}_a$ = 2000 -12000 cfm at 15 psi

$\dot{M}^*$ = 6.0 -6.61

f_m = 0.004 - 0.009181

$k \geq 2.733 - 5.551$ for 3" particle

7.2.4 Friction Factor

Duckworth [45] recently identified some of the representative correlations on pressure gradients and also discussed their practicality for design purposes. Pfeffer, et al. [44], have done an extensive systematic study on pressure drop correlations with suspension in pipe flow. In both studies, due to the different independent variables correlated and the wide range of scattered data involved, no general correlation was deduced, but some trends were noted.

For our study, with reference to a previous investigation [5], some basic design limits on the friction factor, which will be extended to recent results and practice, is presented in the following: For isothermal pipe flow of a gaseous suspension in the system with pipe diameter D, length L, elevation z at one end, and the total flow of solids and air, $\dot{M}_p$ and $\dot{M}_a$ respectively, the pressure drop dP over a length dx is given by:

$$dP = -4 f_m \left(\frac{dx}{D}\right) \cdot \left[\bar{\rho} \cdot (V^2/2)\right] - \left[d(\rho_m V^2)\right] - \rho_m \cdot g \cdot dz \tag{7.4.1}$$

where f_m is the friction factor of the mixture of solid and gas; V, gas velocity; ρ_m, density of mixture; $\rho_m = \rho + \rho_p$; g, gravitational constant for ρg in lbm/ft^3 (ρ in kg/ m^3); and dz, the rise in elevation of dx. In Equation (7.4.1), the first term on the right-hand side is the pressure drop due to friction; the second term, acceleration; and the third term, the gravity effect due to elevation. Note that mass flow G is given by

$$\rho_1 V_1 = P_2 V_2 = V = \dot{M}_a/(\pi/4)D^2 = G \qquad (7.4.2)$$

Subscript 1 denotes inlet and 2, outlet.

The friction factor of turbulent pipe flow of a simple fluid, e.g., air, in a smooth pipe is given by

$$f_a = 0.046/Re^{0.2} \qquad (7.4.3)$$

where the Reynolds number Re is given by

$$Re = \frac{D\rho V}{\mu} = \frac{DG}{\mu} \qquad (7.4.4)$$

where μ is the viscosity of the gas.

For small changes in pressure or density of the gas phase, Equation (7.4.1) is integrated as an incompressible fluid:

$$P_1 - P_2 = 4f_m \frac{L}{D} \frac{G^2}{2\rho} + 1+\dot{M}^* \quad \rho \ (V_2{}^2 - V_1{}^2) +$$

$$(1+\dot{M}^*) \quad \rho \ gz \qquad (7.4.5)$$

for small ϕ, $P \simeq \overline{P}$ of the gas.

$$1-(P_2/P_1)^2 = 4f_m \left(\frac{L}{D}\right) (\rho_1{}^2 \ V_1{}^2 \ RT/P_1{}^2)$$

$$+ \ (1+\dot{M}^*) \ \cdot \ (2G^2 \ RT) \quad \ln(P_1/P_2)$$

$$+ \ (1+\dot{M}^*) \ . \ (2 \ \overline{P}^2 \ gz/RTP_1{}^2) \qquad (7.4.6)$$

for inlet pressure P_1 and velocity V_1; $P = (\overline{P_1} + P_2)/2$.

Soo used Equation (7.4.5) to evaluate the data of Konchesky [52] obtained from the vacuum transport of crushed coal. Data for f_m/f_a versus Re are shown in Figure 7.1 with ranges of $\dot{M}^*$ and pipe size as indicated. Experiments by Sproson, et al. [53], show ranges similar to Konchesky's. Shown in Figure 7.2 are the evaluated data of the straight run of pipes based on Konchesky's study of pressure transport of crushed coal [54]. Also included is the evaluated practical range of the gas-solid mixture friction factor based on the data from the Radmark Pneumatic Conveying System [55]. In this plot, it should be noted that the drag reduction characteristic of the gas-solid flow is a phenomena which still needs investigation. The order of magnitude of the value of the friction factor shows reasonably good agreement with the value of the specific pressure drop defined by J.D. Constance [58] for industrial application.

Equation (7.4.7) shows that when the operating pressure of a pneumatic pipeline is high, the pressure drop due to acceleration and elevation (in hundreds of feet) for a pipeline of many miles in length become minors and the main pressure drop is that of friction.

$$1-(P_2^{\,2}/P_1^{\,2}) = 4\, f_m (L/D)\,(V_1^{\,2}/RT_1) \qquad (7.4.7)$$

for an isothermal flow with velocity V_1 and temperature T_1 at the inlet. The gas temperature T tends to be a constant value for a long distance pipeline because of heat exchange with the surroundings over a large surface area.

Konchesky's results appear to be adequately correlated by the relation proposed by Dogin and Lebedev [56] according to

$$f_m = f_a + A\left(\frac{d}{D}\right)^{0.1} Re^{0.4}\, Fr^{-0.5}\, \rho^*\, \dot{M}^* \qquad (7.4.8)$$

where Fr is the Fronde number

$$Fr = \frac{V^2}{gD} \qquad (7.4.9)$$

which accounts for the gravity effect in horizontal pipe flow. A is a parameter depending on the roughness of the pipe. For the Konchesky data, A appears to be 2×10^{-7} in both pressure and vacuum transport [52,54], instead of $10^{-6} < A < 2 \times 10^{-6}$ proposed by Dogin, et al.

Rose and Barnacle [57] proposed the following correlation:

$$f_m = f^a + \left(\frac{\pi}{8}\right) \dot{M}^* \rho^{*0.5} \psi \tag{7.4.10}$$

ψ was given as a function of Re having a value below 10^{-5} for Re > 35,000. However, calculations from Konchesky's data given $\psi = 0.8 \times 10^4 \doteq 1 \times 10^{-4}$. Coding various sources of data and disregarding other factors, Pfeffer, et al. [44] proposed a simple correlation recommended for predicting pressure drops associated with a fully developed turbulent flow of gas-solid suspensions in smooth tubes.

$$f_m = f_a \left(1+\dot{M}^*\right)^{0.3} \tag{7.4.11}$$

This correlation tends to given an optimistic estimate of pressure drop, and shall be treated as lower bound of f_m as suggested by Soo [5].

7.2.5 Design Approach to a Pneumatic Coal Transport Pipeline

Given the technical experience of the 1962 and 1967 Bureau of Mines' studies on pneumatic transport of coal, our design is based on current technology and information. Emphasis has been placed on:

1) clarification of the gas-solid mixture friction factor,

2) reduction of energy requirements, and

3) the possibility of an intermediate distance pipeline (about 100 miles) without pumping stations, thus eliminating the recompression process for the coal-gas mixture.

A recent finding [5] has indicated that the pipe flow friction factors on which the 1962 study was based were 10 to 50 times higher than those determined from recent experimental data at the

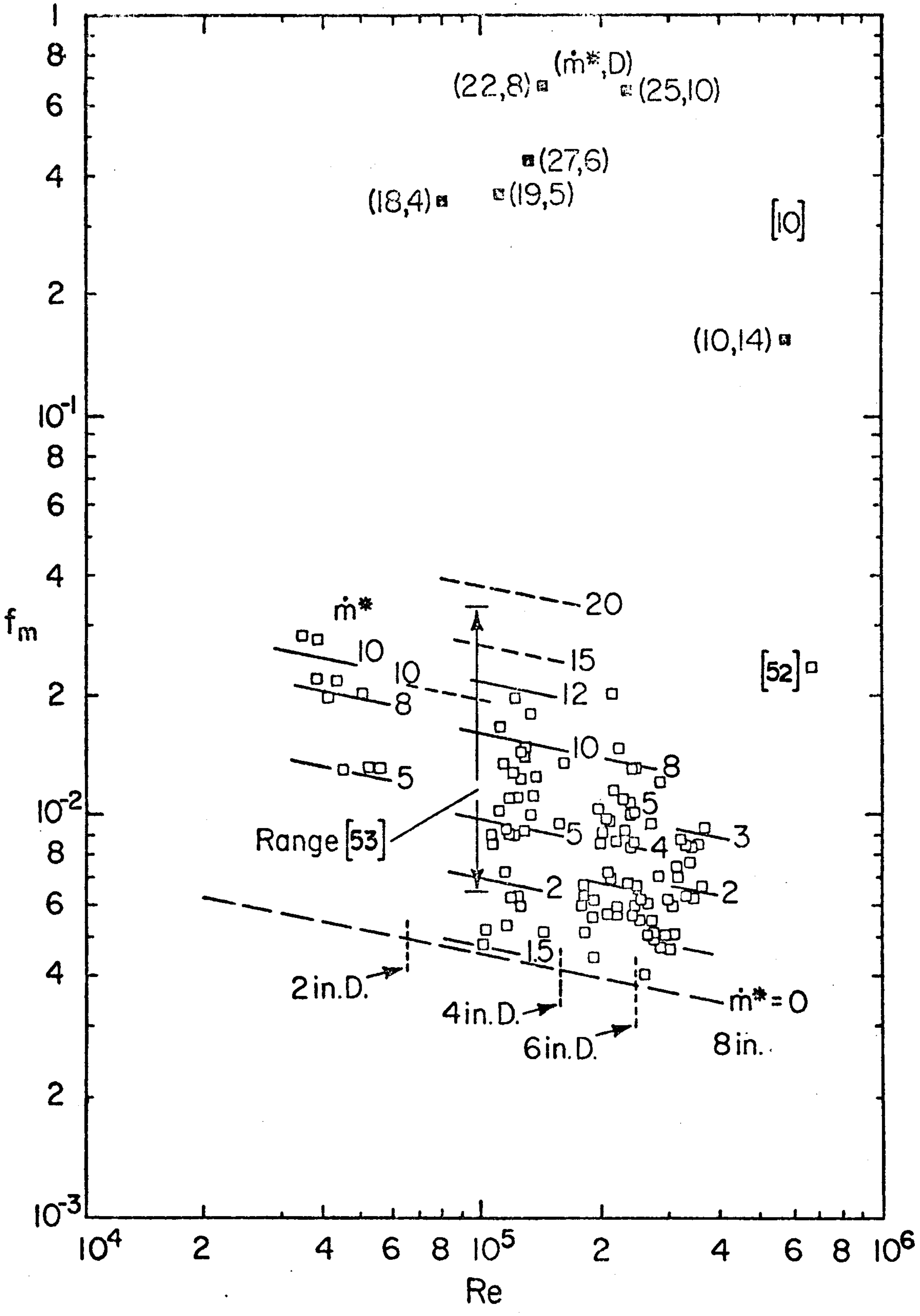
Bureau of Mines [52] and experiments in England [53], as shown in Figure 7.1. This is also supported by our present evaluation of data from reference [54] and additional information from current practice [55].

Equation (7.4.7) shows that as long as a uniform pipe diameter D is used, large differences in pressure P_1 and P_2 at the inlet and outlet will not necessarily increase the pipe length L because of the large pressure drop caused by increased flow velocity at low air density as the pressure is lowered, thus causing greatly increased friction loss. This suggests telescoping the pipe diameters as the pressure is lowered. In this way, the flow velocity is kept just high enough for the suspension but minimizes friction loss. Therefore, an optimum selection of various lengths of standard pipe of various diameters must be made consistent with the constraints of optimum pressure drop and suspension velocity. Based on the analysis presented in Section 7.2.3, a computer program for the design of a telescoping pneumatic coal transport system is formulated. Figure 7.3 illustrates the simplified logic employed.

The pipeline design in this study, for a given transport capacity, calls for a lower pressure drop and power consumption but a larger pipe diameter than those given by the Konchesky formula [52, 54]. Neither design is in error. However, the present study is based on conditions for optimum economical operation. The key is the use of minimum transport velocity. The Konchesky formula is safe, but does not account for this criterion. It is based on his experiments with pipes of uniform diameter at a flow velocity two to three times the minimum transport velocity for a given size and loading of coal. His formula leads to compatible pressure drop, power consumption, and pipe size but the design is not optimum for economic operation.

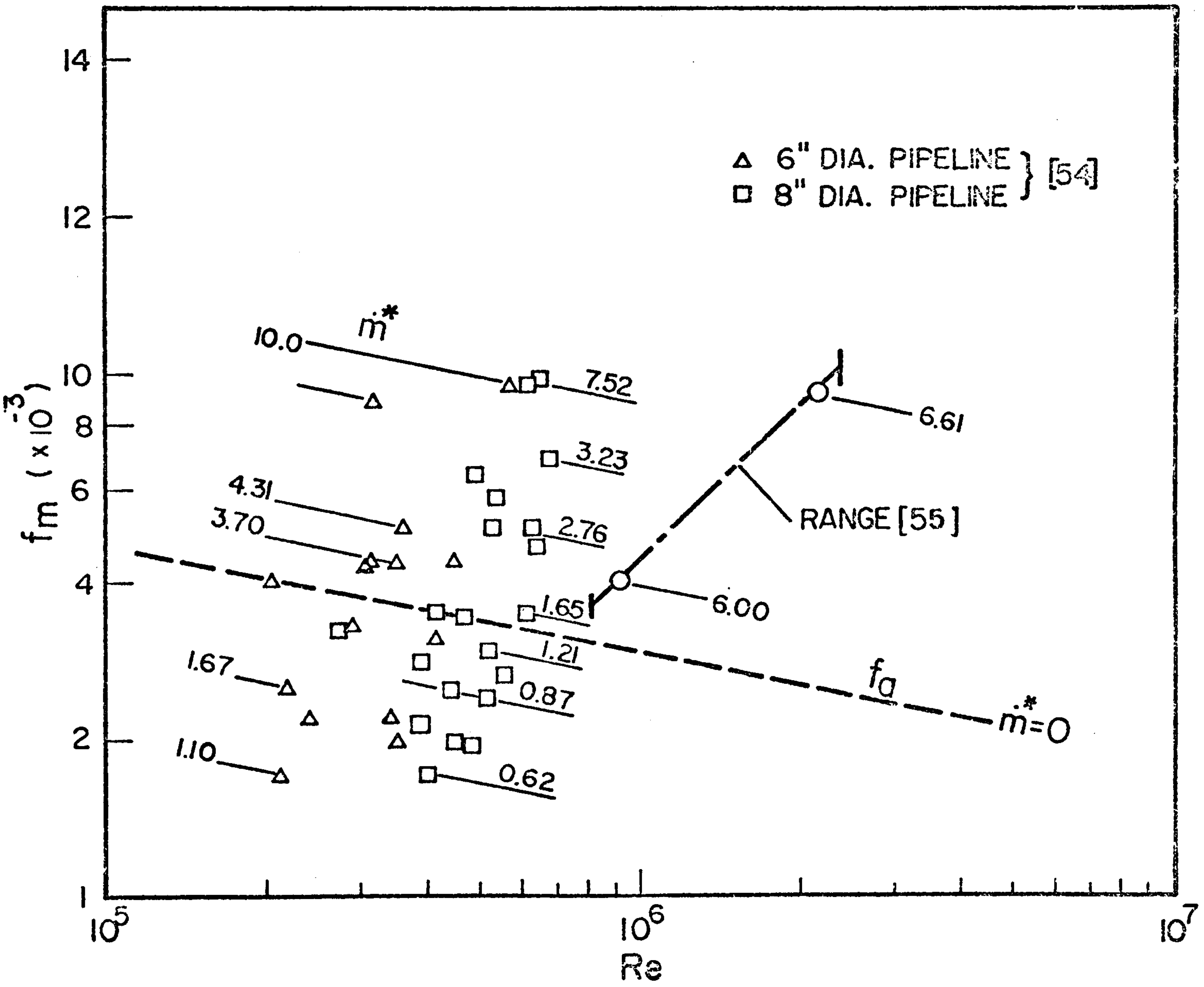
The concept and validation of the optimizing design used in this study is found in sections 7.2 and 7.3. Unsurprisingly the power requirement in this study might be 1/50th that of a design based on the Konchesky formula. The latter is in dimensional form, correlated for uniform pipe size of 8" maximum diameter, with a specified high flow velocity, giving a safe workable design, but at the price of high power consumption.

FIGURE 7.1:



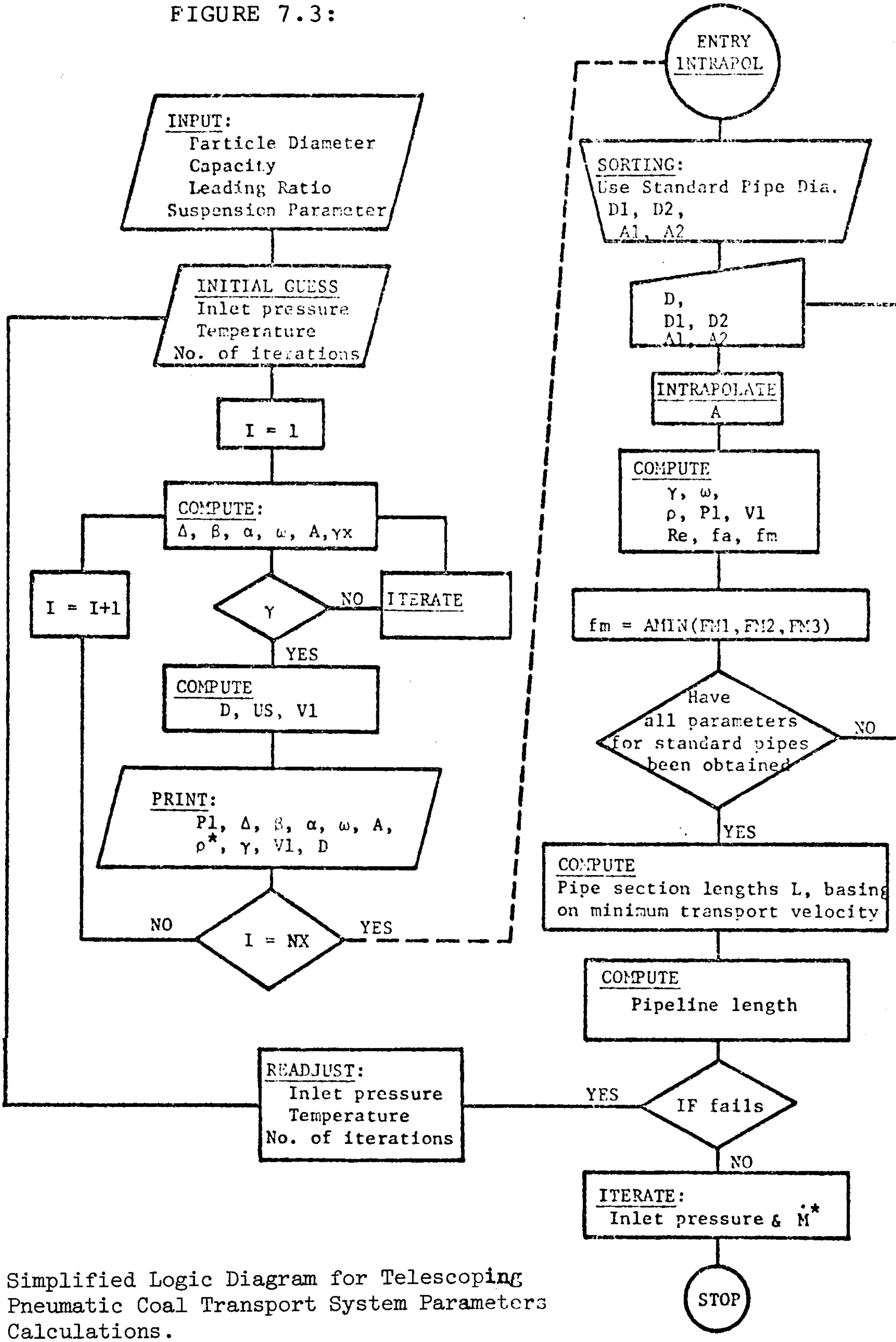
Friction Factor (f_m) of Vacuum Transport of Crushed Coal Suspension at Various Flow Reynolds Numbers(52).

FIGURE 7.2:



Friction Factor (f_m) of Pressure Transport of Crushed Coal Suspension at Various Flow Reynolds Numbers(54). (M^* = lb coal/lb air, D = pipe diameter, inches)

FIGURE 7.3:



Simplified Logic Diagram for Telescoping Pneumatic Coal Transport System Parameters Calculations.

7.3 PILOT FACILITY

A model for this study has been developed with the cooperation of the Peabody Coal Company and the Illinois Power Company. This pneumatic pipeline model is 3.5 miles long and has a transport capacity of 200 tons per hour or 1.584 million tons of coal per year based on operations of 24 hours per day and 330 days per year. The current rail system has a total coal capacity of 18,000 tons per day or 5 million tons per year.

A right-of-way of 50 feet for the pipeline is assumed to be along-side the present rail system (Figure 7.4). Additional land is needed at the mine and an area of 30' x 100' for the receiving facility for unloading (Figure 7.5 and 7.6) is needed at the receiving end. Figure 7.7 shows a layout of the pipeline route.

7.3.1 Conceptual Design of the Pneumatic Coal Transport Pipeline

Table 7.1 provides an outline of the initial design parameters of the pneumatic coal transport system. The initial design configurations of the system are shown on Figures 7.8 and 7.9. Figure 7.8 illustrates the high pressure blow tank system. Its major facilities include coal feeding, air compression, transport pipeline, and separation and receiving facilities. Coal is transferred from the 50 ft. diameter by 200 ft. height storage silo by a 150 ft. by 24 in. belt conveyor which is built across an auxiliary rail track, to a steel superstructure. This steel superstructure houses the feeding facilities which includes a 20 ft. by 14 in. diameter screw feeder and two 500 cu. ft. blow tanks with wye fitting and a motor driven rotary feeder. The tanks are connected so that while one is discharging the other is being filled, so that continuous feeding is possible. The operating cycle time is programmed and automatically controlled. The air source is supplied by a compressor package (motor driven) which also includes an intake filter and silencer.

Ground elevations at the mine and the power plant are 465 ft. and 435 ft. respectively. As the terrain is flat, the pipeline is basically horizontal. The pipeline is laid along the left side of the rail track from the mine to the power plant.

The intersection with a country road which will require an overhead crossing should not cause any difficulty for the layout. The coal-air mixture is separated by using two cyclone separators in series to ensure high recapture efficiency, and the coal-dust laden air is de-dusted by a dust filter before venting into the atmosphere.

Figure 7.9 illustrates the positive-negative (or push-pull) system. This system employs air flows created by the application of both pressure and vacuum principles. This flow operation is similar to that of the blow tanks system except that it has gravity feeding. Based on current technology, this system is limited to 20 psig on the pressure side using a rotary feeder valve, and 10 psig on the vacuum side with a suction blower. Selection of the type of pneumatic system is determined by the allowable solid size, energy requirement and economic feasibility.

7.3.2 Design Calculations

In our design, set here for a 2 x 0" size coal, preliminary analysis suggests a preference for using the blow tank system instead of the push-pull system which is more suitable to 1/4 x 0" coal. Given the design capacity input, the basic parameters required to design telescoping pipelines are determined from the computer program. Figure 7.3 shows the simplified logic for calculating telescoping pneumatic transport system parameters. A self explanatory flowchart of the computer program (Appendix IV) is shown in Figure 7.10. Based on given particle size, transport tonnage rate and distance, loading ratio, and correlated suspension parameter, the computer program determines the air properties along the flow, telescoping diameter, minimum suspension velocity, correlated friction factors, optimum pressure drop and telescoping length. With these, the air and power requirements are then calculated.

For 2 x 0" size coal, based on a capacity of 200 tons per hour and a distance of 3.5 miles, telescoped pipeline configuration and parameters are shown on Figure 7.11. A theoretical power requirement of 1750 hp., for a pressure drop of 122 psig, is indicated. The blower capacity is nearly 8800 scfm. From the air and power requirement results, a detailed major equipment list is tabulated in Table 7.2.

7.3.3 Alternative Design for 1/4 x 0

Based on a pneumatic coal transport system of 3.5 miles and a capacity of 200 tons of 1/4 x 0" size coal per hour, using the loading ratio $\dot{M}^*$ of 10 and suspension parameter (k) of 10, a significant reduction of power requirement is readily seen by comparing Figure 7.11 with Figures 7.12 and 7.13. With the configuration of Figure 7.13, a power reduction as much as 76 percent is possible. Figures 7.12 and 7.13 also signify the effect of telescoping pipeline on the power requirements. From our analysis, it is shown that the loading ratio must be properly selected for an optimal system, as small loading ratios lead to higher power requirements and bigger pipes which in turn lead to higher costs. It is also concluded that there is a significant cost reduction by transporting small size coal. One possible mode of operation is via a storage and primary crushing facility at the delivery end and discharge directly into coal bunkers at the receiving end.

TABLE 7.1: Outline of Initial Design Study

I. PROCESS

- A. Pneumatic
    1. Selection of Types of Pneumatic System
    2. Selection of Optimum or Allowable Solid Size and Concentration
    3. Determination of Minimum Operating Flow Velocity
    4. Determination of Air and Power Requirements.

- B. Structural
    1. Determination of Pipeline Diameter
    2. Telescoping of the Pipeline
    3. Terrain Consideration Including Layout
    4. Establishment of Design Pipeline Life.

- C. Operability - Stability
    1. Selection of Mode of Operation and Emergency Procedures
    2. Establishment of Shutdown and Start-up Technique
    3. Consideration of Hold-up.

II. MECHANICAL

- A. Number and Location of Pump Station
- B. Sizing of Equipment and System Design
- C. System Automation and Control.

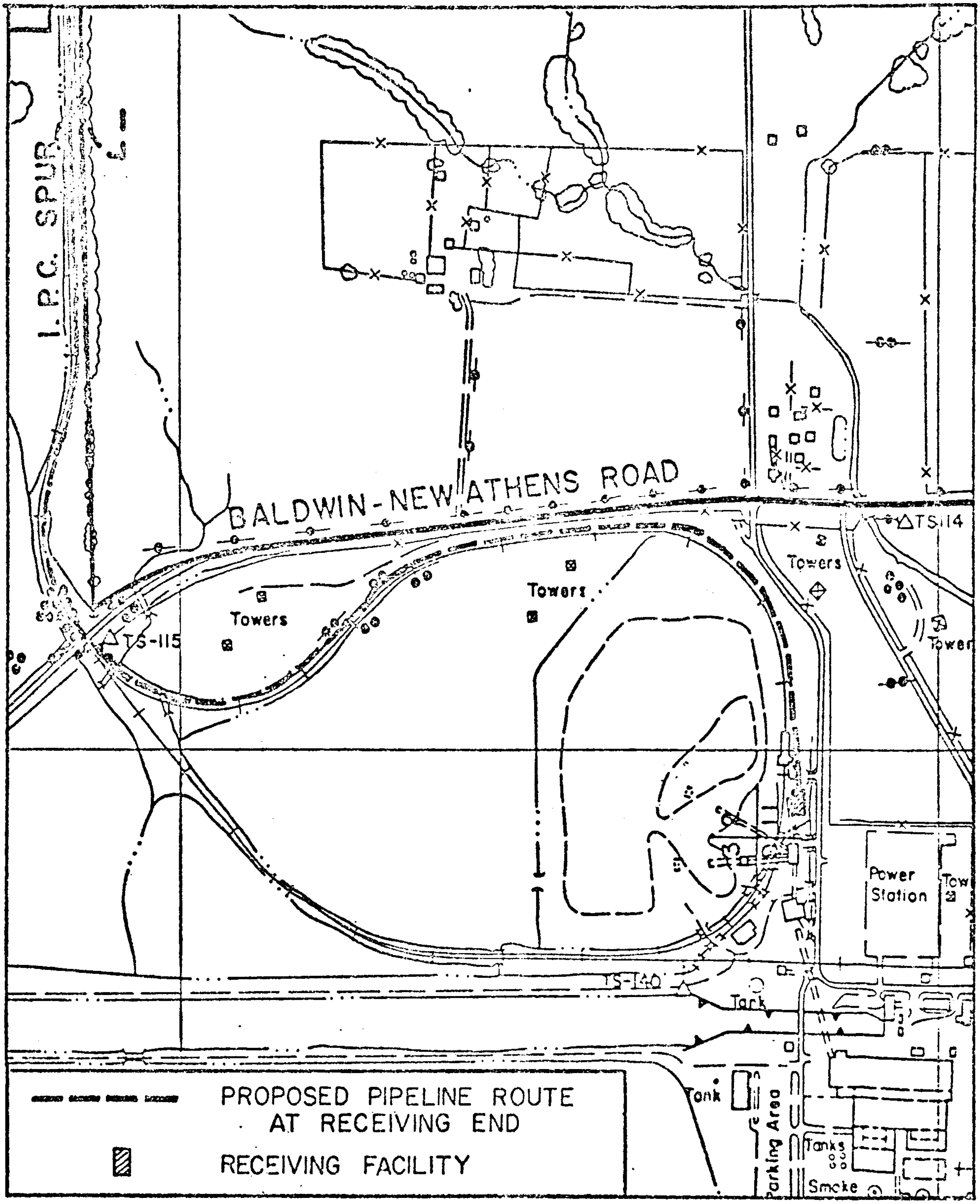
III. ECONOMIC EVALUATION

- A. Capital Investment
- B. Operational Cost
- C. Optimization of Process Design and Cost.

TABLE 7.2: List of Major Equipment for the 3.5 Mile Pilot Pneumatic Coal Transport Pipeline for 200 Tons of 2x0" Coal Per Hour

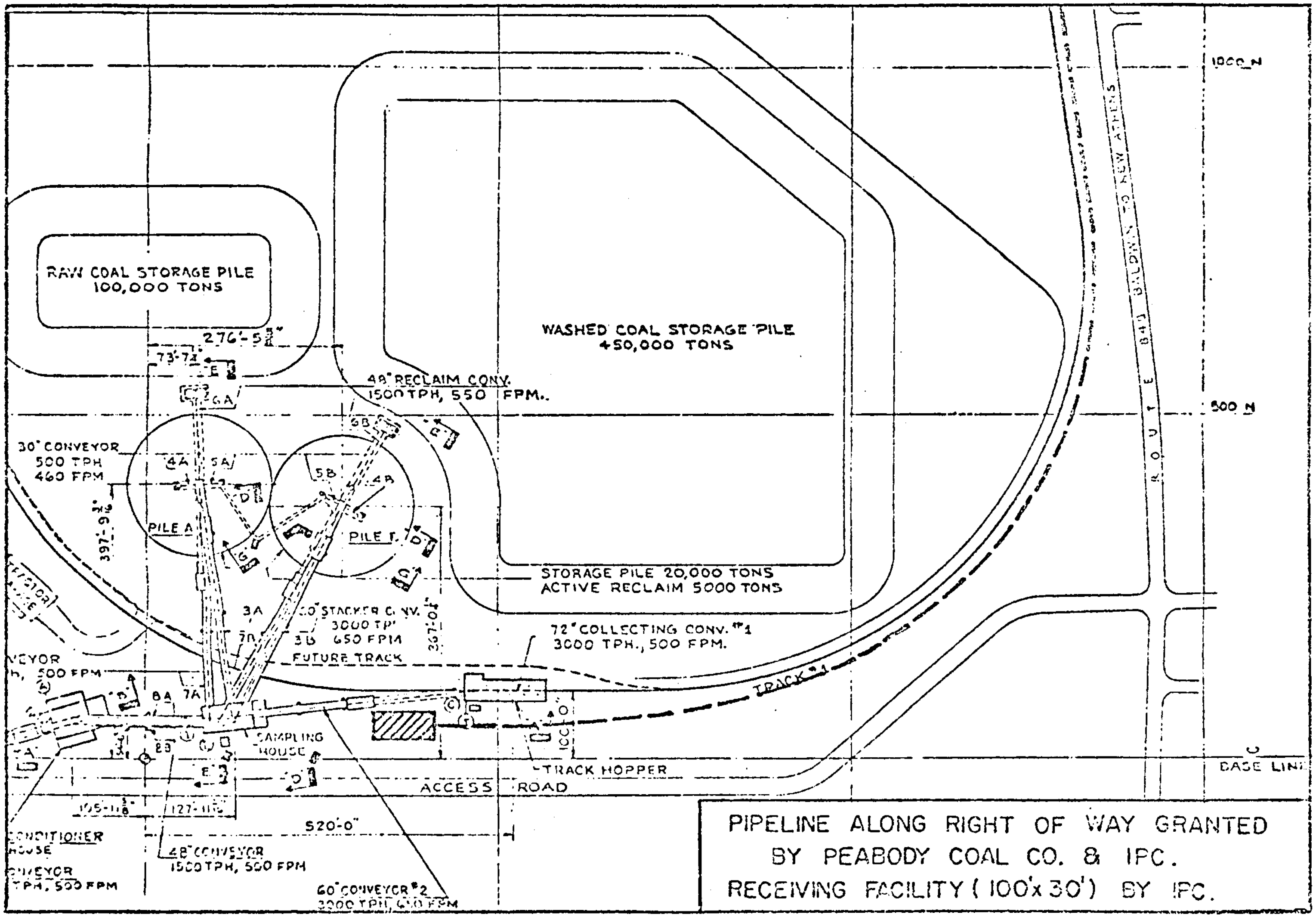
EQUIPMENT	SIZES	REMARKS	AVAILABLE SUPPLIERS
Belt conveyor	150 ft. of 24" belt	300 fpm	
Screw feeder	20 ft. of 14" diameter	with motor and drive	Bulk material handling group of Willis and Paul, Inc.
Blow tanks	two-500 cu.ft.	1/3 hp. motor and drive	Aerodyne Machinery Div., General Resource Corp.
Rotary feeders	two 10" size		A.S.H. Fluid Transport Div., Envirotech Corp.
Compressor package	1920 hp. 8740 SCFM		Ingersoll-Rand Co.
Pipeline	3.5 miles	1.3773 mi. of 8" dia. 1.1747 mi. of 10" dia. 0.47 mi. of 12" dia. 0.478 mi. of 14" dia.	U.S. Steel Corp.
Cyclone separators	two-8740 SCFM		
Duct collector	8740 SCFM	Cloth bags with electric motor shaker	Western Precipitation Div., Joy Manufacturing Co.
Discharge hoppers	500 cu.ft. and 300 cu.ft.		A.S.H. Fluid Transport Div., Envirotech Corp.

FIGURE 7.4:



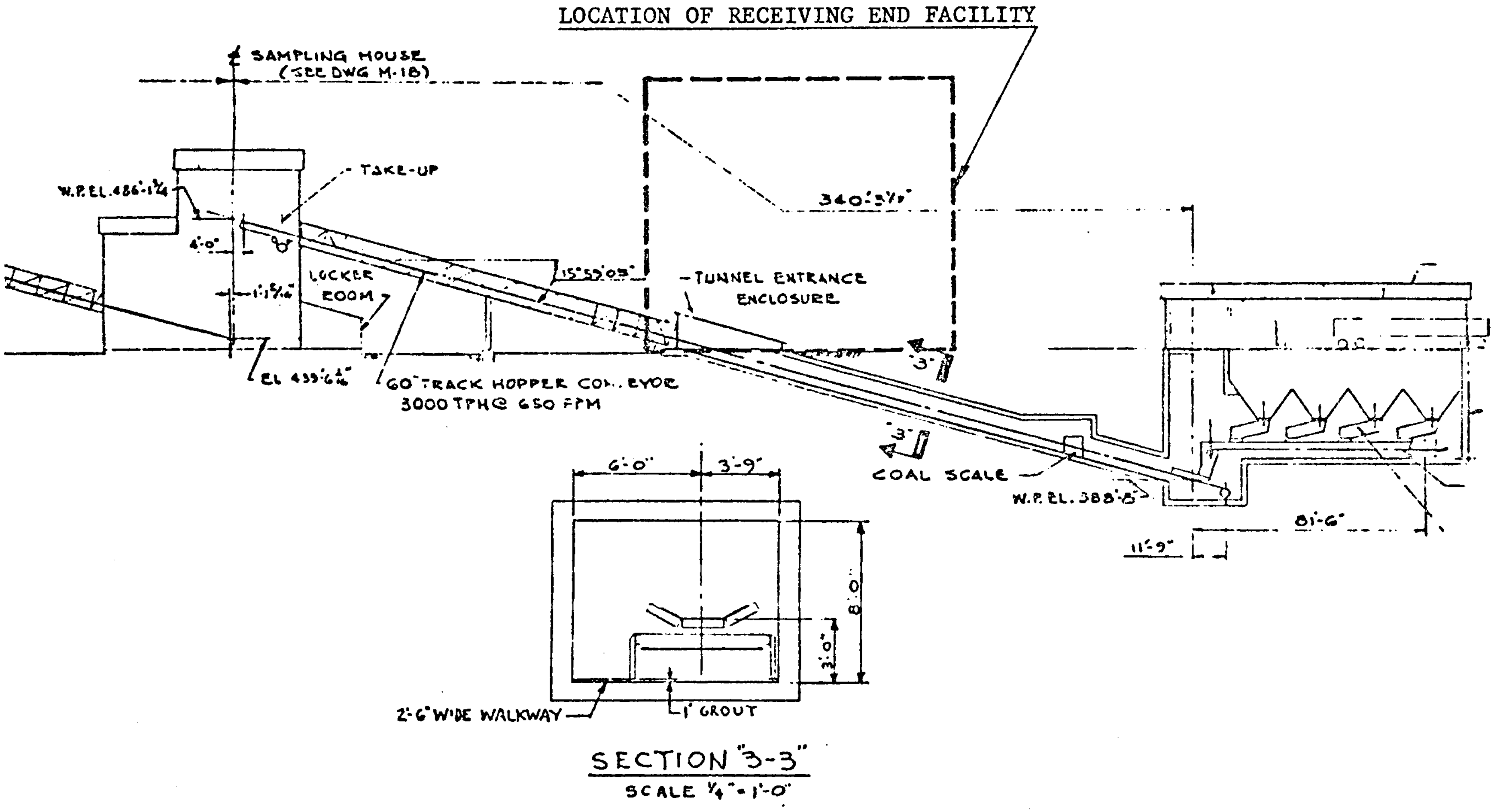
Proposed Pneumatic Coal Pipeline Route at Receiving End

FIGURE 7.5:



Aerial View of Space and Right-of-Way Along Current Railroad and Pipeline Installation Plan at Receiving End in Relation to Current Coal Handling Facilities.

FIGURE 7.6:



Side View of Space for Receiving End Facility Showing Integration into Existing Facilities.

FIGURE 7.7 : Proposed Route of 3.5-mile Pilot Plant of Pneumatic Coal Transport Pipeline.

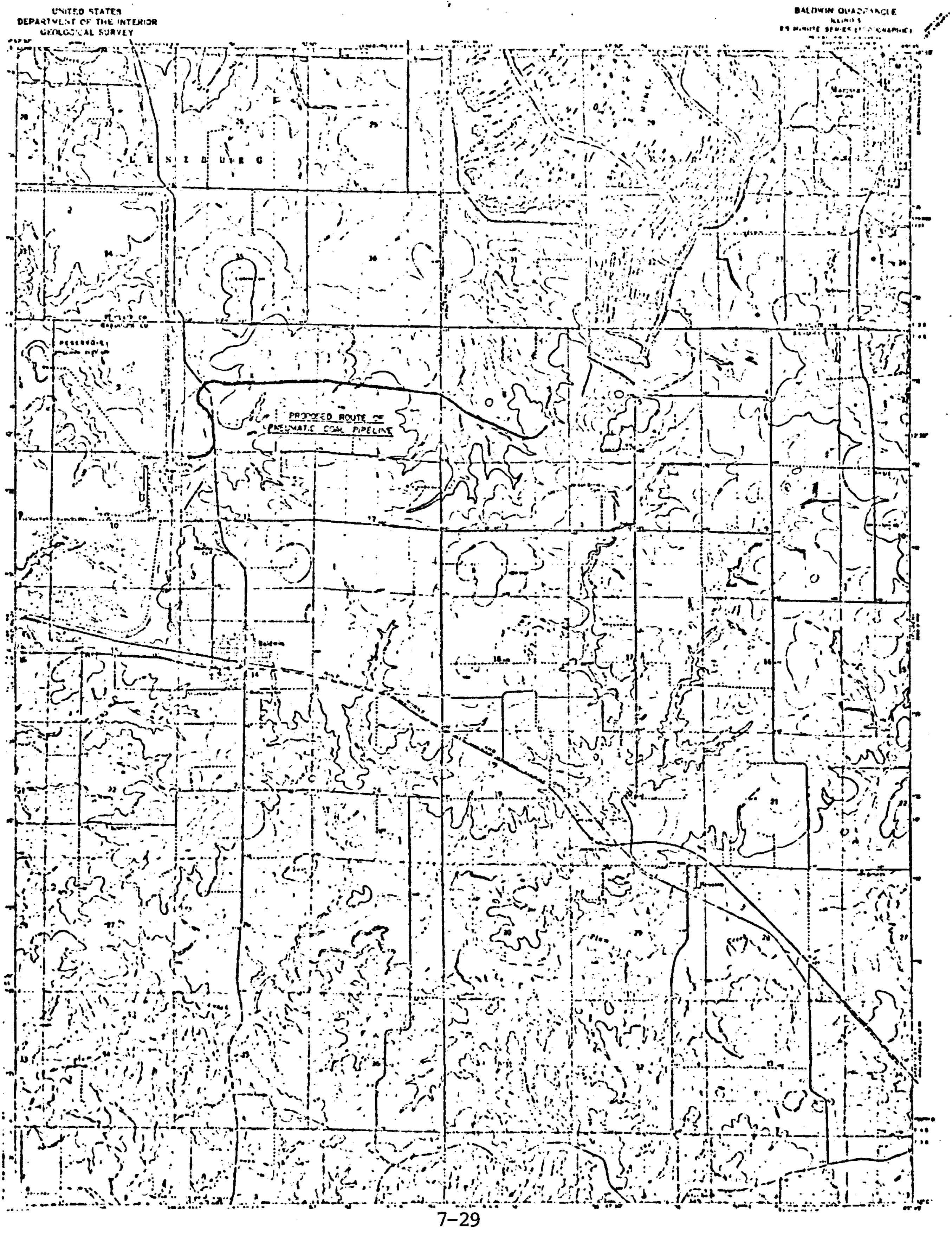
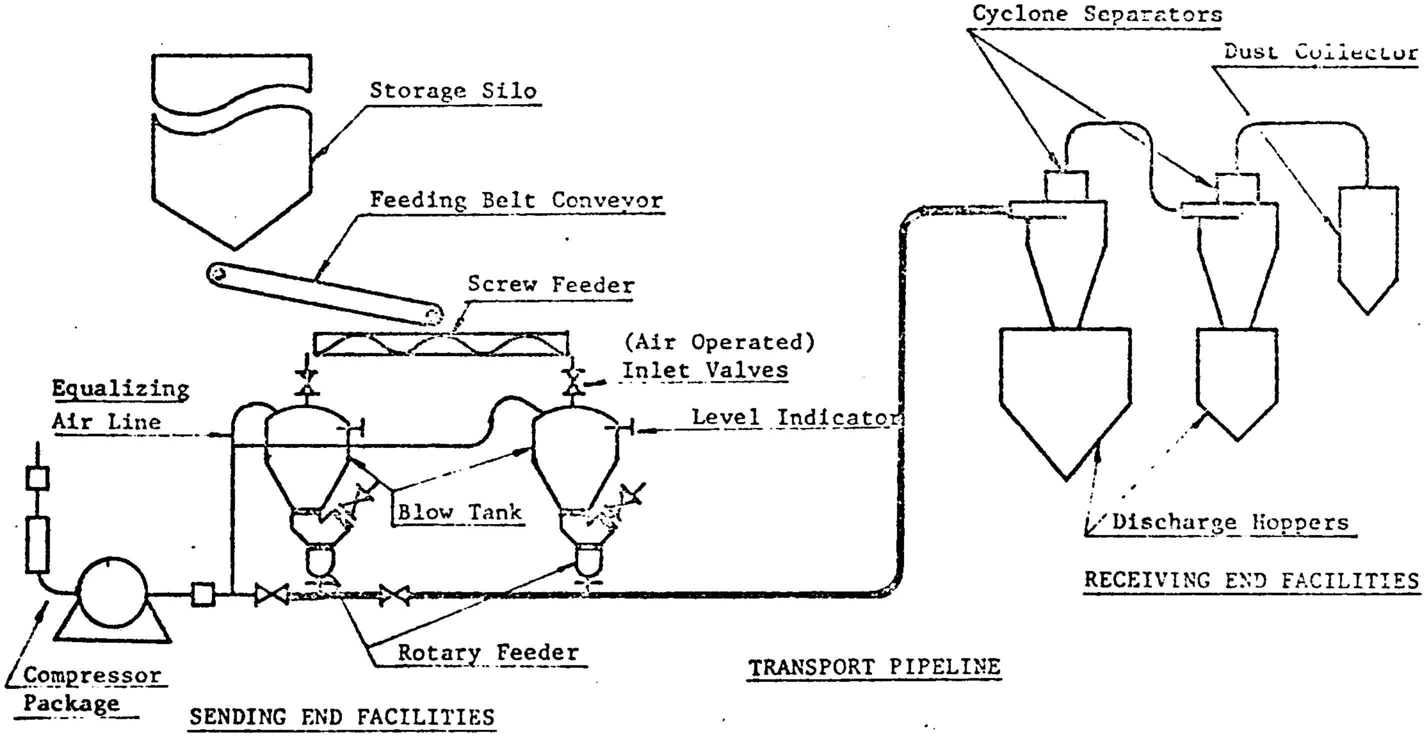


FIGURE 7.8:



Schematic Diagram Showing Pressure (Blow Tank) Pneumatic Transport of Coal.

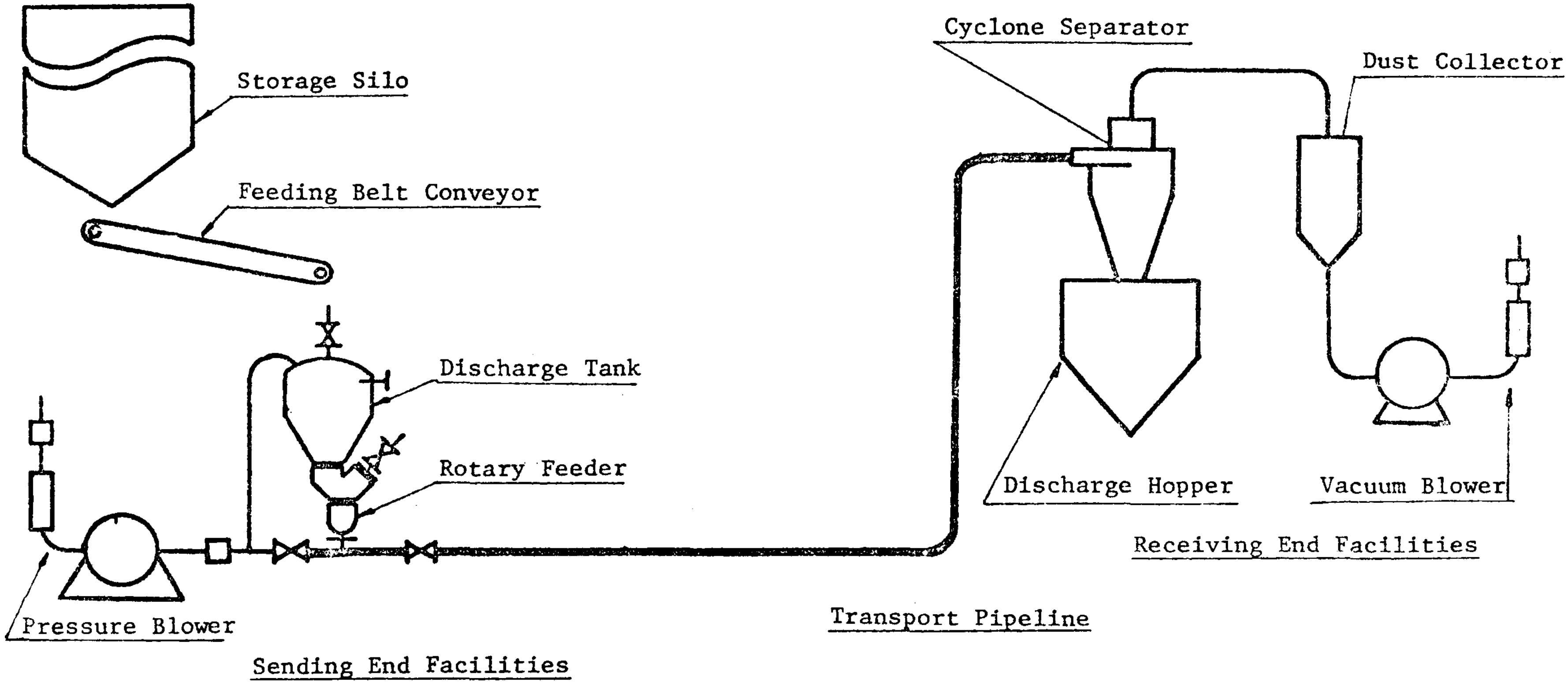
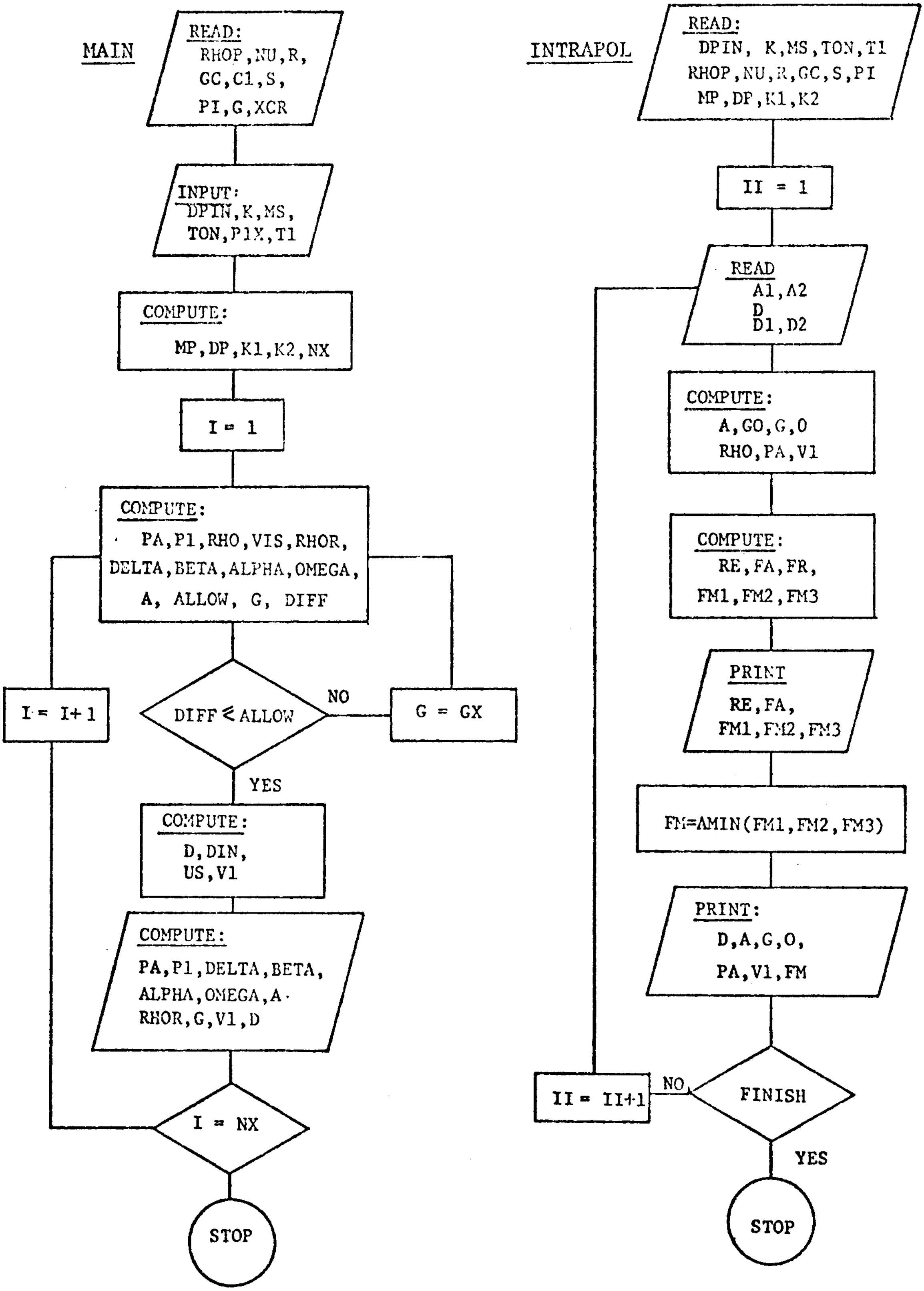


FIGURE 7.9:

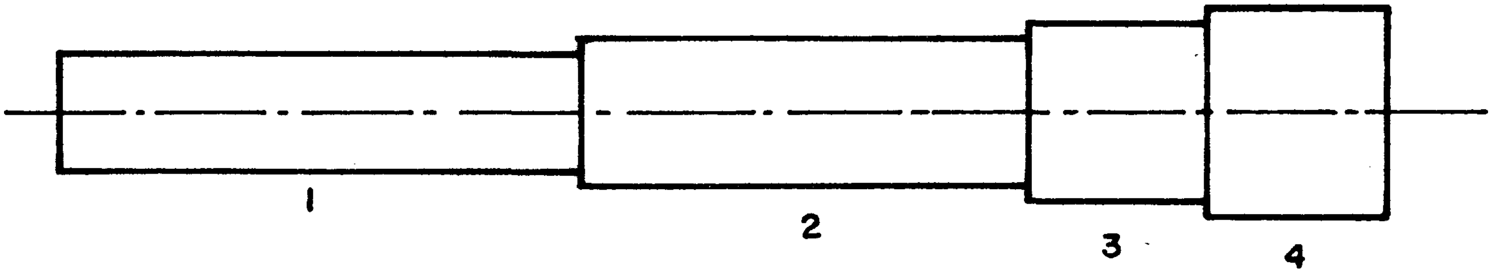
Schematic Diagram Showing Pressure-Vacuum (Push-Pull) Transport of Coal.

FIGURE 7.10



Flow Chart of Computer Programs for Calculating of Telescoping Pneumatic Coal Transport System Parameters.

FIGURE 7.11



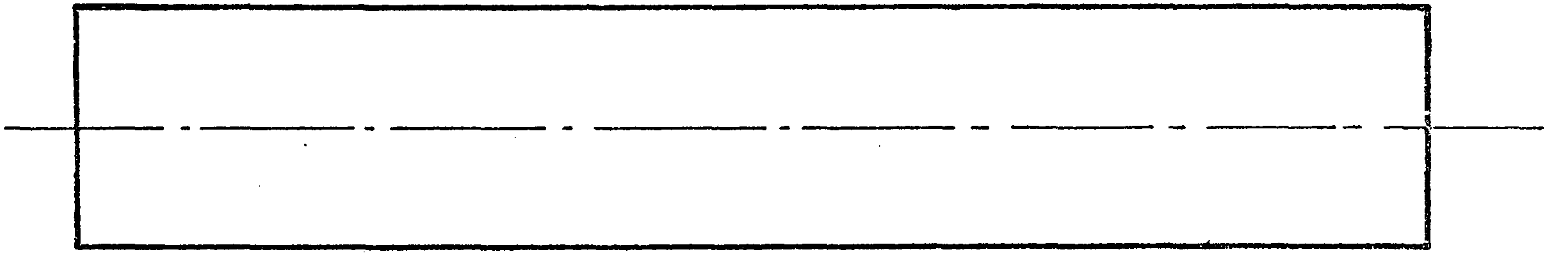
Section	Standard Pipe #20 Nominal Diameter	Standard Pipe #20 Inside Diameter	Section Length	Inlet Pressure	Minimum Transport Velocity
	in.	in.	mile	atm	ft/S
1	8	8.125	1.3773	9.3	67.6
2	10	10.25	1.1747	5.379	86.33
3	12	12.25	0.4705	2.677	121.43
4	14	13.376	0.4775	1.861	146.49

2 x 0" SIZE COAL

CAPACITY = 200 TPH
AIR FLOW = 8738 SCFM
PRESSURE DROP =
THEORETICAL HP = 1751 hp

K = 20
$\dot{M}^*$ = 10

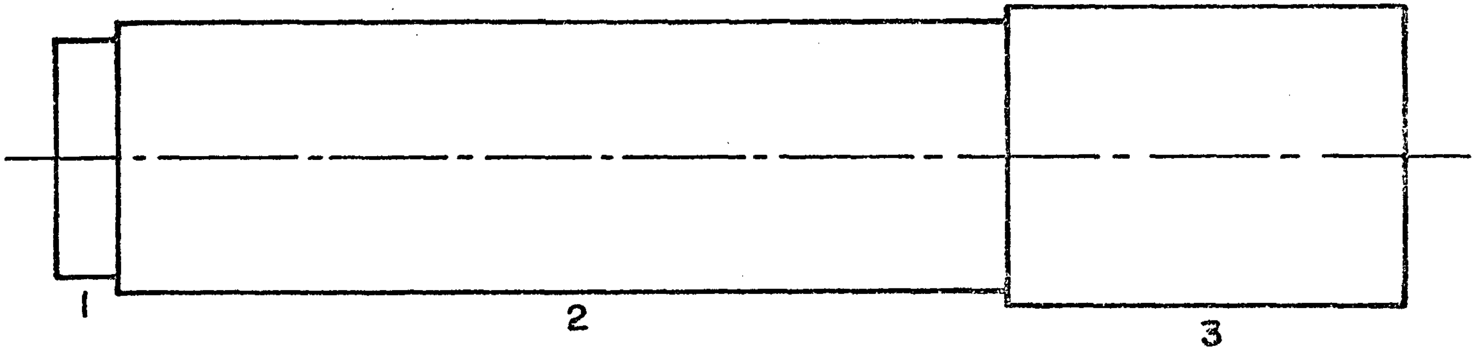
Schematic Diagram of the 3.5-miles Telescoping Pneumatic Coal Transport Pipeline and Flow Parameters for Peabody-Baldwin Pilot Plant of 200 Tons of 2 × 0" Coal Per Hour (k=20).



$K = 10$
$\dot{M}^* = 10$
Nominal diameter = 16 in.
Inside diameter = 15.376 in.
Inlet Pressure = 33.52 psia
Outlet Pressure - 14.7 psia
Minimum Transport Velocity = 48.6 ft/s
Pressure drop = 18.82 psig
Air flow = 8738 SCFM
Theoretical Horsepower = 522 hp.

FIGURE 7.12: Schematic Diagram of a 3.5-miles Pneumatic Coal Transport Pipeline (Constant Diameter) and Flow Parameters for Transport Capacity of 200 Tons of ¼ × 0" Coal Per Hour (k=10).

FIGURE 7.13:



Section	Standard Pipe #20		Section Length	Inlet Pressure	Minimum Transport Velocity
	Nominal Diameter	Inside Diameter			
	in.	in.	mile	psia	ft/s
1	16	15.376	0.161	29.98	52
2	18	17.376	2.293	28.34	60
3	20	19.25	1.036	18.53	66

1/4 x 0" SIZE COAL

CAPACITY = 200 tph
AIR FLOW = 8738 scfm
PRESSURE DROP = 14.28 psig
THEORETICAL HP = 420.7 hp

$K = 10$
$\dot{M}^* = 10$

Schematic Diagram of a 3.5-miles Telescoping Pneumatic Coal Transport Pipeline and Flow Parameters for Transport Capacity of 200 Tons of ¼ × 0" Coal Per Hour (k=10).

7.4 COST EVALUATION OF PILOT PLANT

7.4.1 Capital Cost Estimation

In the previous section, material and energy requirements and balance calculations were made for the conceptual design of a 3.5-mile pneumatic coal transport system for 200 tons of 2 x 0" size coal per hour. The resulting information was utilized in sizing and specifying the major items of equipment. Capital investment was estimated by the method described by Guthrie [59], and Peters and Timmerhaus [60]. The purchased or installed equipment costs were estimated with the aid of cost data for similar items of equipment, cost indices and available cost-capacity factors. Fixed capital investment was then calculated with the aid of the purchased cost and Lange factors [60] for the item. The capital investment figures presented here do not include the costs for standby equipment and spares. However, allowances have been made on estimating contingency costs.

Owing to the similar nature of natural gas pipelines and pneumatic coal pipelines, it is reasonable to make the assumption that the cost for installing a pneumatic coal pipeline should not be very different from that of a natural gas pipeline with the same dimensions. Based on this argument, this assumption should also be applicable to the cost of similar compressor facilities with the same power capacity. Figure 7.14 shows the cost correlation of natural gas pipelines, based on the construction cost which includes material, labor, right-of-way, interest, surveys, engineering, inspection, legal fees, and contingencies as released by the Federal Power Commission in 1974 [61]. Also, the average cost per installed horsepower for compressor facilities was $302 as reported by the FPC [61]. These costs were escalated to 1976 values at the rate of 7 percent per annum.

The bare module cost for the major equipment shown in Table 7.2 is given in Table 7.3. The bare module cost for buildings includes a house for control and administration, one steel superstructure (15' x 30' x 30') for blow tanks at the sending point, and one steel superstructure (20' x 60' x 40') for the separation facilities at the receiving point.

For all building costs, the medium categories [59] were used.

The costs for site development and offsite facilities were estimated at 5 percent and 8 percent, respectively, of the bare module costs of major equipment. Offsite facilities include water, instrument, air, oil, fire protection equipment, power distribution and yard lighting. The charges for engineering and contractors were included and were calculated at 7 percent and 5 percent of the total module cost, respectively.

All bare module costs were based on 1968 data, escalated to mid-1973 by a factor of 1.26 (344.1/273.1) as estimated from the Marshall and Stevens Index, and to 1976 dollars using an assumed annual escalation rate of 7 percent.

A summary of the capital investment estimation for the conceptual design of the pneumatic coal transport system is given in Table 7.4. The fixed capital investment was estimated to be $1,463,700 (1976 $). Working capital was calculated at 10 percent of fixed capital investment. The total capital investment amounted to $1,610,100.

7.4.2 Annual Operating Cost

The total annual cost of the conceptual design of the pneumatic coal transport system was estimated to be $745,600. A summary of these costs is presented in Table 7.5. The pertinent assumptions and bases for these estimates are as follows:

1) 100 percent capacity.

2) 330-day annual operation.

3) Horsepower required for other equipment is considered insignificant compared to that for gas compression. The cost of fuel was estimated on the equivalence of coal required. The assumptions of an average of 10,500 BTU per lb. coal; 10,800 BTU per kw-hour; and up to $15 per ton coal FOB at the mine were also applied (93¢/MMBtu of heat).

4) Operating labor costs were calculated assuming 2 men per shift at an annual wage of up to $20,000 per man or $150,000 total. Supervisory manpower was taken as 20 percent of the operating labor.

5) Maintenance and repairs were calculated at 6 percent of the fixed capital investment to include both material and labor. Operating supplies were assumed to be 15 percent of maintenance and repair.

6) Administrative costs were taken as 40 percent of operating labor; and plant overhead at 50 percent of the sum of operating labor plus supervisory labor plus maintenance and repairs.

7) Fixed charges were assumed to be 50 percent of the total fixed capital investment on a debt to equity ratio of 55 percent to 45 percent. The interest rate on debt and equity were 9 percent and 15 percent respectively.

8) A 25-year plant life with no salvage value for the equipment was assumed for depreciation calculations using the straight line method.

9) Taxes and insurance were each estimated at 1 percent of fixed capital investment.

7.4.3 Cost Analysis

The capital investment estimates are based on a new facilities situation in conjunction with the use of the right-of-way of a railroad system. The output of the cost evaluation of our conceptual design of a 3.5 mile telescoping pneumatic coal transport system of 200 tons of 2 x 0" size coal per hour indicates an investment requirement of $1,610,100 or a $95.84 investment per ton-mile capacity; and a coal transport cost of 13.45¢ per ton-mile.

The coal transport cost for this system is found to be considerably higher than the 1.14¢ per ton-mile transport cost projected by Soo in reference [5] for the same transport distance, but quadruple our design haulage capacity. The differences are due to additional equipment and installation factors considered, a different design basis and a different accounts procedure employed. A cost projection of the pneumatic pipeline versus a belt conveyor (3.5 mile, 18,000 tons per day) as estimated by Soo [5] is included in Table 7.6 for comparison. At 18,000 tons of coal per day, the conveyor belt would ship coal at 3.83¢/ton-mile. Actual operations at 10-12¢/ton-mile have been experienced on a belt conveyor 5 to 6 miles in length [67].

7.4.4 Cost Comparison to Belt Conveyor

A belt conveyor was considered as an alternative to the current unit train. Based on the same design assumptions and accounting procedures used in the conceptual design of a 3.5 mile pneumatic pipeline system, a cost analysis of a 24" conveyor belt system was made. This estimate is independent of the more general one made in Volume 5. The results of the estimated economic analysis are shown in Table 7.7 using the following assumptions:

1) The estimation of conveyor equipment costs and fixed capital costs were based on the cost estimation for a 30" belt reported by the U.S. Department of Interior [10]. Average conveyor equipment and capital costs for the 24" belt were estimated to be $978,700 per mile and $1,397,700 per mile, respectively. These costs were escalated from 1962 to mid-1973 by a factor of 1.443 (344.1/238.5) as estimated from the Marshall and Stevens Index and to 1976 dollars using an assumed annual escalation rate of 7 percent. The conveyor equipment cost included structural work, fire protection and water supply, dust control, mechanical equipment, belting, electrical work, covering and terminal. Capital cost included conveyor equipment cost, construction overhead, contingency, right-of-way, escalation and interest during construction.

2) Working capital was estimated at 10 percent of fixed capital cost.

3) Except for fuel, annual operating costs used the same assumptions as those used in

the estimation of pneumatic coal transport costs.

4) Fuel costs were estimated on 240 hp. motor fuel cost = (\$0.01/Kw-hr) x 240 hp. x 7920 hr. x 0.746 kw/ph.

It was found that the installation of a belt conveyor system is very capital intensive (\$2,050,700 per mile, 1976 \$) and is comparable to the capital cost of constructing a double track railroad (\$1.584x10^6 per mi., 1975 \$) [63]. It requires 5 times the investment of an equivalent pneumatic pipeline system. Analysis of unit transport costs shows that the pipeline has a cost advantage (¢/ton mile) of as much as 3.6 times. Our findings confirm those made in the earlier study [5] (see Table 7.6) that there is a definite cost advantage to the use of a pneumatic pipeline rather than the belt conveyor for this case of coal transportation.

7.4.5 Cost Comparison to Railroad

The receiving facility has a coal transport system consisting of a 3.5-mile roadbed and trackage costing \$400,000 to \$500,000 per mile, 25 100-ton cars valued at \$25,000 to \$30,000 each and two locomotives valued at \$300,000 to \$400,000 each. The total investment was \$3.5 million with a fixed charge of 20 percent. This railroad is run by a 7-man crew costing \$140,000 per year; and includes a fuel cost of \$80,000 per year; maintenance of \$40,000 for cars and locomotives and \$75,000 per year for the tracks. The total annual cost was estimated to be \$1.1 million for a shipment of 4-5 million tons per year. These estimates suggest a charge of 24¢/ton although the cost may be as high as 50¢/ton because of the waste incurred by idle hours, waiting labor, and repairs on the locomotives [66,67].

TABLE 7.3: Bare Module Costs for Major Equipment and Buildings - Pilot Plant (1976 $)

ITEMS	ESTIMATION	1968 COST	1976 COST	REFERENCE
Belt conveyors	$\$540(150)^{0.65}2.18 = \$32,900$	$ 32,900	$ 50,800	(59)
Screw feeder	$\$290(20)^{0.75}2.05 = \$5,620$	5,600	8,700	(59)
Blow tanks	$\$16.1(3740)^{0.65}2.2 = \$7,440$	14,800	23,000	(59)
Rotary feeder	$6000+$1000(motor) = $7,000	14,000	21,600	(62)
Compressor package	$346(1751/90%)		673,200	(61)
Pipeline			141,500*	(61)
Cyclone separators	$\$3(8740)^{0.8}2.18 = \$9,300$	18,600	28,700	(59)
Duct collector	$\$25(8740)^{0.68}2.18 = \$26,100$	26,100	40,300	(59)
Discharge hoppers			10,000	
Total major equipment costs			$997,800	
Control House				
Steel structure:			12,000	
Sending end	$0.51x15'x30'x30' = $6,890	6,890	10,600	(59)
Receiving end	$0.51x20'x60'x40' = $24,480	24,480	37,800	(59)
Total building costs			60,400	

* $(0.325 \times 1.3773 + 0.45 \times 1.1747 + 0.59 \times 0.4705 + 0.74 \times 0.4775) \times 10^5 - 3.5(5500)$

\+ Average U.S. right-of-ways cost/mile (61)

TABLE 7.4: Capital Investment Estimation
Pilot Plant (1976$)

BARE MODULE COSTS

1a,	Major equipments	$ 997,800	
1b,	Buildings	60,400	
1c,	Site development (5% of 1a)	49,900	
1d,	Offsite facilities (8% of 1a)	79,900	
1.	Total Bare Module Cost		$ 1,188,000
2a,	Contractor Fee (5% of 1)	59,400	
2b,	Engineering and Supervision (7% of 1)	83,200	
2.	Total Module Cost		$ 1,330,600
3a,	Contingencies (10% of 2)	133,100	
3.	Fixed Capital Investments		$ 1,463,700
4.	Working Capital (10% of 3)	146,400	
5.	Total Capital Investments		$ 1,610,100

TABLE 7.5: Total Annual Cost Estimation of Pilot Plant (1976$)

I.	ANNUAL FIXED CHARGES		
	A. Fixed Charge (11.7% x 0.5 x 5*)	$ 94,200	
	B. Depreciation (3* 25)	58,500	
	C. Taxes (1% of 3*)	14,600	
	D. Insurance (1% of 3*)	14,600	
			$ 181,900
II.	ANNUAL OPERATION COSTS		
	A. Fuel	$ 93,000	
	B. Labor	150,000	
	C. Supervision (20% of IIB)	30,000	
	D. Maintenance and Supplies (6% of 3*)	87,800	
	E. Operation Supplies (15%) of IID)	13,200	
	F. Administrative Costs (40% of IIB)	60,000	
	G. Plant Overhead (50% of IIB,C,D)	134,000	
			$ 567,900
III.	TOTAL ANNUAL COSTS		$ 749,800
IV.	UNIT COST		
	A. Cost/Ton	47.34¢	
	B. Cost/Ton-Mile	13.53¢	
	C. Investment Cost/Ton per Day-Mile	$ 95.84	

* Cost figure in Table 7.4

Note: For fuel capacity load at 18,000 tons/day

$$\frac{18{,}000\text{tons}0.6}{200\text{x}24} = 2.21$$

Therefore unit costs are 21.3¢/ton and 6.09¢/ton-mile

TABLE 7.6. Cost Projection of Pneumatic Pipeline Versus Belt Conveyor* (3.5 miles, 18,000 tons of 1/4 x 0" coal per day) coal per day)

I. CAPITAL INVESTMENTS	Pneumatic Pipeline		Belt Conveyor	
Land and Improvements	$ 32,500		$ 32,500	
Structures and Buildings	35,000		35,000	
2500-hp. Motor Compressor	325,000			
Piping	25,000			
Bins and Venturi	12,000			
Feeders, Etc.			100,000	
Engineering and Contingencies	68,720		26,800	
Pipeline 16" dia. @ $92072/mile	322,300			
Conveyor Belt @ $1.71 x 10^6/mile			6,000,000	
Electrical Transmission @ $0.24/ft.	4,400		4,400	
Total Capital Investment		$824,900		$ 6,198,700
II. ANNUAL FIXED COSTS				
Fixed Charges	48,300		362,700	
Taxes	13,500		101,600	
Depreciation	33,000		268,000	
		94,800		712,300
III. ANNUAL OPERATING COSTS				
Manpower	75,000		75,000	
Material and Maintenance	9,000		9,000	
Maintenance	5,000		5,000	
Administration and Engineering	44,500		44,500	
Fuel	35,000		35,000	
		168,500		168,500

TABLE 7.6: Cost Projection of Pneumatic Pipeline Versus Belt Conveyor*
(3.5 miles, 18,000 tons of 1/4 x 0" coal per day)
(Continued)

	Pneumatic Pipeline	Belt Conveyor
IV. TOTAL ANNUAL COST	263,300	880,800
V. UNIT COSTS		
A. Cost/ton	4¢	13.4¢
B. Cost/ton-mile	1.14¢	3.83¢
C. Investment Cost/ton per day-mile	$13.1	$ 98.4

*Based on reference (5)

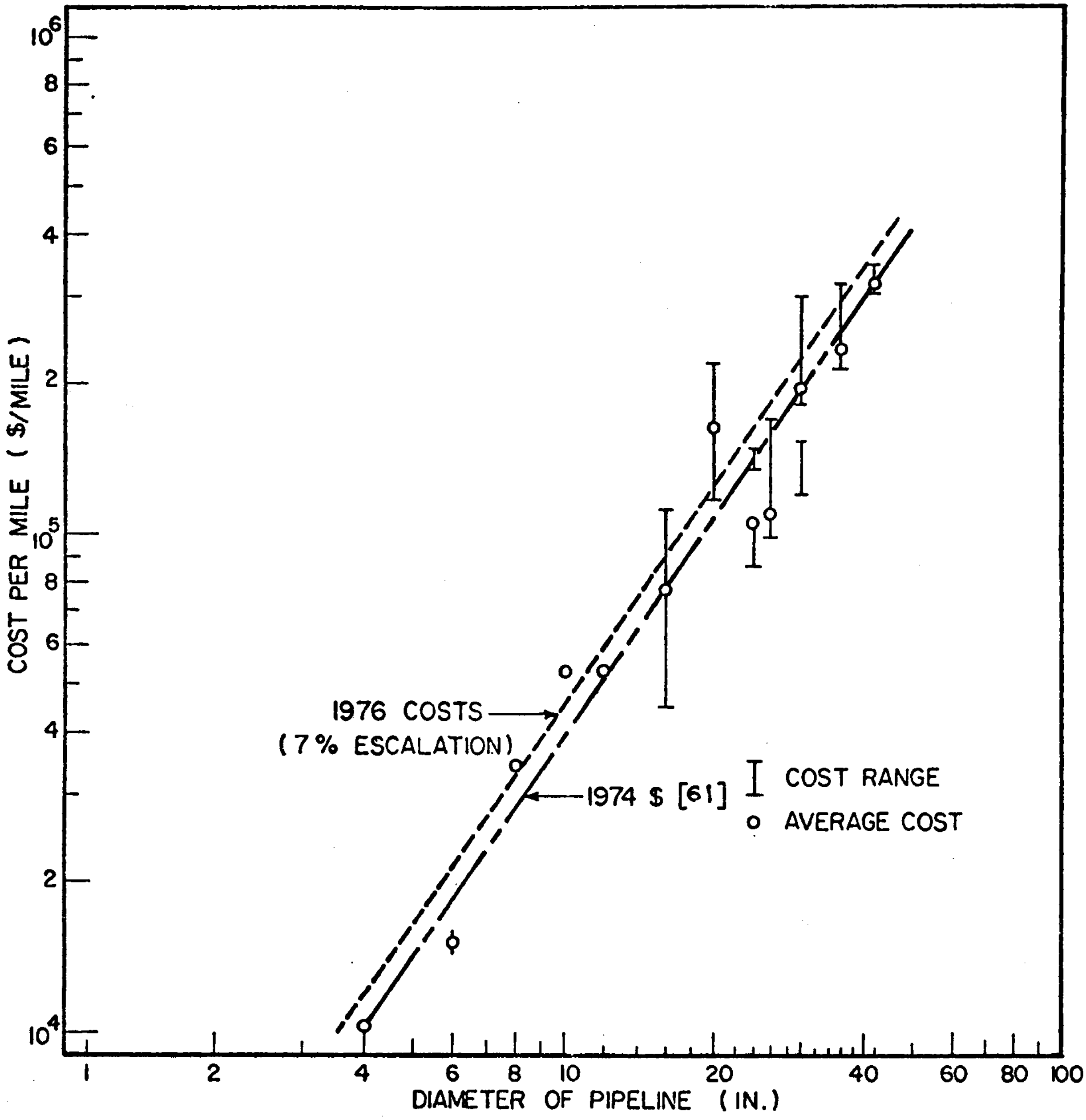
TABLE 7.7: Cost Estimation+of 24" Belt Conveyor System of 3.5 Miles for 200 Tons of 2x0" Coal Per Hour

I. CAPITAL INVESTMENTS		
Conveyor Equipment Costs, @ $1,496,300/mile 1)*	$ 5,237,100	
Fixed Capital Cost, @ $2,050,700/mile 1)		$ 7,177,500
Working Capital		717,800
Total Fixed Capital Investment		$ 7,895,300
II. ANNUAL FIXED COSTS 3)		
A. Fixed Charges	$ 461,900	
B. Depreciation	287,100	
C. Taxes	71,800	
D. Insurance	71,800	$ 891,600
III. ANNUAL OPERATION COSTS		
A. Fuel 4)	$ 14,200	
B. Labor and Supervision 3)	72,000	
C. Maintenance and Repairs 3)	430,700	
D. Operating Supplies 3)	64,600	
E. Administrative Costs 3)	24,000	
F. Plant Overhead 3)	251,300	
		$ 856,800
IV. TOTAL ANNUAL COST		
		$ 1,748,400
V. UNIT COSTS		
A. Cost/Ton		$ 1.104
B. Cost/Ton-Mile		31.53¢
C. Investment Cost/Ton per Day-Mile		$470.0

+ 1976 $

*) Assumption Number

FIGURE 7.14



Transmission Pipeline Construction Costs by Diamer (61).

+ Includes right-of-way costs, U.S. average R.O.W. cost $5500/mile

7.5 OTHER CASES OF APPLICATION

7.5.1 Hypothetical Cases of Application

It was stated earlier in this study that the pneumatic coal pipeline system would be an effective and promising means to supplement future coal transportation by utilizing it as a small-capacity, short-distance coal feeder or distributor to a rail head for small scale applications, and as a large-capacity, intermediate-distance (about 100 miles) coal delivery system if railroad is nonexistent. Thus, two hypothetical pneumatic coal transport systems are developed to evaluate the economics of these applications. Based on these evaluations, we try to formulate the general cost conditions of pneumatic coal transport systems for a range of capacities. The small scale hypothetical system is based on a design capacity of 200 tons of 2 x 0" size coal per hour (4800 tons per day) and a 1000' transport distance, while the large scale system assumes a capacity of 1000 tons of 1/4 x 0" size coal per hour (24,000 tons per day) and a transport distance of 100 miles. The former transport distance is realistic for a short haul loading and unloading system. The latter should be reasonable for a medium length gathering/distribution system. Based on the design procedure outlined in Section 7.3.1, the design parameters for each hypothetical system were generated from a computer program. Because of the short distance involved in the small scale system, telescoping of the pipeline might not be necessary even though it is feasible. The pneumatic system could be pressure, vacuum, or even a push-pull system. The final design should be determined on the basis of power requirements and cost effectiveness. The basic system design parameters for the small and large scale systems are shown in Table 7.8 and Figure 7.15, respectively. The vacuum system is selected for the economic evaluation as it requires a lower power requirement which leads to minimum cost.

7.5.2 Comparison of Costs

Included in the cost evaluation is the previously discussed system, but assuming that smaller sizes of coal (1/4 x 0") are being transported. It is anticipated that there should be a cost advantage over the 2 x 0" size coal, as shipping small size coal requires less power. The system is shown in Figure 7.16 with the design parameters which are employed as the basis for the cost evaluation.

Estimates of the capital investment and annual operating costs required for the three hypothetical pneumatic coal transport systems are shown in Table 7.9. The findings of the conceptual design of a 3.5-mile system shown in Tables 7.3, 7.4 and 7.5, are also summarized in Table 7.9 for direct comparison. The assumptions for cost evaluation, discussed in previous sections (see Sections 7.4.1 and 7.4.2), are also employed in these cost evaluations.

7.5.3 Cost Advantages of Shipping 1/4 x 0

It can be seen in Table 7.9 that there is a significant cost advantage in shipping the smaller size coal. This is estimated as a 27 percent reduction in capital investment and a 22 percent reduction in unit transport cost. An even greater cost advantage may be anticipated. The size of coal being shipped is only a matter of the location of the coal preparation plant (either at the sending point, or the receiving point of the pipeline for mine to power plant operation). The unit coal transport cost should be invariant to the cost of pulverizing the coal as it must be accounted for either at the preparation plant or at the power plant. Power for crushing to 1/4 x 0" size only amounts to 10 to 12 kwh/ton. Shipping of smaller size coal (1/4 - 1") is also technically feasible as future mining and washing techniques require smaller size coal [52,64], while 1/4 x 0" size coal should not cause any problem in present coal burning technology, or such future coal utilization technology as gasification and liquefaction.

For reasons apparently based on explosions in coal mines, some specialists have voiced the concern that a pneumatic pipeline might produce an explosion hazard. This conjecture obviously overlooks both the practice and experience of coal fired electric power plants. In these plants, the common practice is to transfer pulverized coal, of down to 200 mesh or finer, in pipes of larger than 12-in. diameter, using preheated air. The coal to air weight ratio is nearly 1. These facilities are used continually;

explosion is not a known hazard. The reason is that the mixture is fuel rich. Normal combustion requires a coal to air weight ratio close to 1:15. The proposed pipeline system would have a coal to air weight ratio up to 10:1. There is so little air that the flame would be smothered even if deliberately introduced. Furthermore, a mine explosion usually starts with the ignition of methane gas; combustion of coal dust occurring as the combustion wave stirs fine coals into the air. Currently, transferring TNT chips in pneumatic pipelines is common practice.

Concern for the starting and stopping condition, where a low coal to air ratio may occur, can be eased by the lack of sparks during these transients. Pyrite particles in coal may strike sparks during normal steady flow condition, but pyrite particles (specific gravity: 5) of similar size to coal (specific gravity: 1.3) will be the first to settle and the last to be entrained in stopping and starting the flow system.

TABLE 7.8: Flow Parameters for Pressure and Vacuum Short-Distance (1000 feet) Transport System of 200 Tons of 2x0" Coal Per Hour

Transport Mode	Standard Pipe #20		Length	Inlet Pressure	Outlet Pressure	Minimum Transport Velocity	Pressure Drop	Theoretical Horsepower
	Nominal Diameter	Inside Diameter						
	in.	in.	Ft.	psia	psia		psig	hp.
Pressure	12	12.25	1000	23.23	14.7	116.9	8.53	277.4
Vacuum	14	13.376	1000	14.7	10.17	147.0	4.53	218.0

Air flow = 8738 scfm

$K = 20$

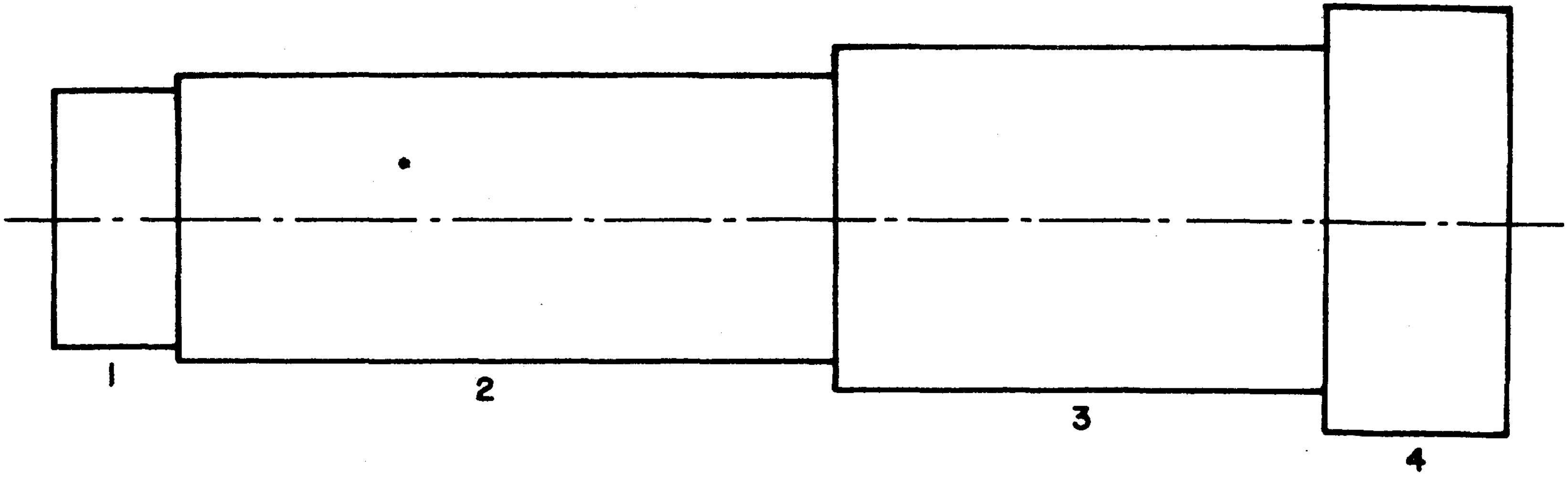
$\dot{M}^* = 10$

TABLE 7.9 Summary of Cost Analysis of Pilot Plant and Other Hypothetical Case of Pneumatic Coal Transport (1976$)

CASES	Pilot Plant	Pilot Plant Alternative	Short Distance	Intermediate Distance
TRANSPORT MODE	Pressure (Fig. 11)	Pressure (Fig. 16)	Vacuum (Table 8)	Pressure (Fig. 15)
SIZE OF COAL	2 × 0"	¼ × 0"	2 × 0"	¼ × 0"
CAPACITY	200 TPH	200 TPH	200 TPH	1000 TPH
TRANSPORT DISTANCE	3.5 Miles	3.5 Miles	1000 Feet	100 Miles
I. CAPITAL INVESTMENTS				
A. Major Equipments				
Belt Conveyor	50,800	50,800		61,200
Screw Feeder	8,700	8,700	8,700	23,000
Blow Tanks	23,000	23,000	10,000	101,500
Rotary Feeders	21,600	21,600	21,600	60,000
Compressor Package	673,000	130,800	29,600*	6,638,700
Pipeline	141,500	400,000	14,000	14,718,600
Cyclone Separators	28,700	28,700	28,700	104,100
Duct Collectors	40,300	40,300	40,300	120,300
Discharge Hoppers	10,000	10,000	10,000	50,000
	$997,800	$713,900	$162,900	$21,877,400
B. Buildings	60,400	60,400	30,000	300,000
C. Site Developments(5% of IA)	49,900	35,700	8,100	1,093,900
D. Offsite Facilities(8% of IA)	79,900	57,100	13,000	1,750,200
	$1,188,000	$867,100	$214,000	$25,021,500
E. Contractors' Fees	59 400	43,400	10,700	1,251,100
F. Engineering and Supervision	83,200	60,700	15,000	1,751,500
	$1,330,600	$971,200	$239,700	$28,024,100
G. Contingencies	133,100	971,000	24,000	2,802,400
I-1 FIXED CAPITAL INVESTMENT	$1,463,700	$1,068,300	$263,700	$30,826,500
H. Working Capital	$146,400	$106,800	$26,400	$3,082,700
I-2 TOTAL CAPITAL INVESTMENT	$1,610,100	$1,175,100	$290,100	$33,909,200
II. ANNUAL FIXED CHARGES				
A. Fixed Charges	94,200	68,700	17,000	1,983,700
B. Depreciation	58,500	42,700	10,500	1,233,100
C. Taxes and Insurance	25,200	21,400	5,280	616,600
	$181,900	$132,800	$32,830	$3,833,400
II. ANNUAL OPERATING COSTS				
A. Fuel	88,700	17,300	11,500	836,800
B. Labor and Supervision	180,000	180,000	75,000	540,000
C. Maintenance and Repairs	87,800	64,100	15,800	1,849,600
D. Operating Supplies	13,200	9,600	2,400	277,400
E. Administrative Costs	60,000	60,000	25,000	180,000
F. Plant Overhead	134,000	122,100	45,400	1,194,800
	$563,700	$453,100	$175,100	$4,878,600
IV. TOTAL ANNUAL COST	$745,600	$585,900	$207,930	$8,712,000
V. UNIT COSTS				
A. Cost/Ton	47.07¢	36.59¢	13.13¢	$ 1.10
B. Cost/Ton-Mile	13.45¢	10.57¢	69.31¢	1.1¢
C. Investment Cost/ton-per-day-mile	$95.84	$70.00	$319.1	$14.13

* $122 Blower hp

FIGURE 7.15



Section	Standard Pipe #20		Section Length	Inlet Pressure	Minimum Transport Velocity
	Nominal Diameter	Inside Diameter			
	in.	in.	mile	atm	ft/s
1	18	17.376	8.50	34.8	20.8
2	20	19.25	45.27	32.25	21.48
3	24	23.25	33.63	16.25	29.22
4	30	29.00	12.60	5.586	54.64

2 x 0" SIZE COAL

CAPACITY = 1000 TPH

AIR FLOW = 43685 SCFM

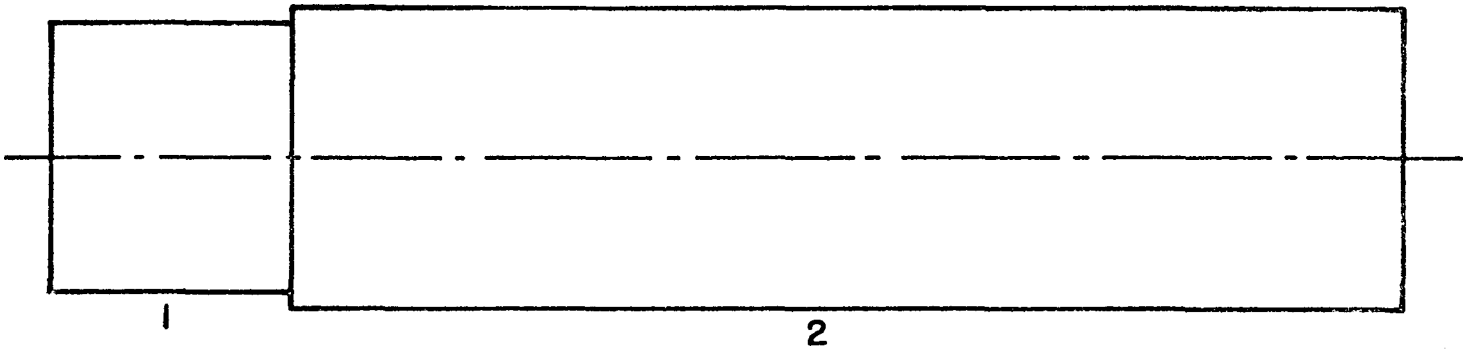
PRESSURE DROP = 33.8 atm

THEORETICAL HP = 16530 hp

K = 20

$\dot{M}^*$ = 10

Schematic Diagram of the 100-miles Telescoping Pneumatic Coal Transport Pipeline and Flow Parameters for Transport Capacity of 200 Tons of ¼ × 0" Coal Per Hour (k=20).



Section	Standard Pipe #20		Section Length	Inlet Pressure	Minimum Transport Velocity
	Nominal Diameter	Inside Diameter			
	in.	in.	mile	psia	ft/s
1	18	17.376	0.623	25.66	49.1
2	24	19.25	2.877	23.855	51.23

1/4 x 0" SIZE COAL

CAPACITY = 200 TPH
AIR FLOW = 8738 SCFM
PRESSURE DROP = 10.96 psig
THEORETICAL HP = 339.25 hp

K = 20
$\dot{M}^*$ = 10

FIGURE 7.16: Schematic Diagram of the 3.5-miles Telescoping Pneumatic Coal Transport Pipeline and Flow Parameters for Transport Capacity of 200 Tons of ¼ × 0" Coal Per Hour (k=20).

7.6 GENERAL DISCUSSION

7.6.1 Short Distance Coal Transport

Installation and experience based on short distance coal movements is plentiful [55]. The results of the economic evaluation of the hypothetical system examined in this study indicates a considerably higher unit transport cost compared with those of larger capacity. Whether the short distance pneumatic coal delivery system can provide costs below those of conventional methods such as belt conveyors remains to be determined. However, from the economic evaluation of belt conveyors shown in Table 7.7, it can also be deduced that the belt conveyor system is more capital intensive ($470 investment/ton-mile to $319.1 of pipeline) and a potential economic advantage of short distance pneumatic pipelines over belt conveyor systems should not be ruled out. Moreover, a short distance pneumatic coal transport system may still be more favorable if a dollar credit can be assigned to eliminating the loading and unloading charges required for rail coal shipment.

7.6.2 A Hyperbolic Cost Model of a Hypothetical Pneumatic Coal Transport Pipeline

The total capital costs for a pneumatic coal transport pipeline based on the conceptual design discussed in detail, and the other three hypothetical pipeline cost estimations were plotted against the corresponding annual ton-mile transport. The graph is shown in Figure 7.17. The arrows indicate the scale to be read. The capital cost requirement for a pneumatic coal transport pipeline may be roughly estimated from Figure 7.17 by finding the capital cost that corresponds to the capacity in annual ton-miles for the pipeline design. Also included in Figure 7.17 is the relation of unit coal transport cost (¢ per ton-mile) to the annual ton-mile transport of the pipeline. Hyperbolic curves were fitted to the data in order to generalize these cost relationships. They resulted in the following equations:

$$C = 252380(ATM)^{-0.513142}$$

for 2 x 0" size coal short distance shipment (below 3.5 miles), and

$$C = 31600(ATM)^{-0.39578}$$

for 1/4 x 0" size coal intermediate shipment (above 3.5 mile to about 100 miles) where.

C = unit coal transport costs in 1976 dollars (mills/ton-mile)

ATM = annual ton-miles transported by the pneumatic coal transport pipeline.

7.6.3 Economic Evaluation of an Intermediate Distance Telescoping Pneumatic Coal Transport Pipeline

The cost evaluation of the hypothetical intermediate distance telescoping pneumatic coal transport pipeline of 100 miles and 1000 tons of 1/4 x 0" size coal per hour capacity yields a capital requirement of $33,909,200. The resulting unit transport cost is 1.1 cents per ton-mile. No direct cost comparison with other transport modes is made in this section. The results obtained from this hypothetical pipeline can serve as a guideline for the cost estimation of a pipeline of medium distance.

An intermediate distance system appears to be best suited as a complement or supplement to a rail system by 1) replacing an abandoned or unprofitable rail line for coal delivery, and 2) completing an existing rail coal shipment network where the cost of building a railroad appears prohibitive. In many cases it is either mandatory from a practical standpoint or just economic to combine unit trains with other modes of coal transportation to achieve a satisfactory mine-to-consumer route. At present, barge/rail shipments are probably the most common combination. Barges are limited by the availability of water routes, which also tend to be less direct. Yet, if lengthy waterways exist, large shipments are efficient. Table 7.10 shows the modal split and distribution cost estimation of rail unit train-barge combination system reported by the Bechtel Study [65] using U.S. Bureau of Mines data. It can be seen that on a tariff basis considerable savings are obtained from this practice. Barge-pneumatic that on a tariff basis considerable savings are obtained from this practice. Barge-pneumatic pipelines and rail-pneumatic pipeline-barge or any combination of these three modes could be an inovative system for achieving lower coal transport costs.

As proposed by Soo [5], an intermediate pneumatic pipeline-rail combination seems a feasible alternative to the 273-mile, 5 x 10^6 tpy Black Mesa coal slurry line in Arizona. His proposed combination consists of a 120-mile pneumatic pipeline from Black Mesa to Winona, by unit train (covered) from Winona to Kingman (220 mile) via the Santa Fe Railroad, and from Kingman by a 30-mile pneumatic line to Mohave. Based on the data supplied by Bechtel [65], the existing slurry line required 1.7¢/ton-mile in 1974, or $5.02/ton and $5.314/ton in 1976 assuming Bechtel's annual escalation rates of 4 percent and 7 percent respectively. From Ballard's cost estimation [13, Table 7.5], the unit cost for Black Mesa ranges from 1.72 - 1.94¢/ton-mile depending on exclusion or inclusion of state tax, these cost figures in 1976 would be $4.883 - $5.508/ton and $5.024 - $5.667/ton at an annual escalation rate of 4 percent and 7 percent respectively.

According to our hyperbolic cost model for the intermediate distance telescoping pneumatic coal transport pipeline (Section 7.6.2), as the annual ton-mile capacities for both pneumatic pipeline sections are well within the range of the model, the 120-mile section of the proposed alternative would be $1.458 per ton while the 30-mile section would be $0.610/ton of coal moved. If the unit transport price of 220-mile unit train shipments were 0.504¢/ton-mile as estimated from reference [13, Table 7.4], the coal transport cost of using this alternative would be $3.255/ton of coal moved. Even if the unit train transport price were doubled, the overall cost of coal shipment would still be $4.423 per ton. Thus, it is anticipated that the proposed alternative application of the intermediate distance pneumatic coal transport pipeline to supplement the incomplete rail coal delivery network is feasible from the standpoint of cost. More important, the proposed alternative would be more significant if dollar credits were assigned to the benefits derived from the elimination of operational and environmental problems associated with the slurry pipeline [13,14].

7.6.4 Cost Evaluation of a Hypothetical Long-Distance, Large-Capacity, Telescoping, Pneumatic Coal Transport Pipeline

If the hyperbolic cost model of the intermediate distance pneumatic coal pipeline is reasonably correct, then its applicability to a long-distance large-capacity pipeline should yield a conservative cost estimate. Lower costs would be expected as annual ton-mile capacity increases. Based on the data provided in Ballard's cost evaluation of a slurry pipeline compared to rail [13, Table 7.5] his results are correlated in terms of annual ton-miles moved (Figure 7.18). The hyperbolic curve for an intermediate distance is plotted and extrapolated to long-distance large-tonnages (i.e., large value of annual ton-miles moved). It is interesting to note that for long-distance large-capacity transport, where railbed is already available, the unit cost of pneumatic transport appears to be comparable with that of railroad with new rail and ties, and only rail with upgrading can provide costs under those indicated for pneumatic transport. However, if railroad is nonexistent, a long-distance telescoping pneumatic pipeline may have a cost advantage over the building of new railroads and slurry pipelines. Another case of the cost comparison based on the cost data from the Bechtel study [65] further confirms these findings and is shown in Figure 7.19. This result may provide a referent for long-term energy transportation planning and policy.

TABLE 7.10: Coal Distribution Modal Split and Distribution Cost Estimate[+]

Modal Split (%)[++]			
Rail	Unit Train	Barge	Cost[+++] ($/Ton)
100	-	-	3.90
46	24	30	3.13
100	-	-	4.55
37	33	30	2.84
24	6	70	2.10
35	31	34	2.46
100	-	-	4.55
82	18	-	5.25
51	49	-	4.10
38	20	42	4.31
-	100	-	4.17
56	44	-	3.41
26	74	-	4.79
64	36	-	4.54
100	-	-	4.51
-	100	-	4.25

[+] Based on Reference [65]

[++] Source: BOM

[+++] Costs are estimated in 1975 dollars

[*] Assumed all rail

[**] Assumed all unit train

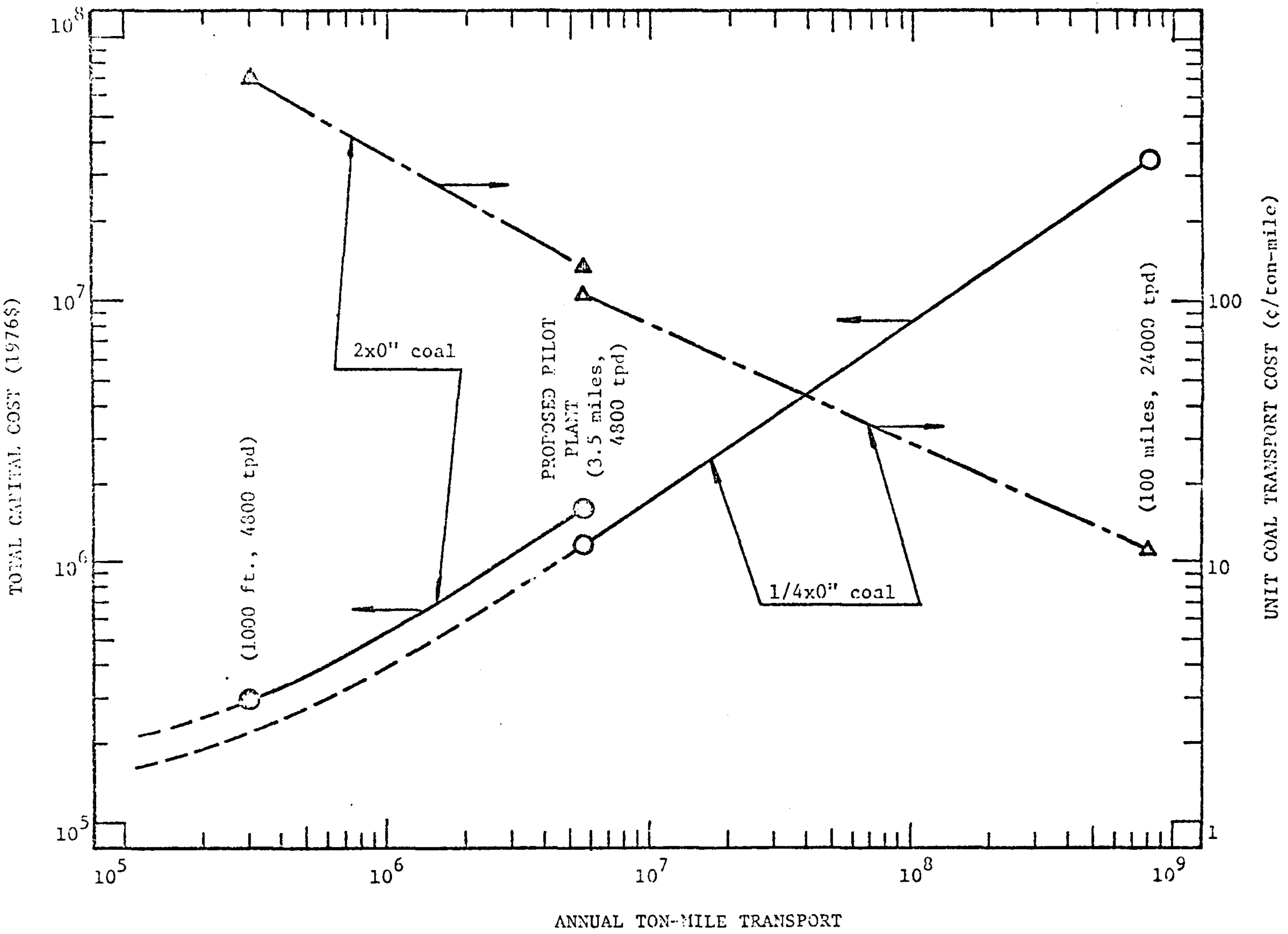
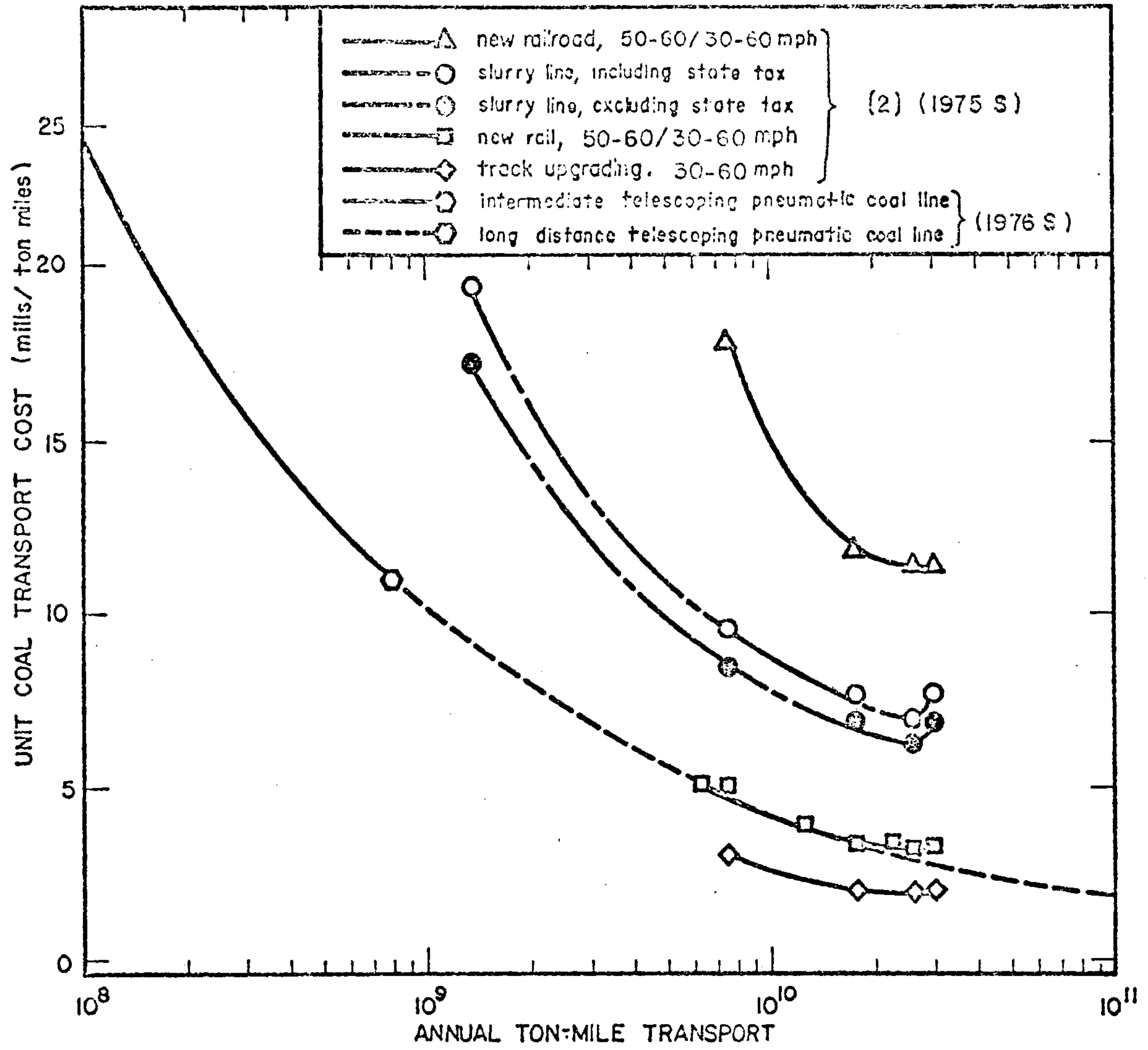


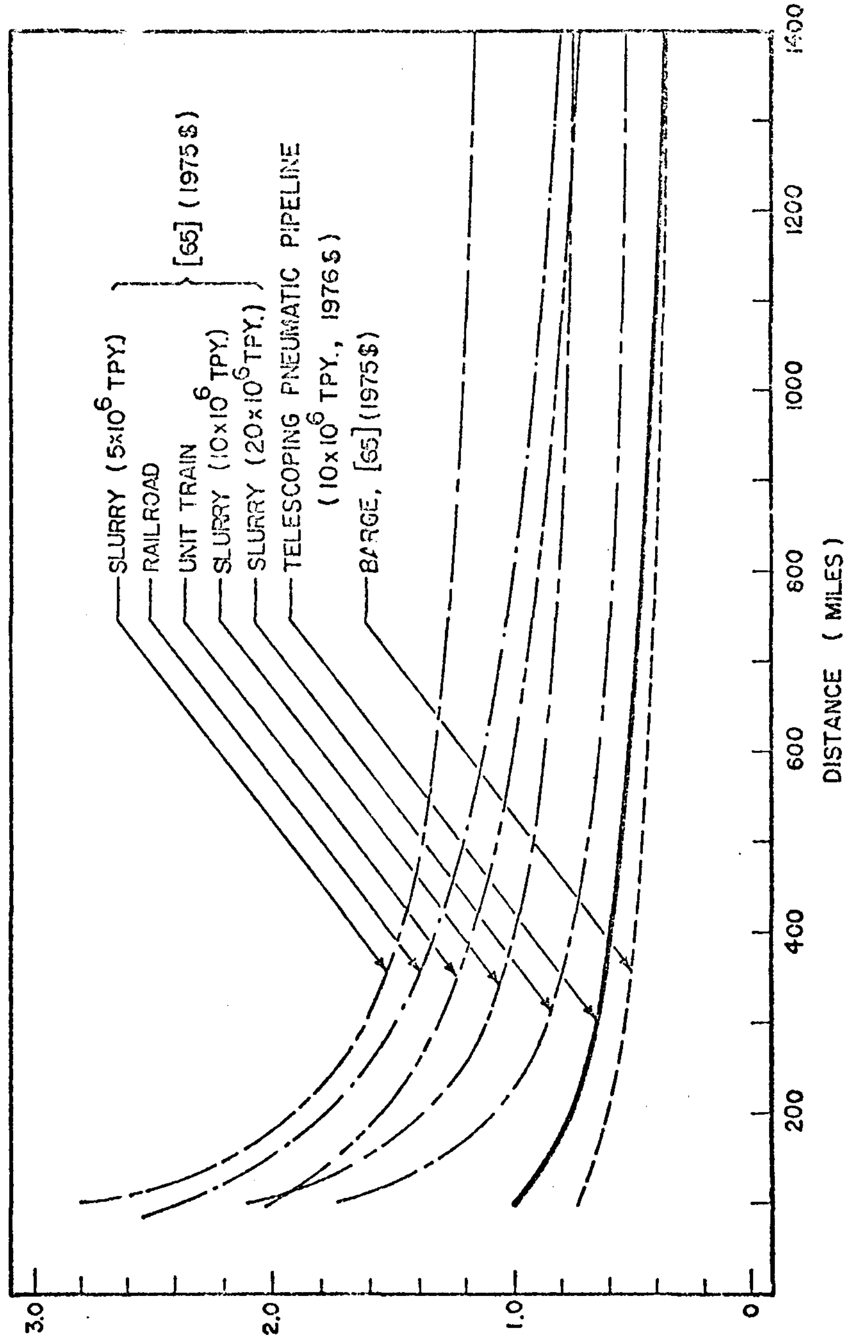
FIGURE 7.17: Total Capital Cost and Unit Transport Cost for Short and Intermediate Distance Pneumatic Coal Pipeline (1976$).

FIGURE 7.18: Cost Comparison Showing Unit Transport Cost Extrapolated From Hyperbolic Cost Model (Eq. 7.2.1) For Long-Distance Large-Capacity Shipment as Compared to Cost Data of Rail and Slurry Pipeline From Reference (13).



Cost Comparison Showing Unit Transport Cost Extrapolated from Hyperbolic Cost Model (Eg. 6.2.1) for Long-Distance Large-Capacity Shipment as Compared to Cost Data of Rail and Slurry Pipeline from Reference (13).

FIGURE 7.19: Unit Coal Transport Cost Extrapolated from Hyperbolic Cost Model (Eq. 7.2.1) for Long-Distance Large-Capacity Shipment and Cost Data of Other Modes of Coal Transportation As from Reference (65).



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