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ECONOMIC ANALYSIS OF COAL LOG PIPELINE TRANSPORTATION OF COAL

by

Henry Liu, Robert Zuniga and James L. Richards

Capsule Pipeline Research Center (CPRC)
University of Missouri-Columbia

January 1993

CPRC Report No. 93-1

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JAMES S. NOBLE

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EXECUTIVE SUMMARY

This economic report is a refinement and an update of a 1990 study conducted by Liu and Wu¹ that compares the cost of transporting coal from mines to power plants by coal log pipeline (CLP) with other modes of transportation including truck, rail and the coal slurry pipeline. The quantities compared are the **unit cost**² which is the cost for transporting a ton of coal through any pipeline of any length in terms of \$/T (dollars per ton) and the **unit-distance transportation cost**³ which is the cost for transporting a ton of coal over a one-mile distance, in terms of \$/TM (dollars per ton per mile). These unit costs were investigated (plotted) as a function of the transportation **distance** and **throughput**. The 1990 study revealed that under a wide range of conditions, CLP is the most economical mode for transporting coal from coal mines to power plants. Great savings can be accomplished by using CLP to transport coal.

The current (1992) study is more conservative than the 1990 study in cost figures for CLP. Still it shows that under many conditions it is more economical to transport coal by CLP than by truck, rail and slurry pipeline. Therefore, this study once more

¹Liu, H. and Wu, J.P. Economic Analysis of Coal Log Pipeline Transportation of Coal, University of Missouri-Columbia Civil Engineering Report, April 1990, 77 pages.

^{2&3}Both the **unit cost** and the **unit-distance cost** are tariffs for transporting coal. They include not only costs but also a built-in profit for the pipeline company.

establishes the economic feasibility of using CLP to transport coal in many situations. The study also has identified key research areas that should be pursued in order to make the CLP technology most cost effective.

In spite of the encouraging findings of this economic study, it should be realized that this is a generic study aimed at the "average conditions" in the United States. Since pipeline costs depend greatly on topographic and geographic factors, generic studies such as this are no substitute for site-specific economic studies which are far more accurate for any particular pipeline project. Still, generic studies are needed to draw general conclusions and investigate trends for CLP in general.

Moreover, it should be recognized that CLP is a not-yet-fully-developed and not-yet-commercialized emerging technology. As such, the economic analysis conducted, no matter how rigorous and detailed, is only as good as the assumptions used in the analysis. Because some of the assumptions cannot be substantiated without further research, different scenarios are investigated herein. This study should be regarded as a preliminary investigation that must be improved later when more is known about CLP through future technological development. Further improvement of this economic study will be done in two years when the development of the technology is more complete. The CLP technology is currently undergoing intensive research and development at the Capsule

Pipeline Research Center (CPRC) in Missouri. Many technical questions concerning the CLP technology will be answered in the next two years which will make the next revision of this report more definite and accurate than what can be done today.

ACKNOWLEDGMENT

Thanks are due to the **Williams Technologies, Inc. (WTI)** which, serving as the Principal Consultant of the coal log pipeline project, has reviewed and provided detailed comments and suggestions on the cost data and the draft report. WTI is uniquely qualified for this role due to its experience in operating the world's longest coal slurry pipeline -- the Black Mesa Pipeline. Another consultant who has conducted a detailed review of the 1990 report and has provided valuable comments and suggestions is **William N. Poundstone**, a former executive vice president of the Consolidation Coal Company with extensive experience in coal slurry pipeline design and operation. The writers also wish to thank several other companies and individuals who have either provided cost data or assisted in this study in other ways. This includes the **Bonnot Company** which has provided cost data on extruders; the **Gundlach Machine Company** which has provided cost information on crushing and grinding of coal and coal logs; the **Barrett, Haentjens & Company** on the cost of centrifugal type slurry pumps; the **Mogas Company** on the cost of high-duty slurry valves, the **Nova Tech Company** on the cost of automatic computer control systems for the CLP; the **Eirich Company** on mixers and extruders; the **Union Carbide Corporation** on polymer additives for drag reduction; the **Graver Company** on water deaeration cost; the **Coal Services Corporation** for coal drying cost; the **Bird Machine Company** for the cost of centrifugal dewatering of coal slurry; the **Division of Transportation, Missouri Department of Economic Development** for freight rates by trucks; and **Dr. Yuyi Lin** of the CPRC who has provided a preliminary design and cost estimate of coal log fabrication machine used in this study. **James L. Ramer & Associates** also provided valuable services in arriving at the preliminary design used in Dr. Lin's design. Finally, excellent typing of this manuscript, by **Voronica Bonaparte**, is appreciated.

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List of Symbols

English

- a = aspect ratio (i.e., coal log length divided by coal log diameter) (dimensionless);
- A_{Li} = area of land needed for inlet facilities (acres);
- A_{mbi} = area for main building at inlet (square feet);
- A_{sf} = area of land needed for sedimentation and flocculation tanks (square feet);
- A_{ti} = area of intake tank (square feet);
- B = width of intake tank (feet);
- B_b = width of main building at inlet (feet);
- B_s = width of sedimentation tank (feet);
- C_a = annual cost of project for any given year;
- C_{ab} = cost of automatic control equipment for each booster station;
- C_{ai} = cost of additional equipment for inlet;
- C_{ao} = cost of automatic control equipment for outlet;
- C_b = total capital cost for each booster station;
- C_{bb} = cost of building for each booster station;
- C_{bh} = cost of binder heating tanks for a CLP;
- C_{bhl} = cost of each binder heating tank;
- C_{bi} = cost of each building for inlet;
- C_{bo} = cost of each building for outlet;
- C_{cd} = cost of centrifugal dewatering equipment;
- C_{ci} = cost of conveyor belts for inlet;

Note: Unless otherwise mentioned, all the costs are in thousand dollars (unit of \$1,000)

- C_{co} = cost of conveyor belts for outlet;
- C_{cp} = cost of compaction machines for coal logs;
- C_{cr} = cost of crushers for coal logs;
- C_{ct} = cost of coating machines for coal logs;
- C_{de} = cost of deaeration equipment for a CLP;
- C_e = cost of extruders for coal logs of a CLP;
- C_{e1} = cost of each extruder;
- C_f = cost of flocculation tank;
- C_{Lb} = cost of land for each booster station;
- C_{Li} = cost of land for inlet;
- C_{Lo} = cost of land for outlet;
- C_{mbi} = cost of main building for inlet;
- C_m = cost of mixers for mixing binder with coal;
- C_{m1} = cost of each mixer;
- C_o = total capital cost for outlet;
- C_{oo} = cost of other outlet equipment;
- C_{pb} = cost of pipeline for each booster station;
- C_{pc} = construction cost of pipeline;
- C_{pg} = cost of pigs needed for a CLP;
- C_{pi} = cost of pipeline construction for inlet;
- C_{p1} = unit cost of pipeline construction (\$1000/mile);
- C_{rb} = cost of access road for each booster station;
- C_{ri} = cost of access roads for inlet;
- C_s = cost of sedimentation tank;
- C_{sb} = cost of substation for each booster station;
- C_{si} = cost of substation for inlet;

- C_{ti} = cost of intake tank;
 C_{ub} = cost of pumps for each booster station;
 C_{ui} = cost of pumps for inlet;
 C_{ul} = cost of each pump;
 C_{vb} = cost of valves for each booster station;
 C_{vi} = cost of valves for inlet;
 C_{vl} = cost of each valve;
 C_{wrb} = cost of water reservoir at each booster station;
 C' = annual operation/maintenance (O/M) cost;
 C'_{bi} = annual cost of binder;
 C'_{cd} = annual cost of centrifugal dewatering of CLP slurry;
 C'_{cl} = annual cost of communication linkage (phone or satellite);
 C'_{cr} = annual cost of crushing coal from 2" to a 0.5" top size;
 C'_{eb} = annual cost of electricity at each booster station;
 C'_{ei} = annual cost of electricity for inlet;
 C'_{eo} = annual cost of electricity for outlet;
 C'_f = annual cost of flocculant;
 C'_{hc} = annual cost of heating coal at CLP inlet;
 C'_{mb} = annual cost of materials at each booster station;
 C'_i = annual total O/M costs for inlet;
 C'_o = annual total O/M costs for outlet;
 C'_{oi} = annual other O/M costs for inlet;
 C'_{oo} = annual other O/M costs for outlet;
 C'_{pb} = annual cost of polymer added at each booster station;
 C'_{pi} = annual cost of polymer used at inlet;

- C'_{pg} = annual cost of transporting pigs by truck;
 C'_{sb} = annual cost of salary and wages at each booster station;
 C'_{si} = annual cost of salary for operating inlet;
 C'_{so} = annual cost of salary for operating outlet;
 C'_w = annual cost of water for a CLP;
 d = depreciation of capital for each year (dimensionless);
 D = pipe diameter (inches or feet);
 D_c = coal log diameter (inches or feet);
 e = equity rate which is the fraction of return, R , on equity financing (dimensionless);
 E_b = annual energy use for each booster station (kwh);
 E_i = annual energy use for operating inlet (kwh);
 F = freight rate (unit-distance) cost which is the cost for transporting unit weight of cargo over unit distance (\$/TM);
 F_{tk} = freight rate for truck (\$/TM);
 H_p = horsepower of pump;
 H_{pa} = horsepower of auxiliary pump;
 H_{pm} = horsepower of main pump;
 H_{ub} = total horsepower of pumps at each booster station;
 I = inflation rate (% per year);
 k = diameter ratio D_c/D (dimensionless);
 K = constant in Eqs. 22 and 23;
 L = length of the pipeline analyzed (miles);
 L_{ci} = length of conveyor belt for inlet (ft);
 L_{co} = length of conveyor belt for outlet (ft);

- L_{Lo} = length of lock (injection/launching tube) (ft);
 L_{mbi} = length of main building at inlet (ft);
 L_{pi} = length of pipe at inlet (ft);
 L_{ti} = length of intake tank (ft);
 L_s = length of sedimentation tank at CLP outlet (ft);
 L_t = length of each coal log train in pipeline (ft);
 M = money borrowed and/or invested in project (\$1,000);
 n = the nth year of pipeline life (an arbitrary integer);
 N = assumed economic life of the pipeline (yrs);
 N_b = number of booster stations for a CLP;
 N_e = number of extruders needed for a CLP;
 N_p = number of pigs needed for operating a CLP;
 N_{pt} = number of pigs transported each year in a CLP;
 N_t = number of binder heating tanks needed for a CLP;
 N_{tr} = number of coal-log trains moving in a CLP of length L ;
 P_b = power for each booster station;
 P_{bb} = power for operating buildings at each booster station;
 P_{bh} = power for binder heating;
 P_{bi} = power for building (heating/air-conditioning) at inlet;
 P_{cd} = power for centrifugal dewatering of CLP slurry;
 P_{ci} = power for conveyors at inlet;
 P_{co} = power for conveyors at outlet;
 P_{op} = power for compaction of coal logs;

Note: All power quantities such as P_b , P_i and so on are in kilowatts (kw).

- P_{cr} = power for coal-log crushers;
 P_{ct} = power for operating coal log coating chambers;
 P_{de} = power for deaeration;
 P_c = power for extruders;
 P_i = total power for operating inlet;
 P_m = power for mixers;
 P_o = total power required for outlet;
 P_{oi} = power for operating other equipment at inlet;
 P_{ub} = power for operating the pumps of each booster station;
 P_{ui} = power for operating pumps at inlet;
 P_{vb} = power for operating valves at each booster station;
 P_{vi} = power for operating valves at inlet;
 Q_b = binder throughput (tons/hr);
 Q_{b1} = throughput of each binder heating tank (tons/hr);
 Q_c = coal throughput of a CLP or slurry pipeline (tons/hr or MT/yr);
 Q_{cs} = throughput of the coal in the slurry of CLP (MT/yr);
 Q_{m1} = throughput of each mixer (tons/hr);
 Q_w = discharge of water through pipeline (cfs);
 Q_{ws} = discharge of water entering sedimentation tank (cfs);
 r = rate of return for money invested in the project (dimensionless);
 R = annual return on investment and interest paid (\$1,000);
 S = specific gravity of coal logs (dimensionless);
 t = annual tax rate (dimensionless);
 T = annual payment of taxes (\$1,000);

- T_d = detention time for sedimentation tank (minutes);
 u = coal log fabrication rate (ft/sec);
 U = unit transportation cost which is the cost for transporting unit weight of coal through a pipeline (\$/T);
 U_o = average present value of unit cost (\$/T)--see Eq. 7;
 U_p = present value of U (\$/T) -- see Eq. 6;
 V = cross sectional mean velocity of water through sedimentation tank at CLP outlet (ft/sec);
 V_L = lift-off velocity (ft/sec);
 V_o = pipeline operational velocity (ft/sec);
 V_t = volume of flocculation tank (ft³);
 W_p = total weight of pigs transported per year for a CLP (tons/yr); and
 W_{pl} = weight of each pig (lbs).

Greek:

- α = linefill rate dimensionless;
 β = binder concentration (fraction or percent of logs by weight);
 δ = discount rate for money dimensionless;
 ϵ = density ratio which is the coal-log density divided by the fluid density (ρ_c/ρ)--same as specific gravity when the fluid is water (dimensionless);
 λ = system availability (percent time in operation);
 θ = polymer concentration in water (parts per million by weight).
 ρ = density of fluid--usually water (slugs/ft³); and
 ρ_c = density of coal logs (slugs/ft³).

1. INTRODUCTION

Transportation experts have for years known the great economic advantage of using pipelines to transport fluids (liquid and gas). The cost for transporting fluids by pipeline is often less than 1/5 of the cost for transporting the same fluids by rail, and less than 1/10 of the cost by truck. This shows the great economic advantages of using pipelines to transport fluids. While transporting solids by pipeline is more difficult and hence more costly than transporting fluids, in many situations the use of pipelines to transport solids still constitutes the most economic way to transport bulk solids over long as well as relatively short distances. This accounts for the worldwide use of slurry pipelines to transport coal and many other minerals as shown in Table 1.* A notable example is the Black Mesa Coal Slurry Pipeline which transports coal from Arizona to Nevada over a distance of 273 miles. This 18-inch-diameter pipeline transports approximately 5 million tons of coal per year. It has been operating successfully since 1970 at 95% availability. The use of relatively short slurry pipelines to transport sand to construction sites and to transport mine tailings and wastes for disposal is even more common.

* All tables are listed in APPENDIX I.

The coal log pipeline (CLP) technology has many potential advantages over the coal slurry pipeline [1]* such as it uses only one-third to one-fifth of the water to transport the same amount of coal transported by slurry pipelines, it can have twice the throughput of a coal slurry pipeline of the same diameter, and dewatering cost is much less. Consequently, it is reasonable to expect that the economics of CLP may surpass that of the coal slurry pipeline in many situations. As will be shown later, the economic analysis conducted herein confirms this speculation.

The cost for transporting each ton of coal from a coal mine to a power plant varies considerably with the distance between the mine and the plant. Generally, longer distances require higher costs. For plants that use coal from a distant source, it is not uncommon that transportation by truck or train constitutes 1/3 or even 1/2 of the delivered cost of the coal. For instance, for transporting low-sulfur coal from Wyoming to Missouri, the transportation cost (by train) in 1992 is approximately \$15 per ton** which is three times as high as the cost of coal sold at the mine sites in the Powder River Basin in Wyoming. Therefore, how to minimize coal transportation costs is of great interest to coal

* Numerals in [] represent corresponding items in REFERENCES.

** This includes not only the direct cost paid to railroads but also the indirect cost to power plants for constructing and operating a rail terminal at each plant.

companies, electric utilities and the general public. The CLP technology offers an opportunity to reduce coal transportation cost substantially in many situations.

The CLP technology was first investigated at the University of Missouri-Columbia (UMC) in a two-year research project sponsored by the Pittsburgh Energy Technology Center (PETC), U.S. Department of Energy (DOE). The project established the preliminary technical feasibility and many promising features of coal log transport through pipelines. Information on this new technology, other than cost information, is contained in a DOE report prepared by Liu and Marrero in 1989 [1].

A preliminary economic assessment of the CLP technology was conducted by Liu and Wu in 1990 [2]. It concluded that in many situations transporting coal by CLP appears to be much more economical than by truck, train and coal slurry pipeline. Since then, an industry consortium has been established to finance the R & D of the CLP technology at UMC, and government support to this R & D effort has been received from DOE's Energy Invention Related Program, from the National Science Foundation (NSF), and from the Missouri Department of Economic Development (MDED). As a result of the expanded research efforts in the last two years, the technology of CLP is significantly more mature today than two years ago, and

so the economic study conducted in 1990 [2] warrants updating and refinement.

The purpose of this study is to update and revise the 1990 economic report [2], taking into account new developments and improved understanding of the CLP technology accomplished since 1990. As in the 1990 report, this study investigates the life-cycle costs of coal log pipelines of different lengths and throughputs, so that the economics of CLP can be compared with that of other competing transportation modes including truck, rail, and coal slurry pipeline.

It should be realized that in spite of the advancements made in the R & D of CLP in the last few years, this is still an emerging (not-yet-fully-developed) technology. Consequently, the actual costs of some components of the CLP process, such as coal log fabrication, cannot be predicted accurately. Neither can the life span and the operation/maintenance costs be predicted accurately. Therefore, the results of this economic analysis of CLP, as it is the case with any major new technology, should not be taken without reservations. They should be regarded as preliminary or interim, and should be improved again in the future as more is learned from research in CLP.

Despite the approximation and the uncertainties involved, generic economic analysis of an emerging major technology such as CLP is highly desirable for the following reasons:

- (1) It helps the developer (researchers) and the financier (sponsors) of the new technology determine whether it is worth the risk to develop the technology.
- (2) By calculating the approximate cost of each component and of the total system, one can see which components have the strongest effect on the total system cost. This helps the developer (researchers) determine the priority and the direction of needed R & D. *Component interaction effects*
- (3) The analysis reveals the least-cost alternative for a working system. This helps in attaining optimum design and in reducing the cost of any commercial CLP system to be built in the future.
- (4) Such an economic analysis forces the researchers to think hard about the details of the system, thereby bringing progress to technology development.

This explains why a generic economic analysis is conducted at this stage prior to the full development of the CLP technology. At the current pace of the R & D in CLP, this economic study should be updated in another two years, reflecting new discoveries and technological and economic changes.

2. NATURE OF STUDY

This study seeks to compare the economics of transporting coal by CLP with that of other existing modes of transport including truck, train, and coal slurry pipeline. The comparison is based on both the **unit cost** of transportation which is the cost (**tariff** more specifically) for transporting unit weight of coal from a coal mine to a power plant, and the **unit-distance cost** of transportation which is the cost (**tariff**) for transporting unit weight of coal over unit distance. The unit cost is given in dollars per ton (**\$/T**); and the unit distance cost (i.e., the **freight rate**) is given in dollars per ton per mile (**\$/TM**). The result is a set of curves showing the variation of the unit cost or the unit distance cost with transportation distance for various throughputs (i.e., transportation volumes or capacity).

The unit cost is calculated using a life-cycle cost analysis method employed by the General Research Corporation [3] and the Office of Technology Assessment (OTA) of the U.S. Congress [4] in assessing the economics of coal slurry pipeline. The method was employed by Liu et al. [5,6] in estimating the cost of transporting coal by hydraulic capsule pipelines (HCP) that use containers and a dual pipeline system, including both a delivery pipe and a return pipe. It was also used by Wu [7] in a grain pipeline study. It is the best method known to the writers for analyzing and comparing

the economics of freight transportation by pipelines with that of other modes.

(are all factors
able to be
economically captured?)

3. SCENARIOS

As is the case with all emerging major technologies, the economics of CLP (Coal Log Pipeline) hinges on some major factors that cannot be predicted with certainty at this stage. Therefore, a meaningful economic study of CLP must consider different possibilities or scenarios. The following 32 scenarios have been selected for this interim study:

(how determined)

- (1) Coal logs are manufactured by a binderless compaction process; each machine can produce 0.2 ft. of coal logs per second; the coal must be heated prior to compaction; sealing of coal log surfaces is needed; the specific gravity of the logs is 1.20; a positive displacement pump having differential pressure of 1,500 psi is used for pump bypass at each pumping stations; opening and closing of valves is completed in 10 seconds; fresh water is unavailable and treated (desalinated) brackish water is used for the pipeline; deaeration of water is required at the intake to minimize pipeline internal corrosion; the length of each coal log train in feet is equal to 200 times the operational velocity V_0 in ft/sec--this results in intake lock length and pump bypass length of $210 V_0$; new pipeline is constructed for the project; the linefill rate of the coal logs is 90%; the system availability is 90%; no drag-reducing additives (polymers) are used in this coal log pipeline system; and the equity rate, e , is 1.0.
- (2) Same as 1, except that the log fabrication machine can produce 0.4 ft/sec of logs.
- (3) Same as 1, except that the log fabrication machine can produce only 0.1 ft/sec of logs.
- (4) Same as 1, except that coal logs surfaces need no sealing treatment, and the specific gravity of the log is increased to 1.35.

- (5) Same as 1, except that the specific gravity of the logs can be reduced to 1.05.
- (6) Same as 1, except that the specific gravity of the coal logs can be reduced to 1.10.
- (7) Same as 1, except that positive displacement pumps of 2,000 psi are used.
- (8) Same as 1, except that positive displacements pumps of 1,000 psi are used.
- (9) Same as 1, except that a set of centrifugal pumps of 500 psi is used.
- (10) Same as 1, except that a "pig" is used to lead each coal log train, and the "pig" must be transported back to pipeline intake by truck.
- (11) Same as 1, except that fresh water is available.
- (12) Same as 1, except that the length of each coal log train is equal to 100 times V_0 , which is half of that of scenario 1.
- (13) Same as 1, except that the length of each coal log train is equal to 400 times V_0 , which is twice that of scenario 1.
- (14) Same as 1, except that instead of constructing a new coal log pipeline, an existing oil or natural gas pipeline is used for (converted to) a CLP. For the converted pipeline, the maximum operating pressure is reduced to 1,000 psi, and the economic life remaining is only 15 years.
- (15) Same as 1, except that the linefill rate of coal logs is 80% instead of 90%. This will allow a valve closure time greater than 10 seconds, if necessary.
- (16) Same as 1, except that no deaeration of water is required.
- (17) Same as 1, except that drag-reducing additives are used.
- (18) Same as 4, except that drag-reducing additives are used.

- (19) Same as 6, except that drag-reducing additives are used.
- (20) Same as 6, except that coal logs are extruded using 1% binder; a low-cost type extruder with extrusion rate of 0.2 ft/sec is used; ordinary mixers (those for mixing asphalt with gravel for road construction) are used for mixing coal with asphalt.
- (21) Same as 20, except that coal logs are extruded using 3% binder.
- (22) Same as 20, except that coal logs are extruded using 5% binder.
- (23) Same as 20, except that special (expensive) extruders are used.
- (24) Same as 1, except that a duplicate lock system is used at the pipeline intake and a duplicate pump bypass is provided at each booster station to increase system reliability (availability) to 95%.
- (25) Same as 4, except that coal slurry is used to suspend and transport coal logs.
- (26) Same as 1, except that certain cost items are assumed to have a life of 15 years only. They include conveyers, compacting and coating machines, deaeration equipment, additional inlet equipment, crushers, automatic control equipment, and other outlet equipment.
- (27) Same as 1, except that a higher-than-normal profit (30% return) is assumed for investment.
- (28) Same as 1, except that the equity rate, e , is assumed to be 0.6.
- (29) Same as 1, except that the equity rate, e , is assumed to be zero.
- (30) Same as 1, except that the discount rate used is 6%-- the same as the inflation rate.
- (31) Same as 1, except that inflation rate, fuel escalation rate, electricity escalation rate, and discount rate are all 1% point below those for scenario 1.
- (32) Same as 26, except that the economic life of the system, other than the components listed in 26, is 45 years.

A summary of the 32 aforementioned scenarios is contained in Table 2.* A brief explanation of the conditions mentioned in each scenario is provided as follows:

Research at the Capsule Pipeline Research Center (CPRC) has shown that medium-strength (unconfined compressive strength of 1,000 psi) coal logs can be produced without binder by compaction of coal at 80°C approximately. Such logs, however, must receive surface treatment to prevent water absorption and loss of strength due to water absorption. More recently, tests showed that higher-strength coal logs can be produced without binder by compaction of coal at 200°C. These higher-strength logs need no surface treatment to reduce water absorption. On the other hand, researchers at CPRC also have demonstrated that coal logs can be extruded with less than 4% binder. They believe that with better mixing of binder with the coal and with improved process control, satisfactory logs can be extruded with as little as 1% binder. However, it is likely that all such extruded logs will need surface treatment against water absorption. This explains why different scenarios were designed for compaction without binder and extrusion with binder with or without surface treatment.

A key factor affecting the cost of compacted logs is the rate or speed at which the logs can be produced by each machine. Since

*All tables are listed in APPENDIX I.

131, 142
this cannot be predicted accurately at present, three production rates, given in scenarios 1, 2 and 3, are used for comparison.

Current research at CPRC indicates that most coal logs, except perhaps the densest type (specific gravity = 1.35), will require surface treatment as by coating with a sealant in order to prevent excessive water absorption and resultant loss of strength. Consequently, sealant treatment of log surfaces is included in all scenarios except 4, 18 and 25.

As shown in Table 3, the lift-off velocity of coal logs can be reduced drastically by decreasing the **density ratio S**, where S is the coal log density ρ_c divided by the fluid density ρ . The value of S can be decreased either by making lighter logs or by using a heavier fluid. Both strategies are investigated in this study. For instance, logs of four different densities or specific gravities are used: specific gravity equal to 1.35 for **scenarios 4, 18, and 25**, 1.05 for **scenario 5**, 1.10 for **scenarios 6, 19, 20, 21, 22, and 23**, and 1.20 for the other scenarios. A heavier-than-water fluid that can be used to reduce the density ratio S for coal log pipelines is coal slurry. Scenario 25 investigates the merit of using slurry to transport heavy coal logs that have a specific gravity equal to 1.35.

To be conservative, this economic study assumes the use of slurry pumps rather than water pumps at booster stations. Both the centrifugal and positive displacement types of slurry pumps may be used. If the centrifugal type is used, due to its relative low head several pumps must be put in stages (series), and the maximum combined pump pressure will be limited to 500 psi approximately. In contrast, each positive displacement pump can generate up to 2,000 psi pressure. This explains why scenario 9 uses centrifugal pumps at 500 psi, whereas in other scenarios a positive displacement pump is used at each pumping station with a pump pressure of 1000, 1500, or 2000 psi. The effect of using pumps of different pressure is explored in scenarios 7, 8 and 9.

It is possible that future commercial systems of CLP will use a "pig" to lead each coal log train in pipe. The "pig" can serve several purposes, such as (1) cleaning the pipe before each coal log train passes through it (this requires a pig with brush around it), (2) controlling the train speed and spacing between logs (this requires a magnetic pig going through a section of the pipe with an electromagnetic break), and (3) protecting the leading log from excessive abrasion. However, using such "pigs" not only increases the capital cost but also the operation costs, for the "pigs" must be transported back by truck to the pipeline intake for reuse. Scenario 10 investigates the cost of using "pigs".

To be conservative, it is assumed in all but scenario 11 that fresh water is not available for the project, and treated (desalted) brackish water is to be used. Scenario 11 investigates the cost saving that can be accomplished if fresh water is available.

In general, longer coal log trains allow longer valve closure time and larger linefill rates. These advantages of longer trains are balanced by the higher costs for the need of longer inlet locks and longer pump bypasses. An optimization of the train length is needed. This explains the exploration of different train lengths in scenarios 1, 12 and 13.

Study has shown that some pipelines that transports domestic crude oil from Wyoming/Montana to Kansas/Missouri are running out of oil and may face shutdown in the next few years, especially if oil price remains as low as in 1992. Great advantages can be gained by converting such existing pipelines to coal log pipelines for transporting coal. The advantages include no right-of-way problems and shorter construction time. However, when an existing pipeline is assumed in this study, the remaining economic life of the pipeline is taken to be 15 years instead of the 30 years assumed for new pipelines. Furthermore, the existing pipeline is assumed to be able to withstand 1,000 psig instead of 2,000 psig for new pipelines. Scenario 14 explores the possible cost savings

that can be accomplished or possible extra costs in using such existing pipelines for coal log transports.

Research at CPRC [8] has shown that by using a special valve stroking strategy, the valves at each pump bypass can be opened and closed in three seconds without producing serious waterhammer problems. This shows that the 10-second valve opening/closure time assumed in all the scenarios is a conservative assumption for calculating the linefill rate. This means the 90% rate assumed is not only realistic but also conservative. However, a system with 80% rate is also analyzed in scenario 15 to determine how sensitive the unit transportation cost is to linefill rates.

Due to the use of water and steel pipe without lining, internal corrosion of the pipe, especially near the intake, will take place if the oxygen dissolved in the water is not removed. For this reason, in all but scenario 16, it is assumed that deaeration is required for CLP. Scenario 16 investigates the cost savings that could be accomplished if deaeration were not needed.

So far, no research has explored the advantage of using polymers (high-molecular-weight, long-chain molecules) for drag reduction (i.e., reduction of energy loss) in coal log pipelines. However, literature indicates that [9] the use of a small amount of certain water soluble polymers such as polyethylene oxide can

reduce drag (frictional loss) in ordinary water or oil pipelines by as much as five times (500%) when the fluid velocity is high and the flow is highly turbulent. Because the operational velocity of CLP used in this study is rather high, the flow is fully turbulent and great benefit of using drag-reducing additives is expected. This explains why the effect of drag-reducing additives is explored in scenarios 17, 18 and 19. Research is needed to verify the predicted effectiveness of polymers in reducing drag in CLP systems.

The effect of using extruders instead of compaction machines to produce coal logs is studied in scenarios 20 through 23. These scenarios explore the use of different percent of binders and two different types of extruders--one common economic type and the other an expensive type.

In all the scenarios except No. 24, a spare pump is included at each pumping station, but no duplicate or spare bypass system is provided. This corresponds to an assumed 90% availability rate. Higher reliability (95% availability) is assumed by providing a duplicate bypass at each intermediate station, and a duplicate lock system at the intake. This corresponds to scenario 24.

In all but scenarios 26 and 32, the economic life of the entire CLP system is assumed to be 30 years. This includes not

only the pipe, pumps, valves and buildings, but also the other equipment. While most new pipelines, pumps, valves, buildings and so on are known to last longer than 30 years, some equipment such as extruders, mixers, computers and so on may need to be replaced once every 15 years. This effect is investigated in scenario 26. Because most pipelines have a life much longer than 30 years, scenario 32 investigates the effect that a longer (45 years) life for pipeline has on coal transportation cost.

The normal rate of return for investment is assumed to be 15% [4]. However, some companies may require a higher return rate, due to the risk involved in using a not-yet-proven new technology. Scenario 27 investigates the economics of CLP systems based on a high (30%) return rate.

Except for scenarios 28 and 29, the equity rate assumed is 1.0. To determine how the equity rate affects results, two other equity rates are investigated: 0.6 for scenario 28, and zero for scenario 29.

In all but scenario 30, it is assumed that the discount rate (which in this study is taken to be the tariff escalation rate for the competing mode of freight transport in the next 30 years) is 8%--same as the fuel escalation rate. This assumption appears reasonable because trucks, trains, barges and ships all use diesel

fuel, and for long distance transportation the freight rates for such modes should be linearly proportional to the price of diesel. The use of the tariff escalation rate for competing freight transport modes as the discount rate allows direct comparison of the average present-value unit cost for CLP with the current tariffs charged by the competing modes. The impact of changing the discount rate is assessed in scenario 30.

In all the first 30 (thirty) scenarios, it is assumed that the inflation rate is 6%, electricity escalation rate is 7% and fuel escalation rate is 8%. Scenario 31 investigates the effect of reducing these rates by 1% point below such assumed values.

Many other cases (scenarios) can be and should be explored, such as some based on quite different interest rates, some based on quite different inflation rates, and some that recycle the water in CLP. These scenarios have not been included in this study due to monetary and time constraints. They will be explored in the future.

(Note: Without losing continuity, those readers not interested in the lengthy presentation of methodologies, assumptions and equations may skip Section 4 through Section 6.4 and go directly to Section 6.5 for discussion of results.)

4. METHODOLOGY FOR CALCULATING UNIT COST

The method used in this study for calculating unit transportation cost is based on the **cash flow analysis** which considers all the revenues (incomes) of a project as a positive cash flow, and all the costs (expenditures) as a negative cash flow. Each cost item during the life cycle (economic life) of the project is treated as a discrete payment (outlay of cash). Those paid at the beginning of the project are the **initial costs**, and those paid subsequently are the **subsequent costs**. For simplicity, all the initial costs are regarded as being paid on the first day of the project, and the subsequent costs as being paid at the end of each year. No payment is made in the middle of each year. This simplifying assumption produces acceptable errors for projects having life time exceeding 10 years. In this report, the "**subsequent costs**" and the "annual cost" are treated as synonyms.

In this report, the **initial costs (capital costs)** include the cost for planning, design and construction of projects, and the **subsequent costs** cover depreciation of capital, return on investment, taxes, insurance and operation and maintenance (O/M). The **O/M costs** include energy cost, materials and supply, repair and maintenance, wages and salaries, and all other miscellaneous annual costs.

In the cash flow analysis, the money borrowed and/or invested (i.e., the capital cost), M , will be paid back each year during the life of the project-- N years. It is assumed that the principal is paid back in N equal installments. This means the payback or depreciation of capital, d , for each year is:

$$d = \frac{M}{N} \quad (1)$$

The return, R , which is a combination of interest on debt financing and return on investment for equity financing, is

$$R = [M - (n-1)d] r \quad (2)$$

where R is the annual return for the n th year ($n \leq N$); and r is the rate of return.

Taxes, T , are paid annually on the return from equity according to:

$$T = R e t \quad (3)$$

where e is the equity rate (i.e., the fraction of return on equity financing); and t is the tax rate. The taxes referred to herein are the corporate income tax, not the property tax which is included separately.

of the capital cost M . The capital cost and the O/M costs for CLP cannot be determined accurately without a detailed engineering cost analysis which is the subject of Section 6.

Assuming that the **unit cost (tariff)** for transporting coal, U , in dollars per ton ($\$/T$) of coal transported through a pipeline, is priced at such a level that the income (revenue) generated from transporting coal for each year exactly balances the annual (subsequent) cost of that year, C_a , we have

$$C_a = U Q_c \quad (4)$$

where Q_c is the throughput in tons of coal per year.

From Eq. 4, the unit cost for transporting coal during any arbitrary year n is

$$U = \frac{C_a}{Q_c} \quad (5)$$

Discounting the unit cost for year n to its present (1992) value yields

$$U_p = \frac{C_a}{Q_c} \frac{1}{(1+\delta)^n} \quad (6)$$

where U_p is the present value of U ; and δ is the discount rate for money.

Adding up all the U_p values for the N years and dividing the result by N gives the average present value of the unit cost as follows:

$$U_o = \frac{1}{N} \sum_{n=1}^N (U_p)_n \quad (7)$$

Why do you want this?
Same as Asset cost? yes, but less intuitive

For simplicity, we shall refer to U_o as the "unit cost." In this report, unless otherwise specified, the term unit cost refers to U_o rather than U or U_p .

Finally, dividing U_o by the pipeline length L yields the unit-distance cost (freight rate) F , namely

$$F = \frac{U_o}{L} \quad (8)$$

The economics of CLP can be established by comparing the unit cost U_o or the freight rate F for CLP with that for slurry pipeline and other modes of coal transportation. U_o can also be compared with the current (1st-year) tariff of rail, truck and barge provided that U_o and U_p are determined by using a discount rate equal to the tariff escalation rate of these competing modes. In this study,

the economics of CLP for each scenario is assessed by plotting U_c and F as a function of pipeline length L and throughput Q_c .

This economic analysis is based on the cash flow diagram shown in Fig 1.* While the horizontal axis of the chart in Fig. 1 represents time in years, the vertical axis represents cash flow--positive (upward) represents income and negative (downward) represents expenditure. To maintain a balance of cash flow at all time, the negative cash flow for each year must balance the positive cash flow (income) of the same year. As mentioned before, the initial or capital cost is paid in the beginning of the project, whereas the subsequent cost for each year is paid at the end of each year.

From Fig. 1, the borrowed and/or invested money at the beginning of the project equals the initial (capital) cost. At the end of the first year, the total expenditure (annual cost) of the year must equal to the income (revenue) generated from transporting coal. The same balance between the annual cost and revenue holds for each of the subsequent years.

The procedure for the life-cycle cost analysis is as follows. For any given coal log pipeline, the initial (capital) cost

* All figures are given in APPENDIX II.

including planning, design, land acquisition, permit application, construction and so forth is estimated. This is set equal to M which can be used in Eqs. 1, 2 and 3 for calculating the values of d , R and T for each year. Property tax, insurance and O/M costs such as salary, energy etc. are separately determined and added to d , R and T to form the total annual cost C_a , of the year. The value of C_a for each year is then used in Eq. 5 to determine the unit cost U , and in Eq. 6 to calculate the discounted (present value of) unit cost, U_p . The values of U and U_p for each year are then listed in a table as shown in Table 15. Adding up the values of U_p for the N years and dividing by N yields the present value of the average unit cost, U_0 . Finally, the present freight rate F is calculated from Eq. 8 by dividing U_0 by the pipeline length L . This indicates how the present unit cost U_0 and the present freight rate F are determined for each pipeline.

The foregoing calculation is carried out for pipelines of different diameters, D , ranging from 4 to 20 inches, and different pipeline lengths, L , from 10 to 2,000 miles. The length L used in each calculation corresponds to a multiple of the distance between neighboring booster stations along each pipeline. The result is a set of curves giving U_0 (or F) versus L for different throughput or diameter. Each set of such curves in a figure (Figures 4 through 35, given in APPENDIX II) represents a different scenario.

5. GENERAL ASSUMPTIONS

Meaningful cost comparison between different modes requires that some general (common) assumptions be made in the cost analyses of all modes. The general assumptions used in this study include:

- All present costs are in 1992 monetary value.
- The return rate, r , is assumed to be 15%. A higher return rate (30%) is assumed in scenario 27 for new technology investment.
- All the items under operational/maintenance (O/M) costs, except for fuel and electricity, escalate at the general inflation rate of $I = 6\%$ per year. (Exception is made in scenario 31 which assumes that $I = 5\%$.)
- The escalation rate for fuel (diesel) is 8% (i.e., 2% above general inflation). The fuel escalation rate is an important factor in computing the cost of coal transportation by trucks and trains, but not by pipeline. (Exception is made in scenario 31 which assumes that the fuel escalation rate is 7%.)
- The escalation rate for electricity is 7% which is 1% point above general inflation. (Exception is made in scenario 31 which assumes that the electricity escalates at 6%.)
- The discount rate δ used is the same as the fuel escalation rate--8%. (Exceptions are made in scenario 30 which assumes that $\delta = 6\%$ and in scenario 31 which assumes that $\delta = 7\%$.)
- The income corporate tax rate is $t = 0.37$ (i.e., 37%).
- The property tax rate is equal to 2% of total capital.
- The insurance rate is equal to 0.5% of total capital.

- The equity rate is $e = 1.0$. This means all the money invested (capital cost) comes from the owner; no money is borrowed. (Exception is made in scenario 28 which assumes that $e = 0.6$ and in scenario 29 which assumes that $e = 0$.)
- The pipeline is assumed to have an economic life of thirty years ($N = 30$). (Exceptions are made for scenario 14 which uses an existing pipeline that has an economic life of fifteen years only, for scenario 26 which assumes that many types of equipment must be replaced every 15 years, and for scenario 32 which assumes a 45-year life).

In addition to these general (fiscal) assumptions, many specific (technical) assumptions also must be made which will be discussed in various places of this report whenever each assumption is needed in the analysis or calculation, or in the discussion of results.