1. INTRODUCTION

Transportation experts have for years known the great economic advantage of using pipelines to transport fluids—both liquid and gas. The cost for transporting fluids by pipeline over long distance 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 pneumatic pipelines to transport bulk materials over short distances [1],* and the use of slurry pipelines to transport coal and many other minerals as reported in [2]. A notable example of slurry pipeline is the Black Mesa 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 solids in dredging and to transport mine tailings and wastes for disposal is even more common.

The **coal log pipeline (CLP)** technology has many potential advantages over the coal slurry pipeline [3] 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 has 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 most situations. As will be shown later, the economic analysis conducted herein confirms this speculation.

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* Numerals in [ ] represents corresponding items in REFERENCES.

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) 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. The cost is even higher for shipping coal from Wyoming to Texas by rail. Therefore, how to minimize coal transportation costs is of great interest to coal 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 invented and patented by Liu and Marrero [4, 5] with patent rights assigned to the Board of Curators of the University of Missouri. The concept 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) [6]. The project established the preliminary technical feasibility and many promising features of coal log transport through pipelines.

A preliminary economic assessment of the CLP technology was conducted by Liu and Wu in 1990 [7]. It concluded that in many situations transporting coal by CLP appears to be 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 of this R & D effort has been received from DOE's Energy Invention Related Program, from DOE Pittsburgh

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* 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, and sometimes owning and operating the railroad cars for hauling coal.

Energy Technology Center, from the National Science Foundation (NSF), and from the Missouri Department of Economic Development (MDED). The Electric Power Research Institute (EPRI) also sponsored a study to assess the need for handling and treatment of coal logs and effluent water at power plants receiving coal from CLP [8]. As a result of the expanded R & D, the technology of CLP was substantially more mature in 1993 than in 1990. This prompted a revision of the 1990 economics report in 1993 [9]. As rapid advancement in the CLP technology has continued through present, another revision of the economics of CLP became necessary in 1995 which resulted in the current report.

The purpose of this report is to update and revise the 1993 report [9], taking into account new developments and improved understanding of the CLP technology accomplished since 1993. As in the two previous reports, 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 over different ranges of distance and throughput. The comparison is based on both **the unit freight cost** which is the cost for transporting unit weight of coal from a coal mine to a power plant, and the **unit-distance freight cost** which is the cost for transporting unit weight of coal over unit distance. The unit freight cost ("**unit cost**" in short) is given in **dollars per ton ($/T)**; and the unit-distance freight cost ("**unit-distance cost**" in short) is given in **dollars per ton per mile ($/TM)**. The result is a set of curves showing the variation of the **unit cost** or the **unit-distance cost** with transportation **distance** (pipeline length) for various **throughputs** (i.e., transportation volumes or capacity).

In the 1990 and 1993 reports [7, 9], the unit cost and the unit distance cost were calculated using a life-cycle cost analysis method employed by the General Research Corporation [10] and the Office of Technology Assessment (OTA) of the U.S. Congress [11] for assessing the economics of coal slurry pipeline. This method, called "**revenue requirements** approach," sets the revenue of each year to be the same as the annual expenditure including returns so that the cash flow of each year is balanced. This method is no longer used in the current report. Instead, this report uses a **net cash flow** approach commonly used by pipeline companies. The use of an approach favored by pipeline companies is justified because it is most likely that future coal log pipelines will be built and owned by pipeline companies under long-term contract with electric utilities. Any cost analysis must satisfy the pipeline company investing in the coal log pipeline.

It should be realized that in spite of the tremendous advancements in CLP in the last four years, CLP is still an emerging (not-yet-fully-developed) technology. Consequently, the actual costs of some components of the CLP process, such as coal log manufacturing cost, still cannot be predicted accurately. Neither can the life span and the operation/maintenance costs be predicted accurately and with certainty. Therefore, the results of this economic analysis, as it is the case with any other major emerging technology, should not be taken without reservations. They should be regarded as preliminary, and should be improved again and again in the future as more is learned from R & D and commercial use of 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) determine whether it is worthy to develop this new 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.

(3) By varying the parameters used in this cost model, the least-cost alternative of a CLP system can be determined. This helps to attain optimum design and to reduce the cost of any commercial CLP system to be built in the future. Such an optimization study will be conducted in the near future.

(4) Such an economic analysis forces the researchers to think hard about the details of the system, thereby bringing progress to technology development.

(5) With minor modifications, the model used in this generic study can be easily adapted to analyze the cost and economics of any particular coal pipeline project. For instance, for a project with significant elevation difference between pipeline inlet and outlet, the elevation difference can easily be incorporated to calculate more accurately the pumping energy and the distance between booster stations. For a pipeline that must cross mountains and/or rivers, the pipeline construction cost used in this generic model can be increased to reflect the situation. For example, each river crossing can be treated as an additional cost item in calculating the pipeline construction cost. The cost of energy (electricity), assumed to be 6 cents per kwh, also can be easily adjusted for site-specific studies.

This explains why a generic economic analysis is conducted 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 changes of technology and economy.

2. METHODOLOGY FOR CALCULATING UNIT COSTS

The method used in this study for calculating unit costs is based on the **net cash flow approach** that considers all the revenues (incomes) of a project as positive cash flow, and all the costs (expenditures) as negative cash flow. The cash flow diagram is shown in Fig. 2.1; the horizontal axis of the chart represents time in years, and the vertical axis represents cash flow. During the life cycle (economic life) of the project, each cash flow is treated as a discrete payment (outlay of cash). Costs paid at the beginning of the project are the **initial costs**, and those paid subsequently are treated as annual outlay (**annual costs**). All initial costs are regarded as being paid on the first day of the project, and all subsequent costs as being paid at the end of each year. No payment is made in the middle of any year. This simplifying assumption is commonly used in cost analysis of engineering projects that have a multi-year life.

The **initial costs (capital costs)** includes the costs for planning, land and right-of-way acquisitions, permit applications, design and construction of the project. On the other hand, the **annual costs** cover depreciation of capital, return on investment, taxes, insurance and operation and maintenance (O/M). The **O/M costs** include energy cost, materials, supplies, repair and maintenance, wages and salaries, and all other miscellaneous costs encountered each year. The capital and the annual costs for CLP are determined from a detailed engineering cost analysis discussed in Section 6.

In the cost analysis model used by OTA (Office of Technology Assessment) and in our previous reports [7, 9], the cash flow is balanced for each year—income equals expenditure. In contrast, in the current report based on net cash flow, the total expenditure of each year (total annual cost) in Fig. 2.1 must be less than the income (revenue) generated from transporting coal. The annual cost for this approach, C_a', includes operation/maintenance (O/M), cost C', property

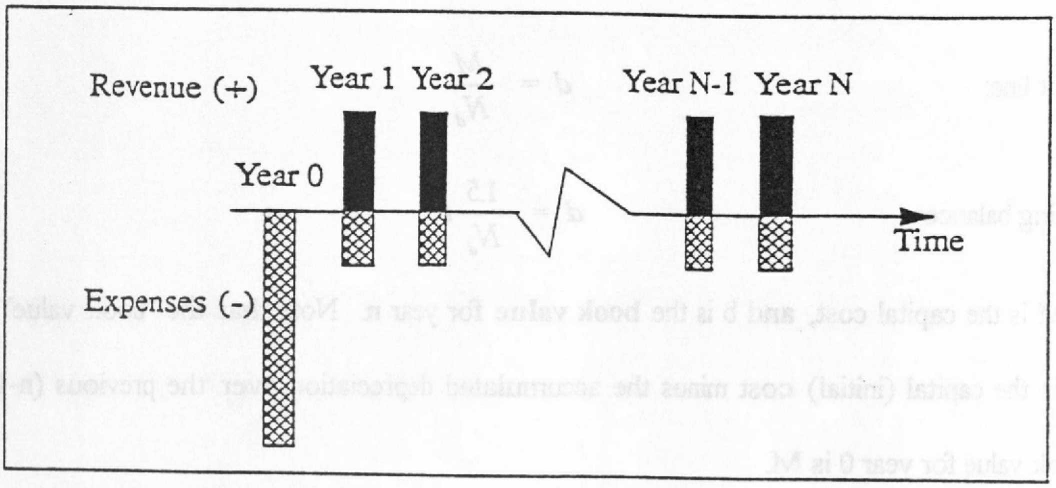

Fig. 2.1. Cash Flow Diagram Based on Net Cash Flow Approach (NCFA)

tax, T_p, and insurance, I_s, namely,

$$C_a' = C' + T_p + I_s \tag{2.1}$$

Note that the O/M cost C' includes energy, binder, water, salaries, etc.

To determine the annual revenue R_a, it is necessary to obtain the after-tax cash flows (ATCF) for each year. The before-tax cash flow (BTCF) is defined as

$$\mathrm{BTCF} = R_a - C_a' \tag{2.2}$$

The after-tax cash flow (ATCF) is defined as

$$ATCF = BTCF - T \tag{2.3}$$

The corporate income tax T is calculated from

$$T = (\mathrm{BTCF} - d)\, t \tag{2.4}$$

where d is the depreciation and t is the corporate income tax rate.

Two different depreciation schedules are used in this report: **straight line** and **150% declining balance** (with 1/2 year conversion), both for a 20-year depreciation life $(N_d = 20)$. This implies that the depreciation for year n is:

Straight line: $$d = \frac{M}{N_d} \tag{2.5}$$

Declining balance: $$d = \frac{1.5}{N_d}b \tag{2.6}$$

where M is the capital cost, and b is the **book value** for year n. Note that the "book value" for any year n is the capital (initial) cost minus the accumulated depreciation over the previous (n-1) years. The book value for year 0 is M.

A cash flow profile as shown in Fig. 2.1 is constructed to allow the BTCF to generate the specified rate of return. This is obtained by setting the annual revenue R_a in such a manner that the sum of the present values of ATCF for N years equals zero. The structure of the cash flow analysis is as illustrated in Table 2.1. The present value of ATCF for year n is calculated from:

$$(ATCF)_o = \frac{(ATCF)_n}{(1+\delta)^n} \tag{2.7}$$

where $(ATCF)_o$ is the present value of ATCF; and $(ATCF)_n$ is the ATCF value for year n.

The discount rate δ used in Eq. 2.7 is the inflation adjusted rate of return calculated from:

$$\delta = r + I + r\,I \tag{2.8}$$

In Eq. 2.8, r is the after-tax return rate; and I is the inflation rate.

Table 2.1. Net Cash Flow Approach Calculation

n	*Revenue* R_a	*Annual Cost* C_a'	*BTCF* $R_a - C_a'$	*Deprec.* d	*Taxable Income* *BTCF - d*	*Tax* T	*ATCF*	*Present Value of ATCF*
0								
1								
2								
…								
N_d								
…								
N								

$$\sum ATCF(present) = 0$$

The annual revenue R_a in Table 1 for any year n is

$$R_a = U_n Q_c \tag{2.9}$$

where Q_c is the throughput of coal in tons per year; and U_n is the unit cost for transporting coal through the pipeline for year n, in dollars per ton ($/T).

Assuming that the unit cost for transport coal by coal log pipeline in the beginning of the project is U, the unit cost for year n is

$$U_n = U(1+\varepsilon)^n \tag{2.10}$$

where ε is the annual rate of increase in tariff— tariff escalation rate.

Substituting Eq. 2.10 into Eq. 2.9 yields

$$R_a = U(1+\varepsilon)^n Q_c \tag{2.11}$$

The value of R_a in Table 2.1 for each year is determined by an iteration procedure in which the values of U and ε are assumed. After first having chosen the tariff escalation rate ε, the value of U can be varied until the sum of the present values of the ATCF for N years equals zero. The correct value of U is the one that makes the sum of the present values of ATCF for N years equal to zero. Henceforce, U will be referred to as the "**present unit cost,**" or simply "**unit cost.**"

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

$$F = \frac{U}{L} \tag{2.12}$$

The economics of CLP can be established by comparing the unit cost U and the freight rate F for CLP with that for other modes of coal transportation. The comparison is meaningful only if compared with the unit cost and the freight rate of the competing mode for the same year, using the same escalation rate for both modes.

The foregoing approach will be used to determine U and F for pipelines of different diameters, D, ranging from 6 to 20 inches, and different pipeline lengths, L, from 10 to 2,000 miles. The result is a set of curves giving U (or F) versus L for different coal throughput or pipeline diameter—see figures in Appendix II. Each figure is for a different scenario. The scenarios will be described in Section 5.

3. GENERAL (FINANCIAL) 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 1994 monetary value.
- The after-tax return rate, r, is assumed to be 15%.
- All the items under operational/maintenance (O/M) costs, including fuel and electricity, escalate at the general inflation rate of I = 3% per year. (Exception is made in Scenarios 8 and 10 which assume that I = 0 (zero) to study the effect of inflation.)
- The tariff escalation rates for coal transportation by CLP and other competing modes are assumed to be the same as the general inflation rate, except for Scenarios 9 and 10.
- The discount rate δ used to calculate the present value of the after-tax cash flow in Eq. 2.7 is based on the inflation-adjusted, after-tax return rate, r--see Eq. 2.8.
- The corporate income 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 1.0. This means all the money invested (capital cost) comes from the owner; no money is borrowed.
- The pipeline is assumed to have an economic life of thirty years (N = 30) except in Scenario 7 where N=20 years.

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. A summary of the technical assumptions are listed in **4.4 Specific (Technical) Assumptions**.

4. CLP SYSTEM DESCRIPTION AND ASSUMPTIONS

4.1 Basic Concept

Coal log pipeline (CLP) is a new technology for transporting coal in which coal at the mine site is treated and compacted into cylindrical shapes (coal logs). Then the coal logs are injected into an underground pipeline filled with water for transportation to destination which may be one or more than one power plants, or to a train station, a barge terminal, or a seaport, for intermodal transportation.

Optimum operation of CLP requires that the coal logs be compacted to a diameter ratio (i.e., log diameter divided by pipe inner diameter) between 0.9 and 0.95, and an aspect ratio (i.e., log length divided by log diameter) between 1.6 and 2.0. The compacted coal logs have a specific gravity in the range 1.25 - 1.35. To minimize coal log wear in pipeline and minimize the energy required for pumping, the water in the pipe must move at a mean velocity of 0.85 V_L (approx.), where V_L is the **lift-off velocity** calculated from [12]:

$$V_L = 7.2\sqrt{(S-1)gak\left(1-k^2\right)D} \tag{4.1}$$

In the above equation, S is the specific gravity of the coal logs; g is the gravitational acceleration; a is the aspect ratio; k is the diameter ratio; and D is the inner diameter of the pipe

4.2 CLP System

A coal log pipeline (CLP) system consists of four major subsystems: inlet, outlet, booster pump and pipeline.

The inlet subsystem can be further divided into three main parts: coal preparation (including crushing, conveying, steam heating and mixing with binder), compaction of coal logs, and injection of coal logs into pipeline—see Fig. 4.1.

Because this economic analysis is to compare coal transportation cost by CLP with other modes such as railroad, the CLP inlet system considered starts with crushing coal from the size normally carried by trains or trucks (2 inches top size). The crusher reduces the coal to a size suitable for making coal logs (1/4 inch top size). For best result, crushing should reduce the coal to a top size about 1/20 of the coal log diameter, and a particle size distribution near that of maximum packing density. Crusher selection and cost are discussed in Appendix II-F. Heating of the crushed coal can best be done by steam heating while the coal is being moved by screw conveyors. Heater is not needed unless heating is required for a given coal log compaction process. When binder is needed for any coal log compaction process, it will be added to the coal in a mixer. The mixer selected and cost are given in Appendix II-I. The mixer is not needed unless binder is used. The most practical binder at present (1995) is Orimulsion which is a low-cost emulsified asphalt imported from Venezuela. Coal log compaction is to be done with a specially designed machine system described in [13] and Appendix II-H. Coal log injection into pipeline is accomplished by the system shown in Fig. 4.2. The injection system operates in a manner described in [14].

The outlet subsystem of CLP is illustrated in Fig. 4.3. It consists of a reservoir to collect the water effluent from the pipe, a conveyor belt to transport the coal logs out of water and to a stock pile, and crushing of the logs by a crusher. Depending on individual preferences, coal logs may or may not be crushed prior to stockpiling. The coal particles in the effluent water are removed (dewatered) through a process illustrated in Fig. 4.4. The dewatering process includes

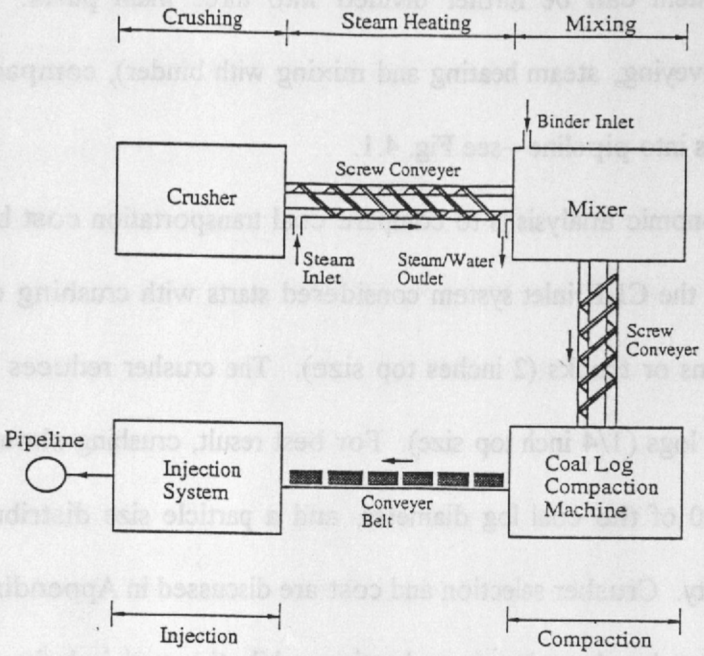

Fig. 4.1 Inlet Sub-System of CLP (Process Diagram)

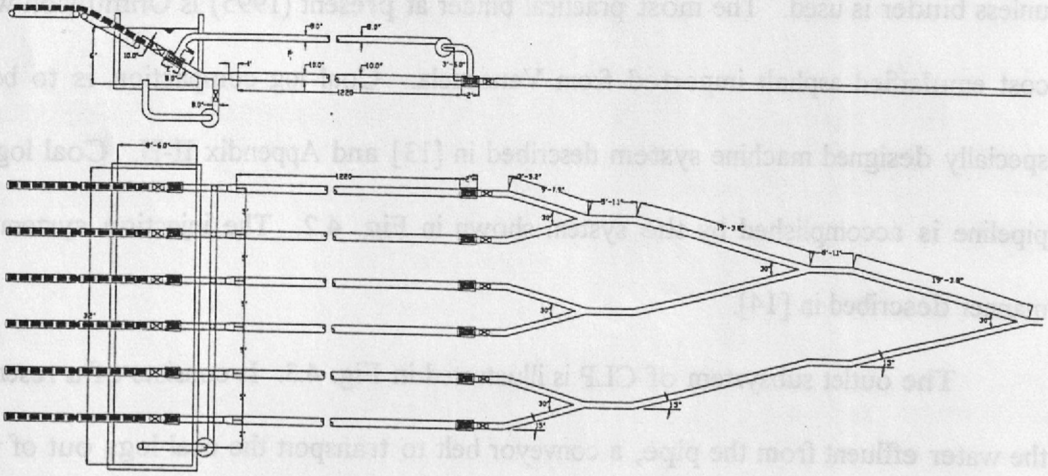

Fig. 4.2 Coal Log Injection Facility (Part of Inlet Sub-System)

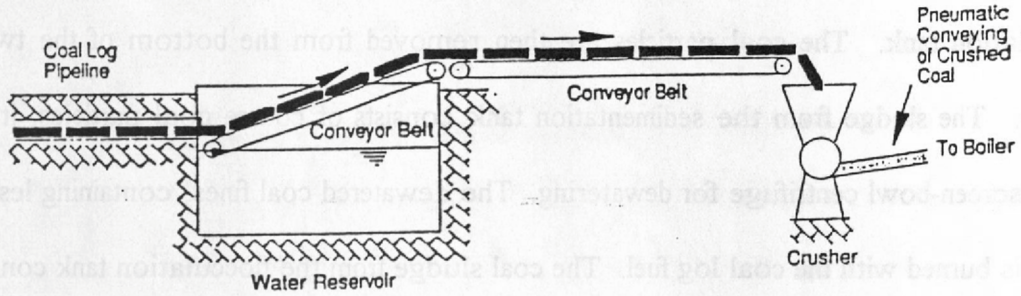

Fig. 4.3 Outlet Sub-System of CLP

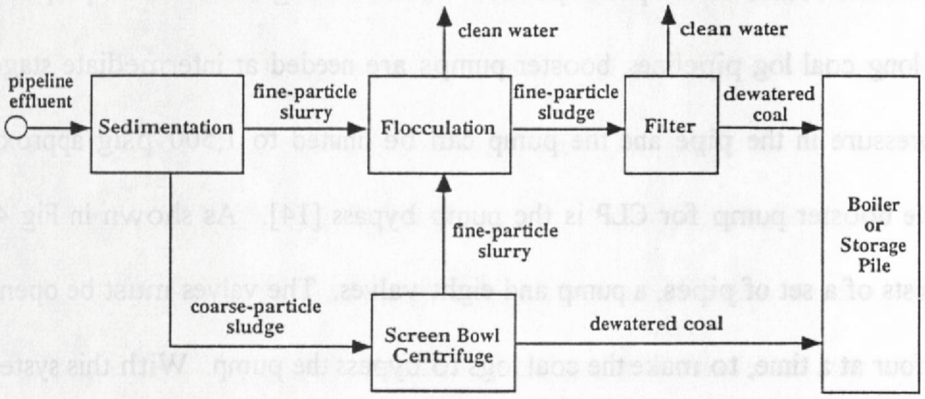

Fig. 4.4 Outlet Dewatering (Process Diagram)

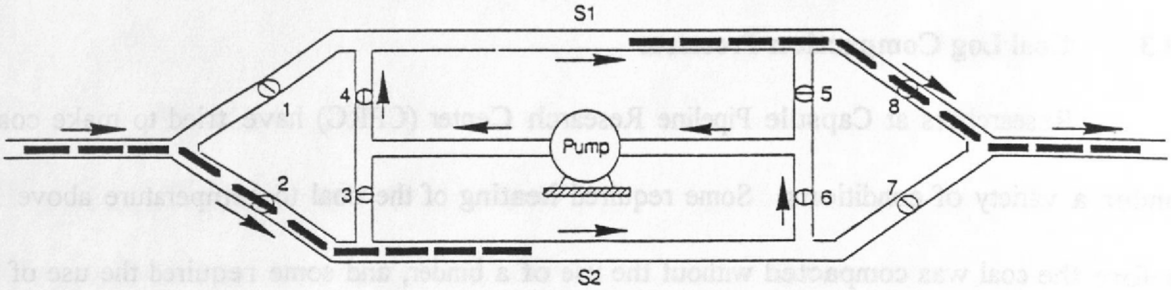

Fig. 4.5 Booster Station (Pump Bypass)

two stages: the larger particles settle in the sedimation tank, and the finer particles settle in the flocculation tank. The coal particles are then removed from the bottom of the two tanks as sludge. The sludge from the sedimentation tank consists of coarse coal particles; it is pumped into a screen-bowl centrifuge for dewatering. The dewatered coal fines, containing less than 30% water is burned with the coal log fuel. The coal sludge from the flocculation tank consists of fine particles; it must be dewatered by filtration rather than centrifuging. The effluent water from the centrifuge is sent back to the flocculation tank for further cleaning. The clean water from the flocculation tank is reused at the power plant for steam cooling and/or other purposes.

For long coal log pipelines, booster pumps are needed at intermediate stages so that the maximum pressure in the pipe and the pump can be limited to 1,500 psig approximately. The most suitable booster pump for CLP is the pump bypass [14]. As shown in Fig 4.5, the pump bypass consists of a set of pipes, a pump and eight valves. The valves must be opened and closed alternately, four at a time, to make the coal logs to bypass the pump. With this system, only water passes through the pump; the logs bypass the pump. Consequently, ordinary slurry pumps or sludge pumps can be used for CLP. Automatic computer control of the CLP system is a must.

4.3 Coal Log Compaction Processes

Researchers at Capsule Pipeline Research Center (CPRC) have tried to make coal logs under a variety of conditions. Some required heating of the coal to temperature above 100°C before the coal was compacted without the use of a binder, and some required the use of 0.5 to 3% binder (Orimulsion) either without heating or with heating to temperature below 100°C. Many other conditions, such as compaction pressure, particle size distribution, mold type, compaction piston (ram) shape and so on, also were found to affect the coal log quality (wear resistance and water resistance).

More than forty different processes were evaluated for wear resistance [15]—determining the distances such logs can endure in a commercial CLP without losing more than 3% weight due to wear. The cost of each of these processes was determined and compared with each other [16]. Based on these studies, eight processes were selected for both subbituminous and bituminous coal. They are process D-1, D-2, D-3, C-2, C-3, and so forth in Table 4.1 for subbituminous coals, and in Table 4.2 for bituminous coal. Note that the numeral following each process indicates the anticipated coal log weight loss in percent due to wear through pipeline. For example, D-3 refers to process D with 3% weight loss and so on.

The use of different processes for different distances ranges and for two different coals represents a sophistication the present economic report over the 1993 report [9]. This degree of sophistication is possible due to extensive coal log wear tests in laboratory pipes since 1993 [17]. Still, it must be realized that the distance ranges listed in Tables 4.1 and 4.2 were estimated from laboratory test data projected to field conditions. Because no coal logs have so far been tested under conditions similar to those encountered by future commercial coal log pipelines, the projections (estimates) used herein must be considered as rough estimates. They must be checked with future tests data in large (at least 6-inch diameter) pipelines constructed in the same manner future CLP will be constructed, including smooth joints, good pipe alignment, mild and precise bendings, etc. Since such a pipeline will be constructed and used for testing coal logs in a pending proposal [18], more definite results on the endurance of coal logs (made of various processes) in

Table 4.1 Coal Log Compaction Processes Selected for Cost Analysis (Subbituminous Coals)

Process Identification	**D-1**	**D-2**	**D-3**
Distance Range (miles)	10-50	50-100	100-200
Binder (% Bitumen)	0	0	0
Pressure (psi)	10,000	10,000	10,000
Temperature (°C)	90	90	90
Process Identification	**C-2**	**C-3**	
Distance Range (miles)	200-400	400-600	
Binder (% Bitumen)	0.5	0.5	
Pressure (psi)	8,000	8,000	
Temperature (°C)	90	90	
Process Identification	**L-1**	**L-2**	**L-3**
Distance Range (miles)	600-700	700-1200	1200-2000
Binder (% Bitumen)	0.5	0.5	0.5
Pressure (psi)	20,000	20,000	20,000
Temperature (°C)	90	90	90

Table 4.2 Coal Log Compaction Process Selected for Cost Analysis (Bituminous Coals)

Process Identification	**D-1**	**D-2**	**D-3**
Distance Range (miles)	10-20	20-40	40-60
Binder (% Bitumen)	0	0	0
Pressure (psi)	10,000	10,000	10,000
Temperature (°C)	90	90	90
Process Identification	**C-2**	**C-3**	
Distance Range (miles)	60-100	100-150	
Binder (% Bitumen)	0.5	0.5	
Pressure (psi)	8,000	8,000	
Temperature (°C)	90	90	
Process Identification	**L-1**	**L-2**	**L-3**
Distance Range (miles)	150-200	200-300	300-900
Binder (% Bitumen)	0.5	0.5	0.5
Pressure (psi)	20,000	20,000	20,000
Temperature (°C)	90	90	90

commercial CLP will be available in the next two years. They will be used in the next revision of the economic report in 1997.

4.4 Specific (Technical) Assumptions

A summary of the specific (technical) assumptions used in this report is given as follows:

1. The coal log fabrication machine is based on a design using hydraulic presses [13].

2. The binder used for making coal log is Orimulsion which costs $65 per ton including transportation cost to pipeline inlet. The Orimulsion contains 70% bitumen (asphalt) and 30% water.

3. Pressure drop along CLP is assumed to be 1.4 times that of water flow in the same pipe at the same velocity.

4. A 70% drag reduction (i.e., 300% reduction in pumping energy) is assumed by using 25 wppm (weight parts per million) of polyethylene oxide (Polyox) at the pipeline intake, and an additional 10 wppm after each booster pump station.

5. The efficiency of the large centrifugal pumps used is 80%. The efficiency of the large positive displacement (piston) pumps used is 90%. Centrifugal pumps are used except in Scenario 11 **(Section 5)**, where piston pumps are used at booster stations.

6. The maximum steady-state pressure in the pipe which exists at the discharge side of the main pumps is 1,500 psig. The lowest steady-state pressure in the pipe which exists at the suction side of the main pumps is 30 psig.

7. Pipes, pump casing, valves and other fittings are all rated at 1,500 psig or above. Valves and other fittings or flowmeters must have full bore to pass coal logs uninhibited. The valves used are Class 900 which is rated for 2,340 psi.

8. Heating of coal is by steam using coal as the fuel.

9. Coal log pipeline is operated at 85% lift-off velocity which is nearly optimum based on current knowledge.

10. Coal log specific gravity is **S** = 1.3; coal log diameter ratio **k** between 0.9 and 0.95; and coal log aspect ratio is **a** = 2.0 (approximately).

11. Coal logs are produced under optimum conditions of compaction. This means beveled logs are produced with single-piece mold having a tapered exit; the mold and the punches

(pistons) must be chrome-plated or made of carbide; the coal particle distribution must create maximum packing density; water content of the coal-particle mixture should be optimized; and so forth.

12. Steel pipe is used with smooth interior and mild bends. Weld protrusions into pipe are eliminated during construction.

13. The injection system has seven parallel locks, one of which is a spare, and it has a duplicate main pump. Pump bypasses are built with duplicates to insure high system reliability (95% availability or $\lambda = 0.95$).

14. The less expensive valves (TK valves) are used for booster stations except in Scenario 12.

5. 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. In the 1993 report [9], a total of 32 scenarios were investigated. Since then, many uncertainties have been removed through better understanding of the CLP technologies and progress in R & D. Still some uncertainties remain at this time (1995) that should be studied in different scenarios. The following 13 scenarios have been selected for inclusion in this 1995 report:

1) The coal log compaction time is 10 seconds. Fresh water is available for the CLP, and the linefill rate of coal logs is 90%. No special pigs are needed for regular operations. No additives are used for drag reduction.

2) Same as 1, except that a drag reducing additive (Polyox) is used.

3) Same as 2, except that coal log compaction time is 30 seconds.

4) Same as 2, except that treated (desalinated) brackish water must be used due to unavailability of fresh water.

5) Same as 2, except that a pig is needed to lead each coal log train.

6) Same as 2, except that linefill rate α is 80% instead of 90%. This will allow a valve closure time greater than 10 seconds, if necessary.

7) Same as 2, except that the economic life of the project is assumed to be 20 years instead of 30 years.

8) Same as 2, except that the tariff escalation rate ε and the inflation rate I are both zero.

9) Same as 2, except that inflation rate I is 3% and tariff escallation rate is zero.

10) Same as 2, except that inflation rate I is zero and tariff escalation rate is 3%.

11) Same as 2, except that piston pumps are used at booster stations.

12) Same as 2, except that the more expensive type of valves (Mogas vlaves) are used.

13) Same as 2, except that an existing pipeline is available, resulting in 30% cost reduction in pipeline construction.

Note that in each of the above scenarios, two types of coals are included: **subbituminous and bituminous**. Therefore, two sets of curves of **U (unit cost)** versus **L (pipeline length)** with **coal throughput Q_c** (or **pipe diameter D**) as a parameter are generated for each scenarios, one for subbituminous coal and the other for bituminous coal. This is shown in **8. RESULTS AND DISCUSSIONS OF CLP COSTS**.

6. CLP COST EQUATIONS: ENGINEERING COST ESTIMATES

Because CLP is an emerging new technology, no cost data exist for it. Such data must be generated from the anticipated cost of each component of a CLP system, and the anticipated O/M costs. Each CLP system analyzed includes four major sub-systems: **inlet** facilities, **outlet** facilities, **pipeline** (including not only the pipe but also valves and fittings distributed along the pipe), and **booster stations**. Each sub-system includes many components. A preliminary design of an 8-inch-diameter CLP system has been completed to determine each of the components required, its size, and operational properties. Details of this design cannot be included in this report. However, Figs. 4.1 through Fig. 4.5 show the main components of three of the sub-systems: inlet, outlet, and booster stations. The pipeline sub-system needs no illustration for it is similar to ordinary pipeline with minor modifications such as smoother joints.

The cost of each component of the 8-inch system was determined from market price, together with the construction, operation and maintenance costs. Using this cost information, appropriate equations were developed to estimate the cost of each component of a CLP system of any pipe size ranging from 4 to 20 inches. These equations form the backbone of this section. The cost in each equation is usually given as a function of pipe diameter D or coal throughput Q_c. Unless otherwise mentioned, costs are given in thousand dollars of 1994 value, D is in feet and Q_c is in tons/hr.

In what follows, the cost for each component of each sub-system will be evaluated first. Then, they will be combined to determine the total initial cost (capital cost) of each sub-system. The O/M cost of each sub-system is evaluated separately in a similar manner. Adding the sub-system costs together yields the total system capital and operational maintenance (O/M) costs. To be complete, the capital cost of each sub-system includes not only the purchased cost of each component but also installation costs, land, buildings, access roads, substations, etc. The O/M costs include not only energy, fuel, salaries and other ordinary O/M costs but also taxes, insurance, patent fees, and a 15% after-tax profit or return.

6.1 Inlet Facilities

As shown in Fig. 4.1, the inlet facilities include crushers, heaters (steam generation plant), mixers, binder storage tank, coal log compaction machine, coal log injection system, and conveyors—both screw conveyors and belt conveyors. Heaters (steam generators) are not needed if room-temperature coal is used with binder. The mixers and the binder storage tanks are not needed unless binder is used. The injection facilities (see Fig. 4.2) include a set of locks (parallel pipes), twelve diffusers, five Y-joints, a main pump (which can be a set of centrifugal pumps in serious or stages, with spare included), and a set of six low-head auxiliary pumps, an intake water tank, a water storage reservoir, and a building to house equipment/facilities excluding the long underground locks and the water reservoir. The exact number of each type of equipment varies with the throughput. It must be determined separately for each pipe size.

The cost of inlet facilities, as it is the case with most other costs, depends on the coal throughput or pipe size. It is determined in the following manners:

(a) Capital Costs

Intake Tank:

The length of the intake tank* is calculated from

$$L_{ti} = 50D \qquad (6.1.1)$$

where D is the pipe diameter in feet; and L_{ti} is the tank length in feet.

Assuming that the width of the intake tank is B = 30D, the area of the tank is

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* The intake tank is a closed tank (reservoir) made of reinforced concrete. It holds the water before the water enters the pipeline.

$$A_{ti} = 30\ DL_{ti} = 1{,}500\ D^2 \qquad (6.1.2)$$

where A_{ti} is in square feet; and D is in feet.

The tank is assumed to cost \$60 per square feet, including design and construction. Therefore, the cost of a completed intake tank is

$$\begin{aligned} C_{ti} &= 60\ A_{ti} = 90{,}000\ D^2 \quad \textit{(dollars)} \\ &= 90\,D^2 \quad \textit{(thousand dollars)} \end{aligned} \qquad (6.1.3)$$

Building:

The length of the inlet main building* is calculated from

$$L_{mbi} = 4\,L_{ti} = 200\,D \qquad (6.1.4)$$

The width of the building is calculated from

$$B_b = 120\,D \qquad (6.1.5)$$

Therefore, the area of the building is

$$A_{mbi} = B_b\ L_{mbi} = 24{,}000\ D^2 \qquad (6.1.6)$$

where D is in feet; and A_{mbi} is in square feet.

The building cost, including design and construction, is assumed to be \$80 per square foot. Therefore, the cost of a completed inlet main building is

$$\begin{aligned} C_{mbi} &= 1{,}920{,}000\ D^2 \quad \textit{(dollars)} \\ &= 1{,}920\,D^2 \quad \textit{(thousand dollars)} \end{aligned} \qquad (6.1.7)$$

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* Note that the main building covers not just the machines, equipment and injection tanks, it also has adequate space for storage, maintenance and office (administration).

Note that for any CLP inlet, a separate small building is needed to house the valves at the downstream end of the locks. Including both this valve station and the main inlet building, the total cost for buildings at a CLP inlet is

$$C_{bi} = 2{,}400\ D^2 \qquad (6.1.8)$$

where D is in feet; and C_{bi} is in thousand dollars.

Land:

The land cost is assumed to be \$2,000 per acre. The total area occupied by each inlet station, including parking, recreational and landscape areas, is assumed to be $A_{Li} = 25$ acres. Thus, the land cost for inlet station is

$$\begin{aligned} C_{Li} &= 2{,}000\ A_{Li} = \$2{,}000 \times 25 = \$50{,}000 \\ &= 50 \qquad \textit{(thousand dollars)} \end{aligned} \qquad (6.1.9)$$

Intake pipe:

In this design, the length of each coal log train is assumed to be

$$L_t = 120\, V_0 \qquad (6.1.10)$$

where V_o is the operational velocity in ft/sec; and L_t is in feet.

The total length of the pipe used at each inlet station is approximately

$$L_{pi} = 12.5\ L_T = 1500\ V_o \qquad (6.1.11)$$

As shown in Appendix II-A (Eq. A-6), the cost for each mile of pipe, including construction, is

$$C_{pl} = 132\, D^{1.34} + 104\, D^{0.87} + 24D + 20 \qquad (6.1.12)$$

where D is the pipe diameter in feet; and the cost C_{pl} is in the unit of \$1,000 per mile. The cost given by Eq. 6.1.12 should be reduced by 10% to account for the reduction in cost for in-station piping.

Therefore, the cost for inlet piping is

$$\begin{aligned} C_{pi} &= 0.9 C_{pl} L_{pi} \\ &= 0.298 V_o (132 D^{1.34} + 104 D^{0.87} + 24D + 20) \end{aligned} \tag{6.1.13}$$

where C_{pi} is in the unit of $1,000.

Note that Eq. 6.1.13 is based on a 7-lock system with one of the 7 locks being a spare in order to attain high reliability $(\lambda = 0.95)$.

Valves:

As discussed in Appendix II-B, the cost of each valve for the inlet station where the water is clean is

$$C_v = 10 D^{1.05} \tag{6.1.14}$$

where D is in ft; and C_v is in thousand dollars.

Due to the fact that the inlet system with 7 locks (one is a spare) requires fourteen 8-inch valves, seven 10-inch valves, and twenty-one 2 1/2-inch valves, the total cost for valves at the inlet of an 8-inch CLP is, from Eq. 6.1.14, $190,000. Based on this, the cost of inlet valves for pipe diameter D is

$$C_{vi} = 292 D^{1.05} \tag{6.1.15}$$

where the cost is in thousand dollars; and D is in ft.

Note that the valves at the inlet are full-bore, high-press (Class 900) gate valves. The more expensive slurry valves (Mogas valves or TK valves) will be used only for pump bypass to be discussed later.

The valve costs given above do not include transportation and installation. An extra 10% should be used for installed valve costs.

Diffusers and Y-Joints:

From Appendix II-D, the total installed cost for the diffusers and Y-Joints needed for any injection system is

$$C_{dyi} = 50.6 D^{0.6} \tag{6.1.16}$$

where D is in ft, and C_{dyi} is in thousand dollars.

Note that a spare diffuser and a spare Y-joint (for an extra lock) are included in Eq. 6.1.16 in order to achieve high reliability $(\lambda = 0.95)$.

Inlet Pumps:

Due to the cleanness of water at the inlet, no slurry pumps are required. The cost of the water pumps at the inlet is, from Appendix II-C,

$$C_{ui} = 0.95(H_p)^{0.6} \tag{6.1.17}$$

where H_p is the total horsepower of the pump; and C_{ui} is in thousand dollars.

The operation of the inlet involves six locks and a main pump. The main pump is a set of five centrifugal pumps in series. Each lock contains an auxiliary pump. To achieve high availability $(\lambda = 0.95)$, a duplicate set of main pumps (another five) and an extra lock (with an extra auxiliary pump) are used. This means the values in Eq. 6.1.17 should be doubled:

$$C_{ui} = 1.90(H_p)^{0.6} \tag{6.1.18}$$