FINAL TECHNICAL REPORT

CONSORTIUM FOR COAL LOG PIPELINE RESEARCH AND DEVELOPMENT

DOE Cooperative Agreement
DE FC 22-93PC92578
8/10/93 to 8/9/96

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I. Executive Summary

The coal log pipeline (CLP) R & D conducted in this United States Department of Energy (DOE) cooperative agreement complemented R & D sponsored by the National Science Foundation, the Missouri Department of Economic Development, the CLP industrial consortium, and the University of Missouri. Studies were conducted in eight principal areas; in each area technical results have been integrated independent of the sponsor. This integration leveraged the DOE cooperative agreement to further the development of coal log pipeline.

In the area of CLP hydrodynamics, a set of equations based on theory and experiment have been developed that predict pressure drop along CLP, coal-log velocity in pipe, lift-off velocity, incipient velocity of coal logs, and lift and drag on coal logs flowing in pipe. Transient CLP effects, for coal log injection and pumping systems, were analyzed both theoretically and experimentally. Valve stroking strategies have been developed to minimize water hammer and to optimize CLP system operation. The automatic control of a CLP system by PC hardware was demonstrated on a laboratory scale. The laboratory apparatus includes a pumping station and multiple injection lines.

A great amount of work was devoted to developing a high-speed, high capacity press to make coal logs. The initial coal log manufacturing techniques used extrusion and relatively high concentration of binder. Progress was made such that the amount of binder is now about 1% and a double-sided piston press is used to compact coal particles. A press is being constructed to produce 5.4 inch diameter logs, rapidly.

Legal research is completed in areas of water rights, eminent domain and pipeline crossings.

Coal log pipeline economics were reevaluated in 1995 to obtain current costs; these costs were compared to existing railroad and truck tariffs. In many instances, the CLP costs for coal transportation are quite favorable. The cost model was evaluated and verified by independent consultants.

End-of-pipeline water treatment was considered and experiments performed. A major concern was solvents used with synthetic polymer for drag reduction purposes. The solvents caused undesirable levels of biological oxygen demand (BOD) and chemical oxygen demand (COD). The combined use of coal slurry and coal log in a pipeline was tested. Such a combination has the advantages of more coal throughput, but some disadvantages of a coal slurry pipeline.

During the last three years, important advancements in the coal log pipeline technology have taken place, and this emerging technology is approaching commercialization. In preparation for a commercial demonstration project, a detailed questionnaire was sent to more than 100 electric utilities and about 50 coal companies

asking each to consider submitting a suitable potential demo project for evaluation. Each project needed have a coal throughput between 1 and 5 million tons a year, and a transportation distance less than 100 miles. Such criteria will make the demo project not too costly because the pipeline is not very large and long, yet large and long enough to be economically competitive with trucks and trains. Fourteen projects were submitted for evaluation. A preliminary evaluation determined that seven of these appear economically feasible. The most promising project will be selected to pursue the first commercial demonstration of CLP. However, before such commercial demonstration can be successful, certain important experiments using new and larger facilities must be conducted.

II. Background

The main objective of this project was to conduct intensive research and development of the Coal Log Pipeline (CLP). Specifically, the R & D was to concentrate on previously neglected and insufficiently studied aspects of CLP which were deemed significant. With improvements in these areas, CLP could be implemented for commercial use within five years. CLP technology is capable of transporting coal logs for long distances. The many potential advantages of CLP over truck and railroad transportation include: lower freight costs, less energy consumption, less air pollution, decreased environmental problems, increased safety, and improved reliability.

Previous studies have shown that CLP is advantageous over slurry pipeline technology. First, CLP uses one-third the water required by a coal slurry pipeline. Second, CLP provides easier coal dewatering. Third, the CLP conveying capacity of coal is twice as much as a slurry transport line of equal diameter. In many situations, the cost for transporting each ton of coal is expected to be less expensive by CLP as compared to other competing modes of transportation such as: truck, unit train and slurry pipeline.

In accordance with the 1990 Amendments of the Clean Air Act, CLP can aid in the transportation of low sulfur coal to distant users which would otherwise be economically unfeasible. For example, the transportation cost of coal from Wyoming to Missouri is three times the cost of the coal itself. With CLP, the transportation overhead would decrease making the low-sulfur coal more marketable. CLP can also enhance the usability of high-sulfur coals by incorporating limestone into the logs as they are fabricated. The limestone can remove sulfur through chemical reaction, thereby, eliminating the need for scrubbers in coal burning facilities, and providing a substantial savings in equipment costs. However, in this study the use of sulfur-capture agents in coal logs was not addressed.

Over 40 people (faculty, graduate students, undergraduate students, technicians, and secretaries) are involved in the CLP R & D activities. The key personnel participating in the research are renowned in the field of freight transport by capsule pipeline technology. Participating faculty and students are diversely represented in several engineering disciplines including: civil, chemical, industrial, mechanical, and mining engineering. In order to address the legal implications of the future coal log pipeline systems in the United States, faculty and students from the Law School have also been involved with the project. A number of general articles are listed in References, R-1 to R-16 on page 28.

The anticipated results from this research will permit the commercial use of CLP. The possibility of transporting coal from coal mines to power plants or to a coal distribution point for further transport by other modes will become a reality. The development of CLP technology will make the United States the world's leader in hydraulic capsule pipeline technology.

III. Scope of Work

The work conducted under the DOE cooperative agreement (DE FC 22-93PC 92578) can be detailed in several tasks as follows:

A. Hydrodynamics of CLP
B. Unsteady and Transient Flow in CLP
C. Automatic Control of CLP System
D. Coal Log Fabrication
E. Legal Research
F. Economic Research
G. End-of-Pipeline Study
H. Substitute Conveying Medium

These tasks were also sponsored by the National Science Foundation, Missouri Department of Economic Development, and an industrial consortium. The principal participants from industry are Associated Electric Cooperative, MAPCO, Southwestern Public Service, Union Electric, Willbros Engineers, Williams Pipeline, and Williams Technologies. Other participants include: Bitor America, Compactconsult, T. J. Gundlach Machine, Nova Tech, Pro-Mark and T. D. Williamson.

The following is a concise description by area of the work that was completed during the three-year period.

IV. Results and Discussion

A. HYDRODYNAMICS OF CLP

1. Statement of Work

The behavior of coal logs moving through the pipeline under steady-state motion and during startup and shutdown must be clearly understood before coal log pipelines can be used commercially. Development of equations for predicting incipient velocity, lift-off velocity, headloss (energy loss), capsule behavior in the train, capsule behavior through bends and slopes, and abrasion (degradation) of coal logs during pipeline transport are required for predicting coal log behavior. The contractor shall attempt to develop these required hydrodynamic equations necessary for predicting the behavior of the coal logs.

Many existing long pipelines for transporting liquids, such as the TransAlaskan Pipeline, use drag reducing additives to reduce energy consumption. It is expected that additives such as polymers and polymer/fiber mixtures can drastically reduce the energy loss in CLP, but this has not yet been tested. The contractor shall conduct a thorough investigation of the effectiveness and the economics of certain promising drag reducing additives for use in CLP.

The exploration of the hydrodynamics of the coal logs will be investigated by use of a combination of theoretical analysis and experimental tests. The tests will be conducted in a 2-inch pipeline first, and then in an 8-inch pipeline.

2. Results and discussion

a. Hydrodynamic formula for coal log flow behavior

An effort has been made to formulate a theory and derive a set of equations for accurate prediction of the behavior of capsule flow in hydraulic capsule pipeline (HCP) which are the same as for CLP. As a result of this effort, a new theory and a set of equations have been derived. The new theory is based on the realization that there are four distinctly different regimes of capsule flow, and the equations for predicting pressure gradient, capsule velocity and so forth differ for different regimes. Experimental data were also collected to verify the accuracy of the theory; the theory showed good agreement with data.

A theory and associated equations have also been derived to predict the pressure gradient, capsule incipient velocity, and capsule drag coefficient for a stationary capsule in pipe. This information is needed to analyze capsule (coal log) motion in pipe during start-up and shut-down of the pipeline system. The theory was substantiated by experiment.

When a cylindrical capsule moved by a liquid flowing in a pipe is stopped by the presence of an obstacle or protrusion on the pipe floor, the capsule may tilt in the pipe. An analysis of three different aspect ratios and three diameter ratios were tested in a small (50.8 mm inside diameter) pipe loop. The experimental values of the capsule drag coefficient compared well with those from theory and a previous test. Data were used to calculate the lift moment coefficient and a dimensionless parameter needed for predicting capsule tilt. Three large capsules with six different specific gravities were also tested in a large (190 mm inside diameter) pipe. Data for both small and large capsules showed good correlation between lift moment coefficient and tilt Froude number. It is shown that in some cases the capsule incipient velocity is governed by the critical tilt velocity.

b. Drag reduction using synthetic polymers

In general, pumping power depends on the drag or resistance to the flow--higher drag causes greater energy consumption. Often, a flow additive is ued to reduce drag and conserve energy. A commonly used additive is polyethylene oxide. This polymer was tried at near lift-off conditions and very positive results were obtained. A drag reduction of 75% is possible by using polyethylene oxide at a concentration of 25 ppm. The use of polyethylene oxide has strong practical implications.

c. Coal log degradation under flow conditions

This part of the research is focused on understanding the various ways (modes) coal logs can be damaged during hydraulic transport through pipe, understanding the damage mechanism of each mode, deriving equations and collecting test data on the damage caused by each mode, and finding ways to mitigate coal log damage/wear through design changes and special operational strategies. So far, the various modes of coal log damage in pipe have been identified. They include: (1) erosion of coal logs by water, (2) abrasion by coal particles in water, (3) abrasion by rough joints, (4) abrasion by jet pumps (only in laboratory systems), (5) abrasion by pipe bends, (6) impact of coal logs on a partially closed valve in an accident, (7) impact (collision) between coal logs, and (8) impact due to water hammer. Experiments to explore some to the most important modes (such as abrasion by rough joints) were conducted.

Abrasive wear tests were conducted in a 2.15-inch horizontal closed-loop steel pipeline and a 2.125-inch horizontal closed-loop Plexiglas pipeline. The erosive wear experiments were carried out in a 2.0-inch Plexiglas pipe loop. Based on the wear test results, it was found that: subbituminous coal is more abrasion-resistant than bituminous coal; higher compaction pressure and higher compaction temperature both help to produce abrasion-resistant logs; steady-state abrasion rate increases with increasing fluid velocity; coal logs with diameter ratio of 0.82 encounter more wear than for diameter ratio of 0.898; coal logs with larger aspect ratios produce less abrasion; applied small force during cooling weakens the logs; longer peak load duration and longer cooling time both help produce more abrasion resistant logs; coal-log weight loss seems to be insensitive to the presence of a small amount (1%) of fine coal particles in water; coal logs in a dense train produce more weight loss than single logs in the closed-loop pipeline test facility; smooth pipeline joints are crucial to reducing coal log abrasion; higher moisture content and weight gain tend to yield higher wear; higher specific gravity and strength enhance abrasion; and pipe erosion is negligible as compared to abrasion for coal logs.

d. Simultaneous coal slurry and log flow

These results are discussed in Section H.

e. Field test of coal logs in large pipe

Coal logs made at the University of Missouri were tested in a 6-inch (nominal) diameter 4.6-mile long commercial steel pipeline in Conway, Kansas. The pipeline belongs to the Mid-America Pipeline Company, and it was constructed for conveying water for industrial purposes--oil recovery and fire fighting.

The Conway test was carried out in two days. Eight sets of coal logs (3 in each set) made of different processes were circulated through the pipeline. Therefore, a total of 24 logs were tested, three at a time.

The Conway test is encouraging. In spite of the adverse test conditions (e.g. 33% below lift-off velocity, short preparation time to make the 5.3-inch logs, relatively rough pipe interior, etc.), the logs behaved well--better than expected. A great deal of information was learned from the test including the following.

1. Hot-water-formed logs had least wear in spite of the fact that the logs had large circumferencial cracks.

2. Coal logs made at Rolla performed very well, albeit their water absorption problem. Four factors may have contributed to the less wear of the Rolla logs: longer logs, finer coal particle size distribution, curing of the logs in air, and a chrome-plated compaction piston.

3. A main objective of the Conway test was to determine whether coal logs can endure long journey through a commercial pipeline without having to prepare the pipe joint in any special way to prevent weld protrusion into pipe. Unfortunately, the Conway test result is inconclusive due to the low velocity used in the test and some other factors, such as the logs were not in a train. Generally, logs moving in a long train protect each other and cause less wear loss. To test the coal logs in the Conway pipeline at or near lift-off velocity will require either the use of a drag-reducing additive, or an additional booster pump. The use of a drag reducing agent, though suggested, was not feasible.

4. The Conway test did not rule out the need for having specially prepared smooth joints for future commercial coal log pipelines, especially if the distance is very long. Such smooth joints can be prepared in one of two ways during construction in the field: (1) grinding each joint from inside the pipe as soon as welding is completed, and (2) use of the Permalok joint.

5. The fact that longer coal logs generally perform better than shorter logs in the Conway test is prompting reconsideration of what the optimum length of coal logs should be for commercial pipelines. It appears that logs of aspect ratio (length-to-diameter ratio) close to 2.0 may be needed to minimize abrasion in pipeline and coal log tilt. More controlled laboratory tests are required to check whether this is correct.

6. The Conway test demonstrated that coal logs inside a commercial pipeline can be restarted from stop without problem.

3. Deliverables

Reports and publications about CLP hydrodynamics were generated, see References A-1 to A-13.

B. UNSTEADY AND TRANSIENT FLOW IN CLP

1. Statement of Work

Operation of a CLP requires periodic closing and opening of valves, and the startup and shutdown of pumps. The effect of these operations cause pressure surges on the coal logs, pipes, valves, and pumps. The contractor shall evaluate the effects of the periodic opening and closing of valves and the operations of the pumps on the coal logs and equipment in pipeline.

A technique (equations and computer program) will be developed that can be utilized to analyze the behavior of coal logs and pressure waves in a coal log pipeline under various operational conditions. The development of a good mathematical model for the pressure wave and coal log interaction is required. This is an essential step in the development of effective methods for controlling pressure surges.

2. Results and Discussion

a. CLP valve movement effects

The unsteady flow associated with an injector system with and without consideration of the water coal-log interaction was studied. During valve switch-over the very high pressure portion of the injector system is connected to the low pressure portion. This cross connection could cause severe flow reversals in the loading pipes (locks). The cross connection problem was eliminated by completing one set of valve adjustments before starting other valve adjustments so that the high and low pressure portions of the injection system are never cross-connected.

The passage of trains through a pump bypass system was also studied. In this passage there was some expansion and compression (an increase and decrease in coal log spacing) as the train approached, moved through, and moved downstream of the bypass. There was, however, very little net change in the train length as a result of passing through a bypass system.

b. Transient flow model

An apparatus was designed and built for studying hydraulic transients in coal log pipeline. In this apparatus, single coal logs with various aspect ratios, diameter ratios and densities were tested. Pressures at two locations were measured with pressure transducers and capsule location was tracked with the use of six photocells located along the pipe. Measurements were recorded at closely spaced time interval via a data acquisition computer.

The measured coal log velocities, coal log displacements and pressures were compared to theoretical values predicted by a slight modification of the rigid capsule model. The theoretical and experiment values were in good agreement for a diameter ratio of 0.85 but only fair for a diameter of 0.7. This suggests that the rigid capsule model might be modified to account for certain coal log end effects that had been neglected in the rigid capsule model.

The coal pipeline Manual of Practice, Chapter 3, describes the methodology developed for the analysis of hydraulic transients.

3. Deliverables

Reports and publications about CLP transient analyses and experiments are listed under References, see B-1 to B-4; describes the methodology developed for the analysis of hydraulic transients.

C. AUTOMATIC CONTROL OF CLP SYSTEM

1. Statement of Work

Automatic control is a must for CLP systems. Since coal log pipelines operate very different from ordinary gas or liquid pipelines, the control hardware and strategies are also different from the ordinary gas and liquid transportation pipelines. Operation of the CLP (injection, pumping, and ejection of coal logs) can be best controlled by a centralized computer interacting with either microprocessors or small computers controlling the various operations. The contractor shall design a control strategy (along with the necessary equipment) required to control the various operations of the CLP.

The utilization of the proper hydrodynamic equations for the CLP along with computer software to control the coal pipeline is the focus of this task.

2. Results and discussion

a. Injection of coal logs into pipeline

A demonstration unit of the entire Coal Log Pipeline (CLP) system was built to study the coordinated control and operational strategies and issues. The total length of the automated small-scale system is approximately 130 ft. and uses 1.25-inch diameter, transparent PVC pipes. It consists of the mechanical subsystems, sensors, interface hardware, and a control workstation with associated software. The mechanical subsystems consist of the injection subsystem, the booster pump subsystem, and the ejection subsystem. The injection subsystem has four-locks each of which is fed by a conveyor belt, sixteen valves, a main pump, and an auxiliary pump. The electric motor-driven conveyor belts are operated at the same velocity as the flow. The ejection system consists of a conveyor belt which transports the coal logs out of the reservoir for storage. A 486-based IBM compatible computer with data acquisition and control cards was selected as the control and coordination platform. The control strategy senses only the leading and trailing logs as opposed to a 'counting' type approach adopted earlier. Air entrapment at the intake is eliminated by diffusers for all the four intake branches. The system is capable of injecting four trains of capsules automatically under the control of the computer with the manual part being only in the loading of the capsules onto the four conveyers. The operation of the three pumps, sixteen valves as well as the diverter and train separator are controlled based on the data input from fifteen magneto-inductive proximity sensors located throughout the system. The leading and trailing capsules in each train have small metallic rings at the front end which trigger the sensors indicating the arrival or departure of a train at a particular sensor location. The control software is user friendly modules for individual device operation and check, as well as trouble shooting.

A large body of knowledge regarding the design and functioning of such a system has been amassed specifically:

(i) The successful redesign of the mechanical subsystems of the test bed system contributed to reliable automatic operation for long periods; more than a year. This was considered a major accomplishment since the mechanical elements, including 3 pumps, 24 valves, and 15 sensors, have to be coordinated and controlled in a reliable manner automatically by the control software.

(ii) Insights into control strategy design have been obtained that are significant for the development of the large scale system. This has been coupled with a 'design for control' approach, with significant emphasis placed on the mechanical design of the subsystems, which considerably minimizes the control overheads, i.e., complexity of the control strategy and the control hardware, making the overall system rugged and reliable.

(iii) A better understanding of the computer and sensor needs for such systems have been developed so that the important and complex issues of redundancy in devices, sensing and control, as well as safety issues can be addressed in a systematic manner.

The controls group is involved with Nova Tech Inc., Kansas City, Missouri, which is a small business partner with the Capsule Pipeline Research Center. The company is engaged in computer interfacing, protocol development and hardware and software implementation issues with several industries, primarily oil and natural gas pipelines. The products they use include Remote Terminal Units, Programmable Logic Controllers (PLCs) and several types of sensors on the hardware side, and communications protocols, and programs related to SCADA operations on the software side. They develop their own hardware and software in addition to using commercially available ones. The involvement of Nova Tech with CPRC is thus mutually beneficial and very relevant to both the parties.

b. Coal log train flow characteristics

Coal logs in a train were tested at lift-off and 50% lift-off velocity; the trains encountered more weight loss than individual coal logs tested separately at the same velocities.

c. Pumping stations

In a pumping station, the main function of the train separator is to ensure adequate spacing between trains as they enter the pump bypass system through the divertor. Several designs have been proposed for such a separator and the most promising one, a flow-bypass type design, has been investigated. This sensing system is to prevent the valve stopper from being engaged when a coal log is present in its path. The entire arrangement is completely under the control of the computer. A periodic sequencing strategy has also been developed and successfully tested. This system thus represents a very good example of a 'design for control' approach where a complex task of controlling the diverter has been achieved reliably using a passive mechanical flow-bypass design with minimal reliance on sensors and without any active devices, and a simple control strategy.

d. Ejection of coal logs from end of pipeline

No studies conducted for this task.

e. CLP automatic control strategy

A Supervisory Control and Data Acquisition (SCADA) System for the planned commercial coal log pipeline system has been designed. The SCADA configuration design for the commercial scale system has been detailed in Chapter 5 for the Manual of Practice. The main design considerations are related to the monitoring of discrete and analog points in addition to discrete and PID control. Since the PLCs offer greatly improved reliability, and the personal computer offers easy-to-use operator interface primarily through many graphics packages, the combination of these two have been selected as the control stations.

3. Deliverables

Reports and publications about the automatic control of CLP system are listed in References, C-1 to C-7.

D. COAL LOG FABRICATION

1. Statement of Work

Means for making economical and durable coal logs must be found before coal log pipelines can be used economically. Coal logs suitable for long-distance and hydrotransport through pipelines are an essential key to the success of this project. Several techniques and ideas exist for producing the most economical and best structurally sound coal logs. The contractor shall investigate new techniques for producing coal logs and also investigated include: hot extrusion with minimum binder, underwater extrusion, vacuum compaction of coal logs, making coal logs with an impermeable outer layer that contains asphalt, and treatment of binderless logs with heat and sealant.

Objectives in this task include the exploration, optimization, and feasibility of various techniques for producing the coal logs.

Several subtasks exist in the overall task of Coal Log Fabrication. These tasks will investigate the methods involved in producing the best possible coal log both in strength and economics. Several techniques to be considered include:

1) vacuum compaction of coal logs,
2) underwater extrusion of coal logs,
3) extrusion of coal logs,
4) treatment of the coal log surfaces in order to minimize water absorption.

1) Vacuum compaction of coal logs

There is considerable evidence that performing the compaction process under vacuum allows coal logs of comparable strength to be manufactured at lower compaction pressures and time. Compaction of binderless coal log and the effects of particle size, particle distribution, and compaction temperature on log strength will be investigated.

2) Underwater extrusion of coal logs

It may be advantageous if coal logs from a fabrication machine can be injected directly into a pressurized, water filled pipeline, so that the coal logs are not exposed to low ambient pressure after fabrication. This subtask will focus on experiments with an underwater extrusion test device using different restrictions (die with different diameters) on the extruder and under different water pressure to show whether the underwater extrusion is feasible and advantageous

3) Extrusion of coal logs

This subtask will examine and improve coal log extrusion. Various parameters affecting extrusion technology will be investigated including: type of coal, particle size, moisture level, binder type and content, extruder design and operating conditions on coal log quality and costs.

4) Treatment of the coal log surfaces in order to minimize water absorption

The final subtask of coal log fabrication will be the investigation of treating the coal log surface with heat or other materials is order to minimize water absorption.

2. Results and discussion

a. Vacuum compaction

The investigation of the effects of vacuum and direct contact steam heating on compaction of coal logs accomplished:

1. The experimental apparatus for applying vacuum and steam directly to the coal in the mold has been designed, fabricated, assembled, and tested/verified. This device applies a constant level of vacuum ranging from 0 to over 27 inches of mercury, or it can apply saturated steam at pressures up to 100 psig.

2. Results have been obtained with vacuum for several different compaction conditions. For vacuum levels ranging from 3 inches of mercury to 27 inches of mercury, improvements in coal log wear have been realized.

3. Result have been obtained with direct contact steam heating for several different conditions, as well. For logs with 0.5% asphalt binder, expressed as percent dry asphalt in the emulsion to dry coal, improvements in coal log wear have been observed.

b. Underwater extrusion

Succeeded in extruding binderless logs at room temperature and also tested the binderless extrusion technology on coal fines from a tailing pond. The fines had about 13% of moisture before extrusion. The fines were extruded as binderless logs; the extrusion resulted in dewatering which is a fringe benefit.

Designed and tested various extrusion dies. Now the extrusion process uses an auger type extruder; it is relatively stable, and extruded logs are physically strong. Water assisted coal log extrusion changed the property of manufactured logs, enabling the logs to maintain strength in 500 psi water for over a week.

Designed fixture and tested underwater extrusion on a 2" auger type extruder. The process showed promise. However, due to the limiting power of the extruder, exit water pressure was too low to provide conclusions to underwater extrusion.

The water assisted extrusion shows some promise. The process is not sensitive to particle size so that the material preparation costs can be reduced. The process requires no heating other than the heat generated by the process itself. The process used no binder, and is stable.

c. Extrusion studies

Extrusion studies using binder were essentially completed prior to the initiation of this grant.

d. Surface treatment of coal logs

A study was conducted to determine if water entrance into dry coal logs could be prevented by impregnating the surface void space. Using sub-bituminous coals from the Rochelle and North Antelope mines of Wyoming, logs and disks were impregnated with coal slurries.

Coal disks were tested for water permeability. Disks were compacted from five different coal particle sizes. The average particle sizes included 725, 450, 350, 225, and 112.5 µm. The effect of slurry impregnation on water permeability was also examined. The experimental results indicated that water permeability decreases linearly with decreasing particle size. The main effect of slurry coating was a 30 fold reduction of the permeability.

Coal logs were tested for water resistance and pipeline circulation.Three types of coal slurry were used to impregnate dry, binderless coal logs: 1) water, 2) stearic acid, and 3) asphalt cement. Water resistance tests immediately indicated that water slurry is not suitable because dry, binderless coal logs are deleteriously effected by the entrance of water. However, stearic acid slurry effectively inhibited water absorption into coal logs. Water resistance of stearic acid slurry impregnated logs depended primarily on coal log compaction temperature. The durability of stearic acid slurry impregnated logs did not depend on impregnation time or vacuum. Due to the abrasive nature of the test pipeline, all stearic acid slurry impregnated coal logs failed during the pipeline circulation tests. Low-density, dry, binderless coal logs compacted at the conditions of 140° C and 10,000 psi and impregnated with an asphalt cement slurry exhibited satisfactory durability during water resistance and pipeline circulation tests.

e. Compaction by press

Conventional briquetting and extrusion machines cannot make coal logs fast enough for commercial CLP transportation of coal. It is important that a special machine be designed to make good logs at a fast rate so that the number of machines required to supply a single pipeline can be reduced to a minimum. Working in this design area has been done. A design was revised several times as the coal log compaction process continued to evolve. The newest designs are based on two concepts: hydraulic press and rotary press. The designs were reviewed by outside consultants from industry.

In 1996, a fast compaction machine system design was completed and submitted for bids to supply coal logs for a hypothetical 6-inch-diameter CLP. This is a 300-ton-force hydraulic press test machine and it will produce one 5.4-inch-diameter coal log in every 20 seconds. The machine will be tested for two years and the test data will allow the Center to design a reliable, efficient and economical coal log compaction machine for future commercial use. The logs will be tested in a new 6-inch-diameter pipeline to be constructed in 1997.

f. Fundamental particle agglomeration studies

A paper was published on the effect of particle charge (zeta potential) on coal log quality and compaction pressure.

3. Deliverables

Reports and publications about coal log extrusion are listed in References, D-1 to D-26.

E. LEGAL RESEARCH

1. Statement of Work

The objectives of performing legal research are to identify legal and institutional obstacles that may impede the future implementation of coal log pipelines, and if obstacles do exist, ways to remove the obstacles need to be suggested. The contractor shall investigate the legal aspects of several subjects associated with CLP. Subjects considered under legal research include: water rights, eminent domain rights, the right to cross railroads, and conversion of ordinary oil or gas pipelines to coal log pipelines.

2. Results and discussion

a. Water rights

(1) *Water discharge issues.* Completed analysis of cases involving water discharges into streams which increase their volume. The issue being addressed is whether such discharges and stream volume increases violate the rights of downstream water users.

(2) *Effect of public trust on eastern and western water rights.* Examined public trust cases which reduce the amount of water available for diversion. These usually are portions of streamflow designated for in stream aquatic habitat and recreation uses.

Since the *Mono Lake* decision in 1983, it has been assumed that all western state prior appropriation systems must leave a portion of the water in the stream for aquatic habitat and recreation purposes. This state obligation is paramount to any prior appropriation rights which may have been granted over the years and could require a cutback in the total quantity of diversions. The public trust thus may reduce the amount of fresh water potentially available for pipeline uses.

(3) *Interstate water allocation.* Summarized law of interstate allocation of river flows and groundwater. [This research is not specific to any particular river basin, since the relevant factors vary greatly from basin to basin.]

Interstate waters are allocated by the U.S. Supreme Court under the equitable apportionment doctrine, which gives each state a "fair share" of those waters. How much that may be cannot be predicted in advance, since disputes are decided on a case-by-case basis. Allocation is not based on priority. Alternatively, states may attempt to negotiate interstate compacts to allocate those waters by agreement.

(4) *Indian water rights.* Summarized law of Indian water rights; analyze authority of Indian tribes to transfer those water rights to non-Indians for off-Reservation use without compliance with state law.

Indian tribes are entitled to reserved water rights sufficient to support the population on the respective Indian Reservations. These rights, determined on a practicable irritable acreage basis, a paramount to any state water rights established after the date the Indian Reservation was created, and preempt any such conflicting state-authorized water uses. The tribes control the use of those reserved water rights on the Reservations. It is not clear whether the tribes can transfer those water rights to non-Indians for off-Reservation use.

These Indian water rights potentially can reduce the amount of water available for pipeline use under state law. It is not clear whether pipelines can validly acquire Indian water rights.

b. Eminent domain

Public service requirement for eminent domain. State utility and railroad eminent domain law is being examined to determine whether the condemnor must provide public service to local residents in order to qualify for exercise of statutory eminent domain power.

c. Pipeline crossing railroads

Common law rights. Determined whether utilities can cross railroads without latter's consent, provided there is no physical interruption or interference with the railroads use.

d. Pipeline conversion

Easement reversion issues. Checked "rails to trails" cases to determine whether the federal and state statutes preventing reversion of abandoned railroad rights-of-way upon conversion to hiking trails causes a compensable taking.

3. Deliverables

Reports and publications about the legal aspects of coal log pipelines are listed in References, E-1 to E-4.

F. ECONOMIC RESEARCH

1. Statement of Work

A preliminary economic study was performed in 1990 which showed that the binder amount in the coal logs was the key factor in determining if the process would be economically feasible. The contractor shall update the 1990 report since the previous report is now obsolete due to improved understanding of the CLP technology and the fluctuation in prices of items associated with the CLP since 1990. In addition, the economics of the CLP shall be updated as research progresses, and the cost of CLP shall be compared with other modes of transport including train, truck, barge, and slurry pipeline.

This task will identify the feasibility of utilizing CLP technology for the transport of coal in the form of logs through pipelines. Also important aspects of the project that need to be addressed or economic feasibility of the CLP technology will be pointed out during this study.

2. Results and discussion

a. Revised economic analyses

Detailed costs of complete CLP systems were studied in 1993. Since then great advancements have been made in many fronts of the CLP technology through the extensive R&D conducted by the Center. These advancements have changed (improved) the way CLP is to be used and this in turn mandated a revision of the 1993 economic report. A new cost study was completed in June 1995. The study incorporated latest know-how and updated cost data.

The economics of CLP is compared with other competing modes of freight transport such as truck and train. The comparison is based on unit cost in dollars per ton of coal which is a function of distance and throughput. The investigation covered a wide range of CLP, from 4-inch to 20-inch diameter pipelines, and a wide range of distances from 10 to 2,000 miles. The economic model has been externally reviewed by a consortium member with extensive experience in cost analysis. The study indicates that CLP is cost competitive over a wide range of transportation distances and throughput.

The cost model developed is general and applicable to a wide range of conditions--different pipe diameters, different lengths (transportation distances), different compaction processes, etc. Development of such a cost model prior to the full development of the CLP technology has the following values.

(a) It enables the researchers to determine the conditions under which the CLP technology is more competitive than competing modes of coal transport such as trucks and trains. This shows the "window of opportunity" which is essential to market assessment.

(b) The model can calculate and print the cost of each component of the CLP system, including various capital costs and operation costs. From such costs one can see which components have the strongest impact on the total system cost, and where the priorities should be in R&D.

(c) The model can be used to determine the least-cost alternative of a CLP system. This helps to attain optimum design and to reduce the cost of any commercial CLP system to be built in the future.

(d) The development of such a cost model forces the researchers to think hard about the details of the systems, thereby bringing progress to technology development.

(e) The rigor and details of the cost model are extraordinary. The model sets an example as to how the cost effectiveness of major technologies should be assessed as a part of R&D program.

The current study is a substantial improvement over the 1993 study due mainly to rapid technology advancements in CLP in the last two years. Many of the things unknown in 1993 are known or better known today, and hence the economic study is less speculative than in 1993. For instance, in 1993, it was thought that a single process of coal log fabrication could be used for CLP of any length. Now it is clear that different compaction processes are applicable to different distance ranges. As another example, in 1993 drag reduction by polymer was used in a scenario without any proof that it works for CLP. Now, through tests in a pipeline, we found that at least under laboratory conditions, proper use of a special polymer called Polyox can produce a maximum of 0.75 drag reduction which means a 400% reduction of the energy used in pumping. Lower than this maximum was used in this economic study when Polyox was used in a particular scenario.

Furthermore, the economic model used in the current study is closer to those used by pipeline industry. This is more conservative than the model used in the 1993 report. The railroad rates used for comparison with the pipeline rates are also updated in the present study. Therefore, this report represents a more accurate, more conservative and updated economic analysis of the CLP technology as compared to the 1993 report. As in the previous report, this study shows that under a wide range of conditions, it is more economical to transport coal by CLP than by truck, rail and slurry pipeline. Therefore, this study once more 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 even more cost effective than under current conditions. In spite of the encouraging finding 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 construction 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.

It should be recognized that CLP is 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 and development, different scenarios are investigated herein.

This study should be regarded as part of an ongoing investigation that must be further improved later when more is known about CLP through future technological development and commercial-use experience. Further improvement of this economic study will be done in two years when the development of the technology is more complete.

b. Verification of economic analysis:

Foster Associates/JD Energy conducted an independent evaluation of the coal log pipeline's (CLP's) commercial feasibility. This evaluation thoroughly reviewed the economic analysis conducted by the Capsule Pipeline Research Center. The criteria used in the evaluation process were: (1) technical feasibility, (2) economic viability, and (3) ability to overcome market impediments. This economic review concluded the following:

(1) Coal log technology is commercially feasible, with the primary need being development of a viable coal log production machine.

(2) Private industry has interest in advancing this project, including a number of nationally known companies and organizations.

(3) Market opportunities exist for coal log pipelines both domestically and abroad.

(4) The best market conditions for the economics of the CLP include the following:

(a) Distances of 50-100 miles from the coal source to the plant;

(b) Truck hauls where road routings are circuitous and/or speed levels are low;

(c) End-users with limited sunk costs in their current transportation delivery and equipment;

(d) Plants that can no longer use traditional coal sources as a result of Phase II of the 1990 Clean Air Act; and

(e) "Captive" end-users who are suspicious of long-term rail rates.

(5) The Capsule Pipeline Research Center's economic analysis represents a reasonable and thorough approach to assess the project. A number of refinements are suggested to the Center's approach, but the basic conclusion of the Center is that CLP can offer competitive rates on a site-specific basis.

3. Deliverables

An extensive report about CLP economic research is listed in Reference see F-1: this is a revision and update of an earlier study completed prior to the DOE award. For the independent verification of CPRC economic analyses see reference F-2.

G. END-OF PIPELINE (EOP) STUDY

1. Statement of Work

The end of the pipeline requirements for the handling and utilization of coal logs at electric utility plants is an area of concern. The contractor shall investigate the methods that the coal can be handled (i.e., dewatered, dried, crushed, stored, and transported to boilers) and how the effluent water must be treated prior to reuse or discharge.

2. Results and Discussion

The results of this research indicate that coal logs can be used by utilities with a minimum of additional equipment such as roll crusher to reduce the delivered logs to 2-in x 0 coal (the size of coal currently supplied to power plants by rail). To ensure satisfactory grinding efficiency coal logs must obtain no more than 5% asphalt binder by weight. Water treatment is needed to remove dissolved iron, manganese, and zinc from the pipeline water. The end-of-pipeline total unit costs for coal log handling and water treatment range from 13 to 47 cents per ton of coal. The cost depends on coal throughput and treatment requirements.

a. EOP water treatment

1. One issue of concern for this coal log pipeline is the quality and reuse of the water effluent from the pipeline. The water from this system is to be treated and then used on site in the cooling system at the power plant. The research in this thesis involved two parts. First, the quality of the used water was tested with the water in contact with the coal over a period of seven days. The coal-water mixture was put under anaerobic conditions in a turbulent environment to simulate coal log moving through the pipeline. The coal-water mixture consisted of 1% or 5% coal in tap water from the University of Missouri-Columbia.

   Two different types of coal and three coal log types (cold formed without Orimulsion, cold formed with 3% Orimulsion, and hot formed with 3% Orimulsion) were used. The coal-water mixtures were tested for chemical oxygen demand, biochemical oxygen demand, sulfate, iron, manganese, dissolved solids, and suspended solids. In addition, the water with coal containing Orimulsion was tested for polynuclear aromatic hydrocarbons, nitrogen compounds, and trace metals. From the results obtained, the polynuclear aromatic hydrocarbons, nitrogen compounds, and trace metals were below maximum contaminant levels and should not present a problem. The used water did contain high amounts of sulfate from leaching of both the coal and the Orimulsion and as expected, the concentration of suspended solids was high and settling will be required to remove these solids.

   The second part of the research consisted of determining the treatment required for reuse of the water in the cooling system. Settling is required to remove the coal particles from the water that have chipped off the coal logs while in the pipeline. The coal sludge is then dewatered to retrieve the coal for use in the combustion process. A coagulation/flocculation technique is used for the removal of the residual coal particles from the water and a jar test was used to determine the optimum coagulant dosage and type of coagulant that would be suitable.

When examining the water quality and treatment of the coal log pipeline effluent, several conclusions can be made:

(1) There is not a significant amount of leaching of iron, manganese, and organics from the coal into the water.

(2) In water with a high alkalinity, the acidic coal does not reduce the pH of the water.

(3) Sulfate does leach from the higher sulfur coal. Also, the use of the Orimulsion binder increases the sulfate concentration that leaches to the water.

(4) The formation of PAH's and nitrogen compounds did not occur in the pipeline effluent.

(5) Trace metals such as arsenic, barium, chromium, and nickel have leached from the coal. These metals may not present a problem when the effluent is diluted and used as part of the cooling water, but the metals may present a problem if the effluent is to be charged directly to a stream or used as drinking water.

(6) Coagulation of suspended coal particles with polyelectrolytes is an option for recovering the coal for combustion. When the coal particles have a negative zeta potential, cationic or nonionic polymers produce good coagulation of the particles. For MAPCO coal anionic polymers can also produce good coagulation.

(7) It is ideal to reuse the pipeline effluent as a portion of the make-up water for the cooling system of the power plant.

(8) Different types of coal, different types of pipeline water sources, and different lengths of time the coal remains in the pipeline can significantly effect quality of the pipeline water.

2. In some longer CLP pipelines, drag reduction polymers, which can sometimes add to water quality problems, are added to reduce energy requirements within the pipeline. One possible use of the pipeline effluent is as cooling water for the end-of-the-line power plant. This would alleviate any required discharge permits and also would reduce the water demands of the power plant. Simulated pipeline effluent containing the drag reducing polymer Chemlink and Polyox was analyzed for its chemical characteristics. The evaluated characteristics were pH, chemical oxygen demand (COD), iron, manganese, sulfate, dissolved solids, total suspended solids, percentage suspended solids removed at two hours due to settling, and biochemical oxygen demand (BOD). Metals, PAHs, aniline, and pyridine were also analyzed.

   The problem present in the use of the pipeline effluent as cooling water is excessive BOD generated by the presence of propylene glycol in the Polyox slurry. Other water quality aspects were largely unaffected by the addition of the polymer. The COD and BOD values were much higher than the normal values found in natural waters. Thus the cooling water system of the power plant becomes much more vulnerable to biofouling than in normal scenarios and biocides will most likely be needed. Because of this, the effluent was evaluated for its biofouling potential when used as cooling water in 1:5, 1:10, and 1:20

approximate dilutions over a five week period. The dilutions represented potential mixing between the effluent and other sources of water because the effluent most likely won't be the sole source of cooling water for the power plant. Significant biofouling occurred. NaOCl was then evaluated as a potential biocide for the biofouling. The biofouling was measured by total weight and by volatile weight measurements evaluated at weekly intervals. The NaOCl biocide treatment proved to be an effective control for biofouling.

The chlorine demand was then determined for the effluent only, without any microbial demand. The chlorine demand was determined to be 0.5-1.5 mg/L, which indicated the chlorination was an economically feasible method of biofoul control.

From the analysis of the pipeline effluent, the water proved to need only limited treatment before being used in a cooling water system. Standard suspended solids removal through coagulation and flocculation is the only treatment needed before using the effluent in the cooling water system. Application of a biocide has been shown to control biofouling of the system caused by an increase of organic matter. The chlorine demand of the water was also determined. From these results, the pipeline effluent was determined to be a feasible source of cooling water for an end-of-the-line power plant.

3. It is shown that the addition of the drag reduction polymers Chemlink and Polyox do not affect the water's pH or dissolved oxygen concentration. Iron, manganese, and sulfate ion concentration also were unaffected by the addition of the polymer. The suspended and dissolved solids concentration was also initially unchanged. However, there was a decrease in particle settlement time due to the polymers and their coagulation effects. The only parameter that was significantly affected by the addition of Polyox was an increase in biochemical oxygen demand and chemical oxygen demand due to the propylene glycol that was used in the polymer slurry. This increase in organic matter indicated potential problems of biofouling within the hypothetical cooling water system at the end of the line power plant.

The comparison between Chemlink and Polyox showed no major differences in water quality other than the increased BOD of Polyox which was mentioned previously.

Chlorination proved to be an effective biocide for potential biofouling control. At a weekly concentration in a batch test (thus considered equivalent to continuous application) of 0.5 mg/L, chlorine effectively inhibited the continued growth of the fouling material.

The chlorine demand was determined to be between 0.5 mg/L and 1.5 mg/L for the Polyox-5% Powder River Basin, cold formed-binderless coal with a COD of 164 mg/l. It was this combination that had the highest COD and BOD and therefore was expected to have the highest possible chlorine demand. When this chlorine demand was used to calculate the COD of the dilutions used in the biofouling evaluation, it was determined that the chlorine demand of diluted waters was low enough that continuos chlorination would be economically feasible as a biocide control.

One aspect that still needs to still be examined is the possible formation of disinfection by-products from the chlorination. Their formation is most likely inevitable, but it should only be a concern if the cooling water will be discharged into a receiving body of water. This aspect of the pipeline effluent containing polymers should still be evaluated if chlorination is to be used.

b. EOP coal log crushing
Experiments were completed prior to the initiation of this project.

c. EOP coal log handling and storage
No experiments were done for this task.

3. Deliverables

Two reports of water treatment are available; see References G-1 and G-2.

H. SUBSTITUTE CONVEYING MEDIUM

1. Statement of Work

The higher specific gravity of coal-water as compared to water-alone will create a near neutrally buoyant environment for the coal log. This will enable the transportation of the logs at a lower velocity with less energy loss and less degradation compared to using water-alone to transport the coal logs. More coal per water on a unit basis will be realized by using coal-water slurry. The contractor shall determine the equations required for predicting the conveying parameters when utilizing coal-water slurry as the conveying medium. Also, the effects of the slurry on coal log degradation and abrasion will be studied to provide guidance to the feasibility of using coal-water slurry.

2. Results and discussion

The use of coal slurry instead of water in a coal log pipeline (CLP) is investigated for the first time. This investigation reveals significant differences and possible benefits by using coal slurry instead of water in CLPs. The lift-off velocity, and capsule and total pressure gradients presented for a 5.08 cm pipeline with capsule geometry's, k=0.75, S=1.3, and a =2 and 4. The formula for lift-off velocity is Equation 1, on the next page. The variables k, S and a are defined as follows: k is the ratio of the log diameter to inside pipe diameter; S is the ratio of the log density to the density of water; a is the length-to-diameter ratio of the coal log. Aluminum-Plexiglas capsules are used to simulate the coal logs. The coal slurry significantly lowered the lift-off velocity, and transported more coal per total pressure gradient than coal logs in water.

There are four flow regimes in a hydraulic capsule pipeline. In regime 1 the capsule is stationary and water flows around the capsule. In the other three regimes the capsules move in flowing water. Regime 2 corresponds to initial capsule motion, regime 3 is when the capsule velocity exceeds the bulk fluid velocity, and regime 4 corresponds to capsule velocities greater than or equal to lift-off velocity. For regime 4, the head loss is only 15-30% greater than that of equivalent pipeline flow without capsules at the same bulk rate velocity.

The capsule pressure gradient was nearly constant over HCP 2, 3 and 4 flow regimes in a coal slurry indicating that the optimal operation velocity range may be much larger for coal slurry compared to water.

a. Slurry-coal log flow theory

The lift-off velocity (V_L) of capsules is calculated by the following equation,

$$V_L = 7.2\sqrt{|S-1|gak(1-k^2)D} \qquad (1)$$

where S is the density ratio between the coal logs and the bulk fluid (ρ_c/ρ_b),ρ_c is the density of the coal logs, ρ_b is the bulk fluid density, g is the acceleration due to gravity, a is the aspect ratio (L_c/D_c), L_c is the length of the coal log, k is the diameter ratio (D_c/D), D_c is the coal log diameter, and D is the pipe diameter.

Logs with high specific gravity (≥1.25) in large pipes can easily give rise to a lift-off velocity higher than 3 m/s which causes practical problems. Significant decrease in the lift-off velocity can be accomplished most effectively by increasing the density of the bulk fluid by using coal slurry instead of water. Holding g, a, k and D constant, in the ratio of V_L for the water medium versus coal slurry (γ) is:

$$\gamma = \frac{(V_L)_{water}}{(V_L)_{slurry}} = \sqrt{\frac{S-1}{\beta-1}} \qquad (2)$$

where β is the density ratio of the coal log to coal slurry (ρ_c/ρ_s).

Values of γ are tabulated below for coal logs with S between 1.2 and 1.35. This tabulation indicates that the lift-off velocity of the coal log is reduced between 32% and 59.6%, for S between 1.2 and 1.3. The calculations assume that above equation for lift-off velocity is valid for coal slurry, the coal slurry behaves as a homogeneous fluid, and use the commerical coal slurry properties.

Table 1. Coal slurry effects on the lift-off velocity

S	β	γ	% Reduction of V_L $(1-1/\gamma) \times 100$
1.20	1.033	2.473	59.6
1.25	1.071	1.817	45.0
1.30	1.119	1.589	37.0
1.35	1.168	1.471	32.0

b. Slurry-coal logs experiments

Pressure drop along coal logs in slurry and water were measured using two differential pressure transducers (Omega, model PX 154), each transducer being referenced to its own column of water. To determine lift-off velocity and the angle of attack of a capsule, electromikes are used in conjunction with aluminum "dummy" coal logs. A metal surface is needed for the electromikes to operate properly. As a capsule passes an electromike, several data points determined the angle of the log relative to the pipe wall (angle of attack). The spacing between the two electromikes divided by the time difference between the electromike signals gives the velocity of the capsules.

The bulk flow velocity of the coal slurry will be determined by an ultrasonic flow meter (Polysonics, model MST-P). All measuring devices are connected to a Macintosh IIci. In the experimental test facility the pump is configured similar to a conventional centrifugal pump but uses a set of smooth metal plates rotating normal to the incoming flow to pump the fluid. The fluid is pushed through the pump housing by the boundary layer produced by the rotating plates; this design minimizes coal particle degradation.

The coal slurry used is from the Black Mesa Pipeline of Williams Technology, Inc. located in Kayenta, Arizona. Coal slurry characteristics are summarized next:

Slurry concentration (by weight)	48.6%
Coal particle specific gravity	1.400
Slurry specific gravity	1.162

The maximum coal particle diameter is approximately 1 mm, with a mean particle diameter of 280 μm.

Coal slurry transports capsules in a pipeline much different than the conventional CLP system which uses water. The coal slurry lowers the lift-off velocity of the capsules which enables one to transport more dense coal logs than the conventional CLP. The lift-off velocity correlation used for capsules in water (Eqn. 1) underestimates the lift-off velocity in coal slurry by approximately 10% for the capsules used in this investigation. More data are required to fully evaluate the lift-off equation.

The capsule pressure drop is nearly constant in coal slurry which includes CLP regimes 2, 3 and 4, (regimes described on previous page). The added energy loss caused by the capsule train is constant over a large velocity range. Therefore, the operational velocity in coal slurry may have a large velocity range compared to the conventional CLP which must be maintained within ±15% of the lift-off velocity. Further work is required to assess the degradation of coal logs for regimes 2, 3 and 4.

The capsules in coal slurry increased the total pressure gradient 3% to 5% compared to 15% to 30% for capsules in water at lift-off (Richards, 1992). The coal slurry pressure gradient is much greater than the pressure gradient caused by water alone. Generally, the total pressure gradient is slightly greater for capsules in coal slurry compared to capsules in water at the same bulk velocity. However, since the coal slurry transports denser coal logs, the mass of coal transported per total pressure gradient is greater in coal slurry than water.

c. Coal log degradation in slurry flow

No experiments were performed to elucidate this task.

3. Deliverables

The reports on coal log/slurry flow-are listed in References, H-1 to H-3.

V. Recommendations

Additional studies are needed in studied areas as follows:

(1) Economic analysis of CLP needs to be updated to include costs for (1) a tested coal log machine at near commercial production rates and (2) a specific-site for coal log pipeline application.

(2) Abrasion rate of coal logs in at least 6-inch diameter pipe line without the effects of a jet-pump.

(3) Degradation rates of synthetic polymers for drag reduction in CLP need to be determined without the effect of shear from water pumps.

(4) Transient pressure effects on coal log pipeline performance in 6-inch diameter (or greater) pipeline need to be experimentally measured.

(5) Booster station design and operation for large diameter pipelines need to be tested.

New studies are suggested to determine the following critical CLP issue, commercial scale CLP system operation including coal log manufacture.

A special pipeline facility to test coal logs under conditions similar to those encountered in future commercial coal log pipelines needs to be constructed and demonstrated. In addition, a coal log fabrication machine that can rapidly manufacture coal logs to supply the logs for testing in the pipeline (6-inch diameter) of least 1/2 mile length.

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