Arkansas Water
Resources Center

WATER RESOURCES ASPECTS OF COAL TRANSPORTATION BY SLURRY PIPELINE

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The use of slurry pipelines for transporting large volumes of coal over long distances has received widespread and increasing interest in the past few years. Several reasons account for this increased attention including the apparent long-term economic and other advantages of large volume-long distance slurry pipelines over unit train shipment of coal, the technical success of the Consolidated Coal Company and Black Mesa slurry pipelines, the increasing price of natural gas and petroleum fuels, declining natural gas reserves and activity by both the state and Federal governments.

By general acknowledgement, a substantial increase in utilization of the nation's coal reserves will be required to meet the nation's short- and mid-term energy needs and to reduce the nation's dependence on imported petroleum. If these needs are to be satisfied, new large fossil-fuel fired furnaces will have to be coal-fired and conversion of numerous existing natural gas or oil-fired furnaces to coal will be required.

The increased coal consumption will require that adjustments be made in both coal mining and coal transportation capabilities as well as in the coal utilization capacity. Concerning coal transportation, the alternatives for transporting the large volumes of coal required include expansion and upgrading of rail capacity, construction of coal slurry pipelines, barging (where applicable), generation of electric power with subsequent transmission of the power by extra high voltage (EHV) transmission lines (either conventional or cryogenic), gasification or liquefaction of the coal with subsequent movement of the gas or liquid fuel to the use site, or by a combination of these alternatives.

An examination of the location of the nation's coal reserves indicates the transportation requirements that will occur as the nation's coal resources are developed. As shown on Figure 1, the major coal reserves are located in four general areas. These are the Western deposits in the Rocky Mountain area, the bituminous deposits in the Oklahoma, Kansas, Missouri, Nebraska, Iowa, Illinois, Indiana and Kentucky area, the lignite deposits in the Texas, Louisiana, Arkansas, Mississippi and southern Alabama area and the bituminous deposits in the Appalachian area. Smaller deposits are scattered throughout much of the country. The Eastern coal deposits are generally located closer to markets than are the coal deposits in the Rocky Mountain area. The longer distances to markets involved in developing the Western coal reserves and the low-sulfur content of the Western coal, among other factors, have focused most of the coal slurry pipeline activity on movement of the Western coal. Figure 2 shows the coal slurry pipelines that have been built and that have been considered in some detail. The Consolidated Coal Company pipeline was the first major coal slurry pipeline constructed and operated. It extended from Cadiz, Ohio to Cleveland and provided coal for Cleveland Electric Illuminating Company's Eastlake Station. The Black Mesa pipeline was constructed in the late 1960's and extends from the Black Mesa coal mine in northern Arizona to Southern California Edison's Mohave Station in Southern Nevada. Pipelines in various stages of development include the Energy Transportation Systems, Inc., Houston Natural Gas, Montana/Houston pipeline, Nevada Power Company and Gulf

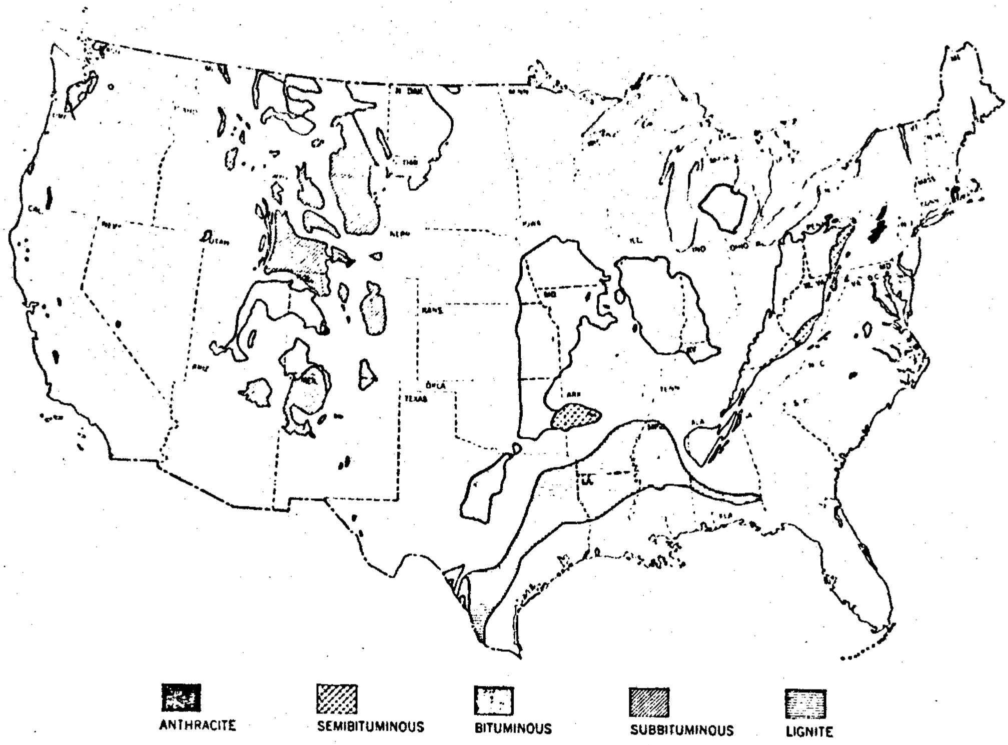


Figure 1. Map of United States Coals (After Fryling(1))

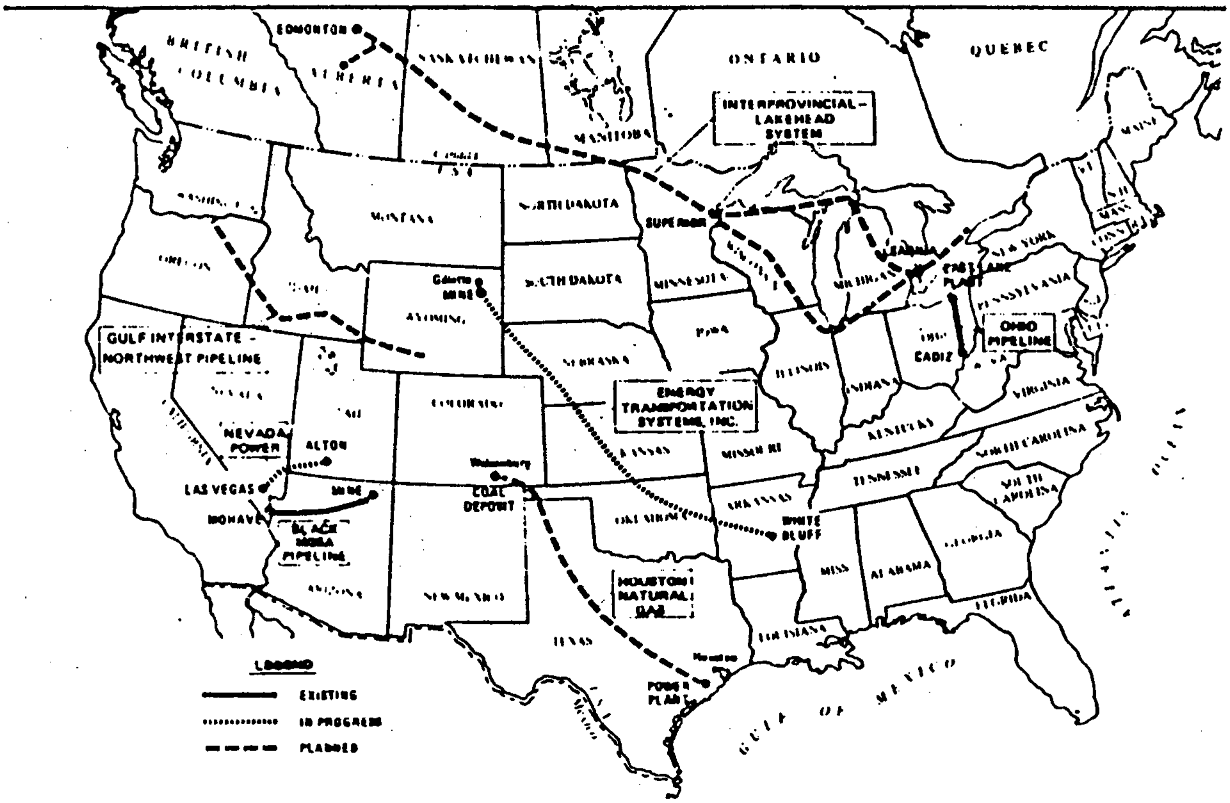


Figure 2. Existing and Planned Coal Slurry Pipelines in the United States

Interstate-Northwest Pipeline pipelines.

Water Resources Aspects of Coal Transportation

Although awareness that the nation's water resources are limited is increasing, the Eastern United States has an abundant supply of water relative to the Western states. In this context, the Eastern states refer to the 31 contiguous states east of a line extending generally northward from the Texas-Louisiana boundary. The 17 contiguous states West of this line all utilize the appropriation water doctrine for the purpose of maximizing benefits from the available water resources. Because of the more limited water resources in the West, the impact of the transportation method(s) used requires more careful consideration. However, the potential water resource impacts of the development of the Eastern coals must also be evaluated. Table I shows the incremental water requirements for energy production in 1985 as estimated by the National Academy of Engineering (2). Using these figures to develop approximate relationships, the data in Table II show the relative water requirements for the various alternatives.

TABLE II

Approximate Water Requirements at
Source for Transportation Alternatives
(Based on 1000 MW equivalency)

	Cubic Feet per Second	Acre-feet per Year
Unit train	Negligible	Negligible
Coal slurry pipeline*	2.54	1,840
Synthetic gas ***	10.26	7,430
Synthetic liquid	13.54	9,810
Electric power generation**	27.63	20,000

* Based on 8500 $\frac{\text{BTU}}{\text{kw}}$ coal, 10,000 $\frac{\text{Btu}}{\text{lb}}$ heat rate and 0.65 load factor.
** Taken directly from Table I.
*** Based on 1000 $\frac{\text{Btu}}{\text{kw}}$ gas, 10,000 $\frac{\text{Btu}}{\text{lb}}$ heat rate and 0.65 load factor.

TABLE I

Incremental Water Supplies Required for Energy Production in 1985

Resource Development	Amount of Water, Thousands Acre-Feet per Year
Increased coal production in the West, surface-mining reclamation for 500 million tons/year	24
Coal slurry pipelines to transport Western coal, 100 millions tons/year	55
New coal-lignite electric generating capacity, 170 gigawatts	3,400
New nuclear electric generating capacity, 325 gigawatts	7,150
Oil from shale, 1 million barrels per day	160
Synthetic gas from coal, 1.1 million barrels per day oil equivalent (21 gasification plants, each with 250 million cubic feet per day capabity)	250
Synthetic liquids from coal, 0.6 million barrels per day	180
TOTAL	11,219

Although these data are only approximate, they do show the relative water requirements of the several alternatives. Thus, from the water resources viewpoint, unit train shipment of coal would be the most acceptable transportation method in the arid West with coal slurry pipelining being the second best alternative. For Eastern coals where water is more abundant, any of the alternatives would be acceptable from the water resources viewpoint providing reasonable siting criteria were used in the site selection process.

Considerations Involved in the Selection of Alternatives. In addition to the volumetric water resources considerations, a variety of factors have been advanced by the proponents and opponents of the several transportation methods. Several of these are included to generally characterize the considerations involved.

Gasification/Liquefaction with Subsequent Transportation. Both coal gasification and liquefaction must still be considered in the experimental stage, although demonstration programs are being conducted. The question of whether the cost of the gasified and liquefied fuels will ever be sufficiently low to be competitive with coal for use in large fossil-fuel fired furnaces remains. Additionally, the limited water resources in the West will undoubtedly inhibit widespread adoption of gasification/liquefaction for the Western coal. Obviously, water from the Upper Missouri basin could be used for these processes but such usage will preclude other beneficial utilization at some future time and would probably not be acceptable to the Western states. It is conceivable that national needs may dictate that Upper Missouri water be used for widespread gasification/liquefaction processing, but the best procedure would appear to attempt to develop the Western coal resources with minimum adverse impact on the Western water resources. Water could be transported from a more distant point on the Missouri River or from another source where the adverse impact would be less significant but this procedure would further increase the cost of the gasified or liquefied fuel.

Electric Power Production with Transmission by EHV Power Lines. The two major disadvantages of locating electric power generating stations at or near the coal source in the West are the large water requirements for cooling and the losses encountered by conventional extra high voltage (EHV) power lines. Additionally, the construction of numerous large generation stations near the coal resources could likely cause an adverse sociological and environmental impact from the point of view of the residents. Figure 3 shows a comparison of the costs of transporting energy by unit train (coal), coal slurry pipelining and extra high voltage power lines. Of the three alternatives shown for transporting coal energy, the EHV costs are the highest, the unit train shipment the more economical for less than about six million tons per year and coal slurry pipelining the most economical for greater than about six million tons per year. Regardless of whether one agrees with the exact costs reported, the placement of the curves on the graph do generally indicate the relative economics of the three alternatives. Should cryogenic extra high voltage power lines become available, both technically and economically, at some time in the future, EHV could assume a greater role. However, considerable research and developmental work remains before cryogenic extra high voltage power transmission becomes a reality on a widespread basis. The use of dry cooling towers for rejecting heat from power plants for the

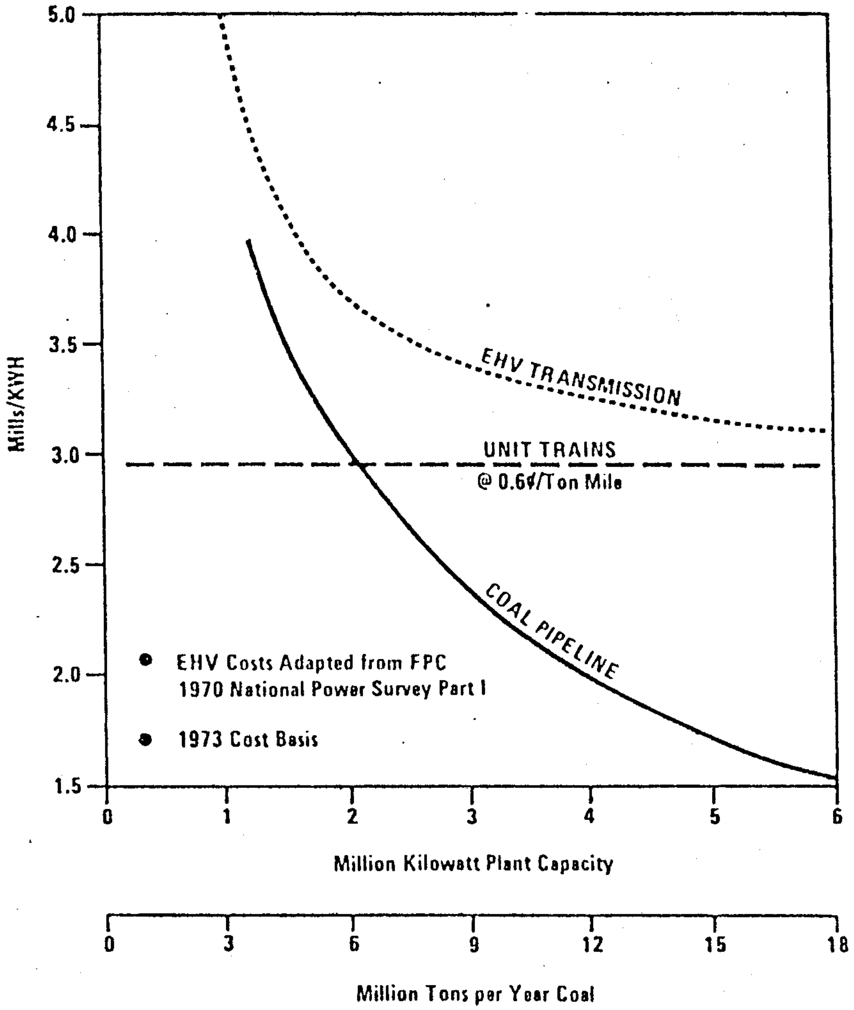


Figure 3. Comparison of alternate modes of coal energy transmission, for 1000-mile transport distance. (After Wasp and Thompson (3))

purpose of minimizing water requirements could be a major consideration. In general, both the capital and operating costs of dry cooling towers are greater than for wet cooling towers. Thus, the use of dry cooling towers would result in a larger delivered cost of electric power for the generation at the coal source with transmission by extra high voltage power lines alternative.

<u>Coal Slurry Pipelining versus Rail Shipment</u>. Because of the factors previously identified, much of the emphasis has been focused on using unit trains and coal slurry pipelining for transporting most of the Western coal to markets. Additionally, private firms developing coal slurry pipeline projects have not had eminent domain authority as do firms developing natural gas and petroluem product pipelines. For this reason, considerable attention has been directed towards the coal slurry-unit train alternatives. At least two states, Oklahoma and Texas, have passed legislation providing eminent domain authority for coal pipelines. Congress has considered such legislation and has held hearings in both the House and Senate (4,5). Hearings have been held on the current bill (HR 1609, Coal Pipeline Act of 1977). A variety of considerations have been advanced by both the opponents and proponents of coal slurry pipelines. Many of these relate to economic, environmental and social considerations. Slurry pipeline proponents point to the noise levels of unit trains; the frequency of passage of unit trains through communities, particularly near the coal mines; the potential range fire hazards caused by frequent passage of trains through range land (hot boxes, etc.); the loss of coal from unit trains during shipment (estimated to be as much as one percent of the coal transported by rail in open cars; the high reliability of coal slurry pipelines; the reduced impact of inflation

over a long period on transportation costs of coal delivered by slurry pipeline; reduced susceptibility to electric power generation interruption by strikes and other labor problems; lower steel and other material requirements for pipelines than for equivalent rail transportation capacity; lower adverse esthetic effects of pipelines, the safety factor of slurry pipelines, lower long-term transportation costs and other considerations. Opponents of slurry pipelines point to the larger water demand of slurry pipelines than for rail shipment; the adverse effect the use of slurry pipelines would have on the financial and economic welfare of railroads; the environmental impact of slurry pipelines; the lower labor requirements (less jobs) of slurry pipelines compared with railroads and other factors as disadvantages of slurry pipelines.

Concerning the economic considerations, slurry pipelines apparently have long-term advantages for large volume-long distance transportation coal movement. Figure 4 shows the relative costs of rail shipment and slurry pipelining for several distances. As indicated by these curves, slurry pipelining is competitive when large volumes and long distances over extended time periods are involved unless site specific factors are significant. Figure 5 shows projected escalation curves for pipeline and unit train shipment of coal. Pipelines are capital intensive, but the variable costs are a relatively low proportion of the total cost. One estimate of the cost breakdown for slurry pipelines is shown in Table III.

Because coal slurry pipelining is less labor intensive than is rail shipment of coal, the proponents of slurry pipelines point to the reduced likelihood of interruptions in electric power and other industrial

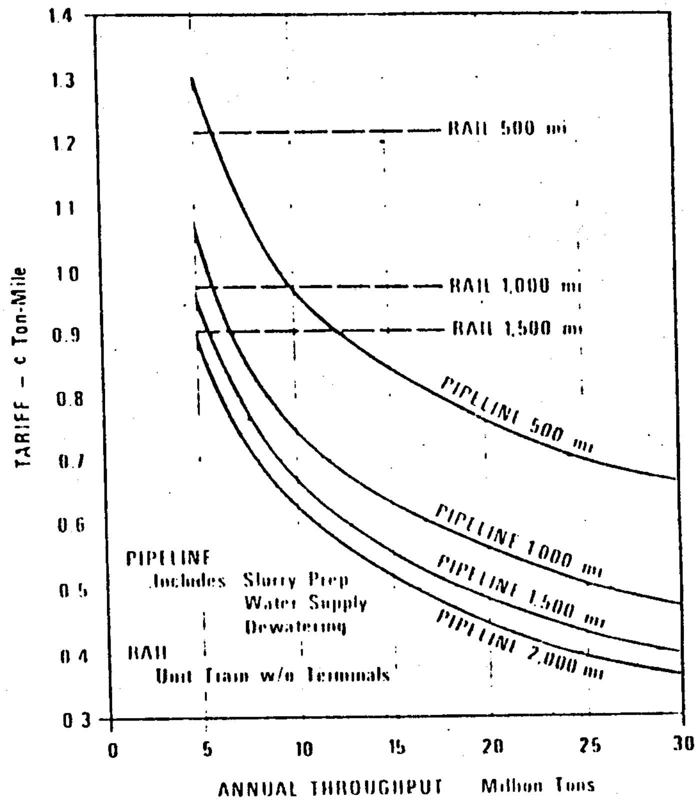
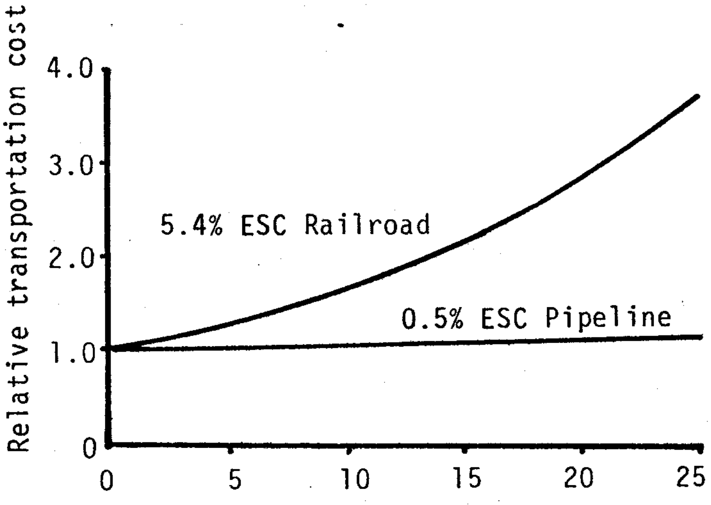


Figure 4. Coal Slurry Pipeline
Transportation Costs
(After Wasp (6))



TIME (YEARS)

Figure 5. Inflation on Coal Transport Costs
(Basis 3.6 % GNP Inflation Rate)
(Excerpted from Mining Congress Journal(2)

TABLE III

Cost Breakdown of Slurry Pipelines
(Excerpted from Pipeline Industry (7)

Factor	Percentage of Total Cost
Fixed cost	84
Variable costs	
Power	6
Labor	5
Supplies	5
Total	100

production when slurry pipelining is used. Management personnel could operate the slurry pipelining system should labor problems develop. Obviously, coal can be and usually is stock-piled at the plant site when unit trains are used to minimize the impact of labor difficulties on the plant operation. With this procedure, only extensive strikes would severely affect power or other industrial production. Disadvantages of stockpiling of coal are potential adverse environmental impacts from surface runoff, leaching through the stored coal, and the cost of funds tied-up by the unused fuel.

The arguments that:noise levels of unit trains are significant; large numbers of unit trains would increase the danger at railroad-highway grade crossings; community disruption would occur when large numbers of trains pass through communities near the coal reserves; the potential for fire hazards would be increased because of the additional unit trains; most of the physical facilities required by slurry pipelines (pipeline) are buried and, thus have less adverse esthetic effects - all must be considered, but do not necessarily bear on the water resources aspects of coal slurry pipelines. Similarly, railroad arguments that passage of the Coal Pipeline Act of 1977 would have an adverse effect on the financial and economic welfare of the nation's railroads must be considered but does not have a direct bearing on the water resource considerations.

General Description of the Coal Slurry Pipelining Process

Basically, the coal slurry pipelining process consists of crushing and grinding the coal to a size that will allow suspension in water, mixing the coal and water (slurry formation), movement of the slurry through the pipeline by pumping, and separation of the coal solids from the liquid at the receiving station. Separation processes and operations may include flocculation, sedimentation and centrifugation or vacuum filtration. The size of the coal solids in the slurry vary somewhat depending on site specific considerations, but the general size characteristics can be illustrated by the coal gradation used in the Consolidated Company pipeline as shown in Table IV.

TABLE IV

Pipeline Coal Size Characteristics
(After Frey, Jonakin & Caracristi (8))

Screen Mesh	Percent Retained
8	0.7
14	6.9
28	18.2
48	18.9
100	15.1
200	10.4
325	6.3
-325	23.5
Total	100.0

Because most modern large coal-fired furnaces use pulverized coal, crushing and grinding of the coal at either the source or at the use site is acceptable. Figure 6 shows the flow diagram of the overall coal slurry pipeline operation.

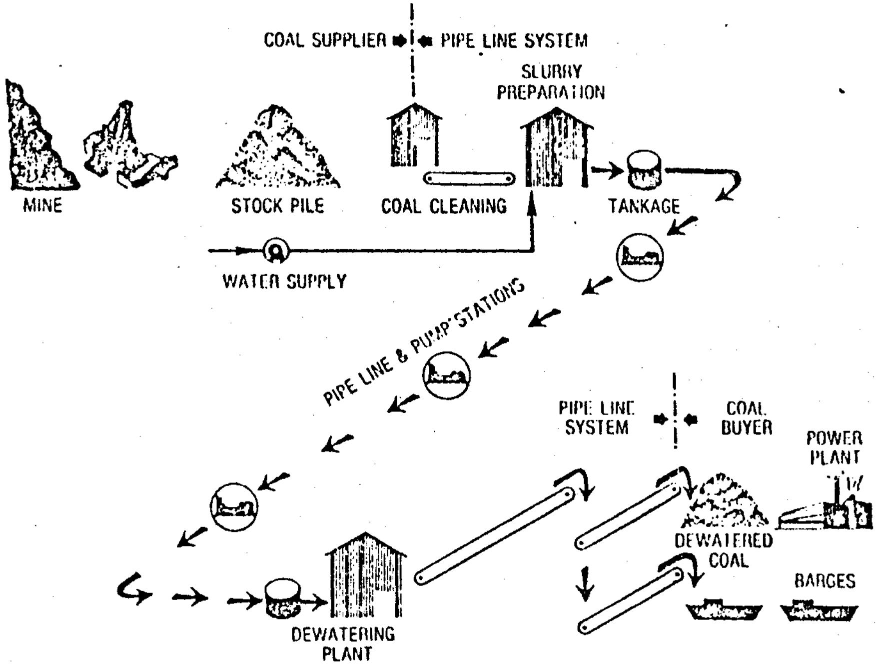


Figure 6. Flow diagram of a long distance coal slurry pipeline system. (Reprinted from Pipeline Industry, May, 1975 (7)).

History of Coal Slurry Pipelines

The concept of transporting coal by slurry pipeline is an old one. However, the first major coal slurry pipeline was not constructed until the mid-1950's. This pipeline, constructed by the Consolidated Coal Company, moved coal from Cadiz, Ohio, to Cleveland Electric Illuminating Company's Eastlake Station (9). Disagreement with existing freight rates apparently was the motivation for developing the slurry pipeline project. The pipeline was used for only about six years because a subsequent reduction in freight rates made rail shipment more economical (9). However, the pipeline was maintained in a "ready" status should the rail freight rates again increase sufficiently that pipeline shipment would be more economical (9). The pipeline was small (108 miles). Operations at the slurry preparation plant were unique primarily because the plant was designed for operation with either two or three shifts per day whereas the pipeline was to be operated twenty-four hours per day, seven days per week. Essentially, the slurry preparation plant consisted of screening, crushing, storage, mixing, and slurry storage facilities. Clean 3/8" X 0 coal was initially screened with the screen undersize stored in drag tanks. The screen oversize was either crushed or stored in a storage pond. If crushed, the screen oversize was either sent to the drag tanks or to a second storage pond depending on the quantity of coal needed for the pipeline at that particular time. The very fine coal that was carried over with the overflow from the drag tanks was stored in a third pond. Storage in three ponds rather than in a single pond was used to avoid segregation by size fractions. By preventing segregation by size, the fractions could be recombined in the proportions required (9).

Dewatering of the liquid-solids mixture was accomplished by thickening, vacuum filtration and flash drying. The general dewatering scheme was thickening to about 60 percent solids (by weight), vacuum filtration to about 20% moisture and flash drying to the extent desired. The dried material was then stored until needed. Particulates from the drier were collected and either sent to the boiler or flocculated and returned to the vacuum filter. The filtrate from the vacuum filter was flocculated and settled before discharge (9).

The second major coal system constructed was the Black Mesa pipeline which transports coal from the Black Mesa coal mine in northern Arizona to the Mohave Power Station in southern Nevada. This pipeline has been in operation since 1970 and has displayed excellent operational characteristics. Some plugging occurred during start-up until the optimal size gradation was established, but the plugging was minimal and did not cause major difficulty (10). Reported availability of the pipeline has exceeded 99 percent (10). The Black Mesa slurry system is 273 miles in length and is eighteen inches in diameter for most of the distance. Pipeline size was reduced to 12 inches for the purpose of increasing headloss as the line descends from the mountainous terrain to the Colorado River valley.

Coal preparation consists of crushing and wet grinding the two-inch coal received from the mine to minus one-eighth inch in a two-step operation. Dry crushing and impact mills are followed by wet grinding and rod mills where the slurry is formed (10).

Coal is dewatered at the Mohave generating station by centrifu-

Department of Interior. The research program has three major objectives which are to: 1) identify the type and extent of water quality changes that will occur as a result of the coal slurry pipelining process; 2) determine the technical feasibility of using poor-quality water, such as treated municipal and industrial wastewater, as the slurry medium; and 3) to determine the treatment measures suitable for use in restoring the slurry wastewater quality to acceptable levels. The research program is in the final year of a three-year program and will be completed in June, 1978.

The conceptual design of the research program was general, rather than being specific for one pipeline, to allow general application of the data. Consequently, several parameters, which would be fixed for a specific pipeline, were varied. These include coal source, slurry make-up water quality, slurry solids concentration, coal gradation, and residence time. Five "types" of water have been used in the research program to date including distilled water, "surface" water, ground water, municipal wastewater and industrial wastewater. More than one water source were used for the ground water and industrial wastewater. The purpose of using distilled water was to provide data which could be readily reproduced. Both the slurry solids concentration and coal gradation have been varied in the experimental work. To insure that the slurry solids concentrations used would bracket the concentrations that would be encountered in slurry pipeline systems, solids concentrations of 40, 50, and 60 percent by weight were chosen. A slurry pipeline using a 40 percent solids concentration would be both economic and water inefficient. It is conceivable that future developments may allow use of a 60 percent solids concentration slurry by using polymers or other measures to minimize water requirements. However, the 60 percent slurry should provide an acceptable upper solids concentration. Coal gradation was varied in a similar manner.

The general approach used in the research program was to evaluate the water quality changes that would occur under both aerobic and anaerobic conditions. This approach was used because both environmental conditions can be expected in a full-scale system. If surface water is used for the slurry medium, it will ordinarily have free dissolved oxygen present. Additionally, the wet grinding of coal and mixing of the coal and water (slurry formation) will ordinarily be conducted in the presence of air, thus assuring that the slurry is initially aerobic. The amount of dissolved oxygen present may vary, but some can be expected to be present. The dissolved oxygen concentration could conceivably vary from a relatively small concentration to a saturation value and possibly could be supersaturated in some instances. Once the slurry has been charged to the pipeline, no additional free molecular oxygen will be available unless the slurry is exposed to air such as in a dump pond or should the pipeline be evacuated of slurry for repair or other reasons. Oxygen consuming materials, both inorganic and organic, will depress the dissolved oxygen concentration and will ordinarily deplete the available molecular oxygen, thus developing an anaerobic environment. The reactions are different under anaerobic conditions than under aerobic conditions for some parameters. In addition to the aerobic environment initially in the pipeline, the slurry storage at the originating station, the dump ponds (if or when needed), slurry storage at the receiving station, and the dewatering operation will normally be aerobic. Thus, the environment could vary from aerobic to anaerobic and back to aerobic from the time the slurry is formed until dewatering has been completed.

The agitation vessels were designed and constructed to provide varying degrees of agitation, again to bracket the conditions that should be encountered. Twelve of the twenty-four agitation vessels were designed as closed vessels and were equipped with ports for adding nitrogen gas to form a blanket on top of the liquid in the vessel to maintain an anaerobic environment.

The research work is being completed in three phases corresponding to the three objectives of the research program. The data accumulated over the two-and-one-half year period are too voluminous to include all of it in this report, rather the general results will be summarized.

Phase I Results

The objective of this phase was to identify and characterize the water quality changes that will occur in the coal slurry pipelining operation. The highest concentration water quality parameters are included in Table V.

There are a variety of trace elements that are present in coal. Most of these are not leached from the coal in substantial concentrations. Table VI shows one assessment of the potential toxicity of trace elements in coal.

TABLE V

Major Water Quality Parameters in the Slurry Wastewater

Alkalinity
Biochemical oxygen demand
Calcium hardness
Chemical oxygen demand
Chloride
Magnesium
Nitrate
pH
Potassium
Silica
Sodium
Specific conductance
Sulfate
Total hardness

Table VII shows one assessment of the aquatic effects of trace elements in coal.

The concentrations of several parameters were below the detectable limits of the test procedure used. These include chromium, copper, iron, manganese, mercury, phosphate and zinc. Atomic absorption was used for the metals determinations. The detectable limits of the test procedures are included in Table VIII.

Alkalinity. Alkalinity in water may consist of the bicarbonate, carbonate and hydroxide ions depending on pH. The primary effect of alkalinity is that it serves as a buffer which resists changes in pH as do other weak acids and bases. When no buffering capacity is present in water, the pH can fluctuate radically when only small amounts of either acids or bases are present. Conversely, a water with a large buffering capacity will reflect only small changes in

TABLE VI

Potential Toxicity of Trace Elements in Coal

Element	Terrestrial		
	Plant	Animal	Aquatic
Antimony	Medium	High*	Low*
Arsenic	Low	Low	Low
Beryllium	Medium	High	High*
Bismuth	Medium	Low	Low*
Boron	High	Medium	Low*
Cadmium	High	High	High
Chromium	High	Medium	Medium
Cobalt	High	Medium	High
Copper	High	Medium	High
Fluoride	High	High	Low
Lead	Low	Medium	Medium
Mercury	Medium	High*	High
Molybdenum	Low	Medium	Low
Nickel	High	High	Medium
Tantalum	High	High	Medium
Tin	Low	Low	Low
Titanium	Low	Low*	Medium*
Tungsten	Medium	Medium*	Low*
Vanadium	High	Low*	Medium*
Zinc	Low	Medium	Medium

* Uncertain

Table VII

Aquatic Effects of Trace Elements Derived from Life-Time Operation of a 1400-$MW_{(e)}$ Coal-Fired Power Plant

Element	Projected water concentrations after 40 years (μg/liter)	Estimated "no-effect" concentrations (μg/liter)
Hg	0.05	0.05 (animal, chronic)
Cd	0.1	0.1 (animal, chronic)
Be	0.06	1.5 (animal, acute)
Co	0.6	10 (animal, chronic)
Cu	0.03	10 (animal, chronic)
Zn	3	30 (animal, chronic)
Tl	0.04	30 (animal, acute)
Pb	0.7	30 (animal, chronic)
Ni	0.1	30 (animal, chronic)
V	0.53	50 (animal, acute)
Cr	0.01	100 (amimal, chronic)
Ti		100 (plant, acute)
Se	0.08	125 (animal and plant, acute)
B		220 (animal, acute)
Sn	0.6	350 (animal, chronic)
Mn	3	500 (animal, acute)
As	0.03	500 (animal, chronic)
Sb	0.05	500 (animal, acute)
Mo	0.001	2500 (plant, acute)
F	0.4	7000 (animal, chronic)
W	1	

TABLE VIII

Detectable Limits of Tests for Selected Parameters in the Slurry Wastewater

Chromium	0.1 ng/ml
Copper	0.09 ng/ml
Iron	0.12 ng/ml
Manganese	0.055 ng/ml
Mercury	7.5 ng/ml
Phosphate	0.01 ng/ml
Zinc	0.018 ng/ml

pH even when relatively large quantities of acids or bases are added. Water with extremely large concentrations of alkalinity is caustic and is unacceptable, but the concentrations encountered in the coal slurry experimental work were not in the caustic range. Figure 7 shows the total alkalinity concentrations in the slurry wastewater as a function of residence time under an aerobic environment. As shown on the figure, the alkalinity concentrations were reduced as the residence time increased. This is generally typical of the alkalinity data obtained throughout the experimental work.

The impurities in coal vary from one source to another and, to some extent, within the same seam. Consequently, the amount of alkalinity that will leach from the coal can be expected to vary.

There is a considerable data base concerning the amount of alkaline material in coal when one considers the calcium oxide (the

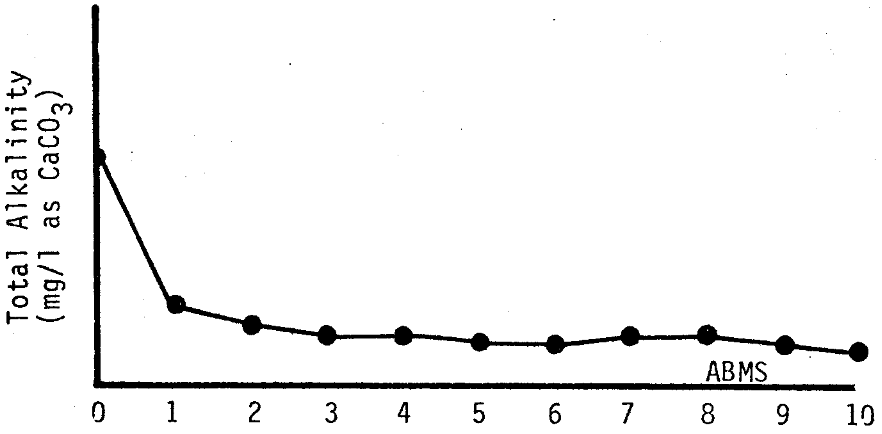


Figure 7 . Total Alkalinity Concentrations in the Slurry Wastewater as a Function of Residence Time

carbonate and bicarbonate, if present, are calcined in the furnace) in the flyash from coal-fired power plants. In two electric power generating stations (Colstrip Station, Montana Electric Power and Sherburn Station, Northern States Power) the calcium oxide in the flyash (from 17 to 20 percent, by weight) is used as the primary source of alkaline material for the flue gas desulfurization systems at these stations. Both stations use coal from the Colstrip, Montana area. In other installations using low sulfur coal, electrostatic precipitator design has been altered because of the increased resistivities of the flyash caused largely by the higher calcium oxide content of the Western coal flyash when compared with most Eastern coals.

Oxidation of the sulfur that is removed from the coal results in substantial quantities of sulfate in the slurry wastewater. However, the pH values of the slurry wastewater from the low-sulfur Western coals used in the experimental work were only moderately acidic. Generally, these values ranged from 5.5 to 7.0. Consequently, no acid mine drainage characteristics have been observed. There are several reasons for maintenance of the pH in a range higher than that encountered under acid mine drainage characteristics. The sulfur content of most Eastern coals is considerably higher than for the low-sulfur Western coal. Second, the form in which most of the sulfur occurs in coal is different between Eastern and Western coal. Sulfur occurs in coal in three forms: 1) pyritic; 2) organic; and 3) sulfate sulfur. The organic sulfur is chemically bound with the coal and, consequently, does not leach readily. Most of the sulfur in Western coal is usually organic with only a small fraction of the sulfur present as pyritic. Conversely, a substantial fraction of the sulfur present in most Eastern coals is pyritic. A major portion of pyritic sulfur can usually be removed by washing, magnetic separation and/or other methods. Third, the alkaline source present in the Western coal is present in relatively large quantities compared with Eastern coal. In the Western coal used in the experimental work conducted to date, the alkalinity concentrations have been depressed following long residence times but have not dropped to zero in any of the experimental work. It is probable that a simultaneous neutralization of the alkalinity in the slurry media and leaching of the alkalinity source in the coal occurs in the longer residence time circumstances. Additionally, other weak bases and weak acids become more significant when the carbonate-bicarbonate alkalinity is reduced. Figure 8 shows the alkalinity concentrations with time for 40 and 50 percent solids concentrations slurries under aerobic conditions with distilled water used as the slurry media. As shown on this figure, the alkalinity started to decrease following a residence time of 24 hours. Although the coal and water sources were different for Figures 7 and 8, the same general tendency would apparently have resulted had the time for Figure 8 been extended. Figure 9 shows a comparison of the alkalinity concentrations in the slurry wastewater from two coals with distilled water as the slurry media. These curves illustrate the differences in alkalinity concentrations resulting from the two coals. However, the alkalinity concentrations at the end of 60 hours were about the same.

Aluminum. The concentrations of aluminum in the slurry wastewater were low, generally less than one part per million. Figure 10 shows the aluminum concentrations for a 50 percent solids slurry with distilled water used as the slurry media. This curve is generally typical of those resulting from the distilled water studies.

Biochemical oxygen demand. Biochemical oxygen demand can be defined as the quantity of molecular oxygen required to stabilize the biodegradable fraction of a waste by aerobic biochemical action. The two biochemical oxygen demand values ordinarily used are the five-day biochemical oxygen demand (BOD_5) and the ultimate biochemical oxygen demand (BOD_u or BOD_{ult}). The five-day biochemical oxygen demand refers to the quantity of oxygen required to stabilize a waste after a five-day incubation period. The ultimate biochemical oxygen demand represents the maximum quantity of waste that can be stabilized

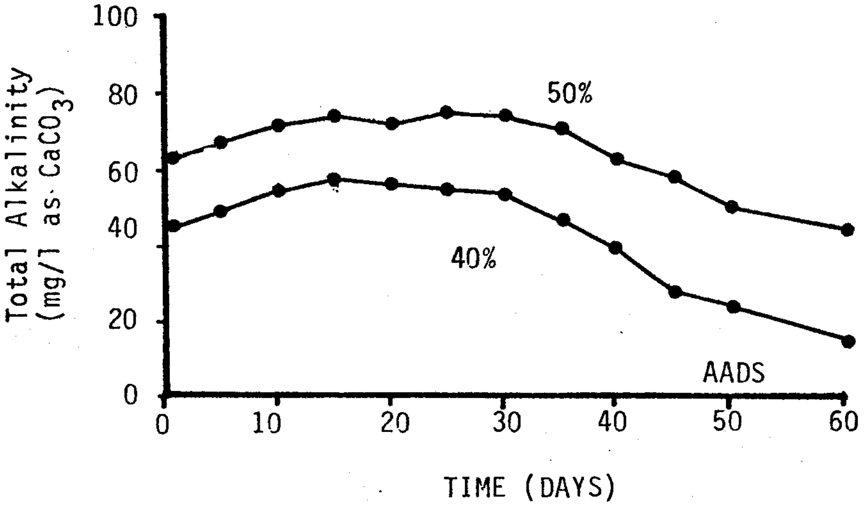


Figure 8. Total Alkalinity Concentrations in the Slurry Wastewater as a Function of Residence Time and Slurry Solids Concentration

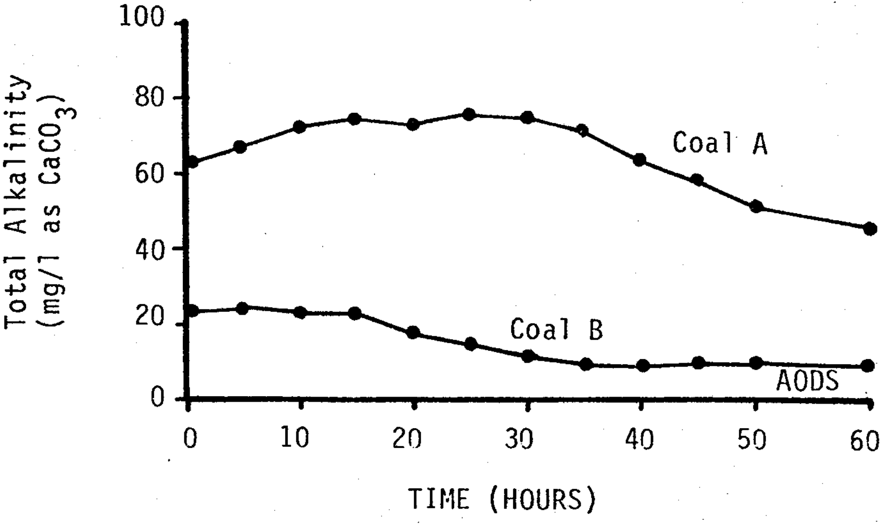


Figure 9. Total Alkalinity in the Slurry Wastewater as a Function of Coal Source and Residence Time

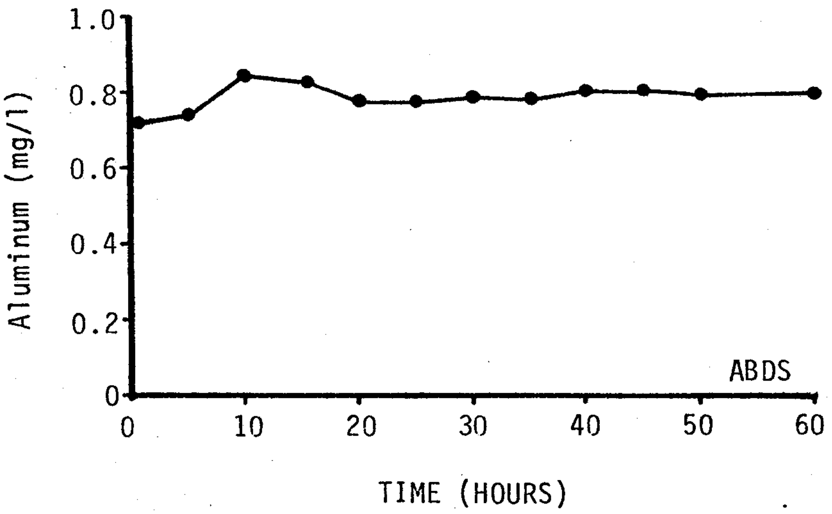


Figure 10. Aluminum Concentrations in the Slurry Wastewater as a Function of Residence Time

biologically. For "typical" domestic wastewater, the ultimate biochemical oxygen demand is usually exerted within 25 to 30 days and generally is about 1.5 times the five-day biochemical oxygen demand. These relationships do not, however, necessarily occur in industrial wastewaters. Such wastewaters may range from non-biodegradable to readily biodegradable depending on the type of organic material present. Figure 11 shows a "typical" biochemical oxygen demand curve for domestic wastewater. The lower curve represents the carbonaceous demand with the upper curve representing nitrogenous demand. The carbonaceous demand refers to the quantity of oxygen required to stabilize the carbon in the waste. The nitrogenous demand refers to the quantity of oxygen required to convert the nitrogen in the waste to nitrate (NO_3).

Figure 12 shows three biochemical oxygen demand curves that can occur for various industrial wastewaters. Curve A represents a wastewater that is non-biodegradable, has little biochemical oxygen demand or requires acclimation. Acclimation of microorganisms (when possible) can be accomplished by growing the microorganisms on a similar synthetic or natural media with gradual substitution of the wastewater until the microorganisms are acclimated. Curve B represents a wastewater that required acclimation but that was relatively easy to acclimate. Curve C represents a "typical" domestic wastewater included for comparison purposes. These curves are included as background because the biochemical oxygen demand curve for the slurry wastewater is unusual. An ultimate biochemical oxygen demand curve representing the slurry wastewater for one coal source is shown on

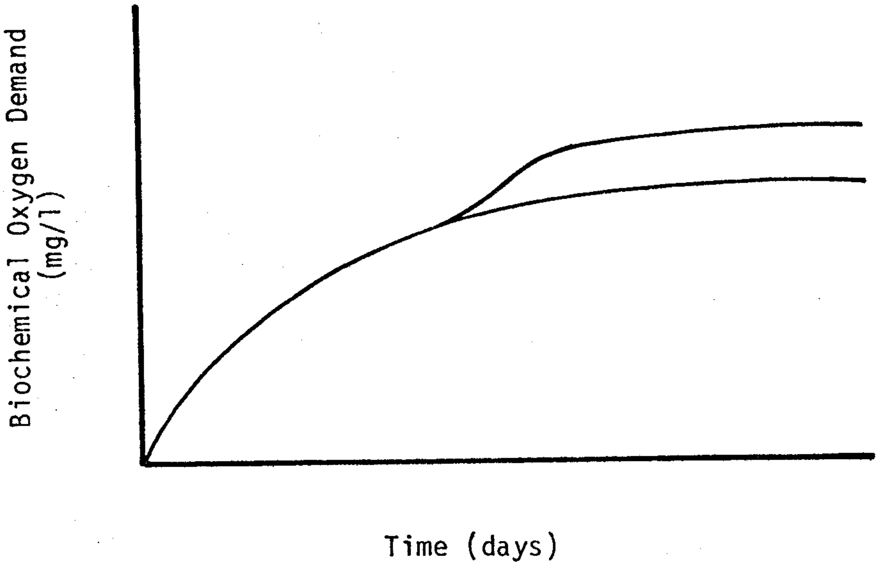


Figure 11. Typical Ultimate Biochemical Oxygen Demand Curve

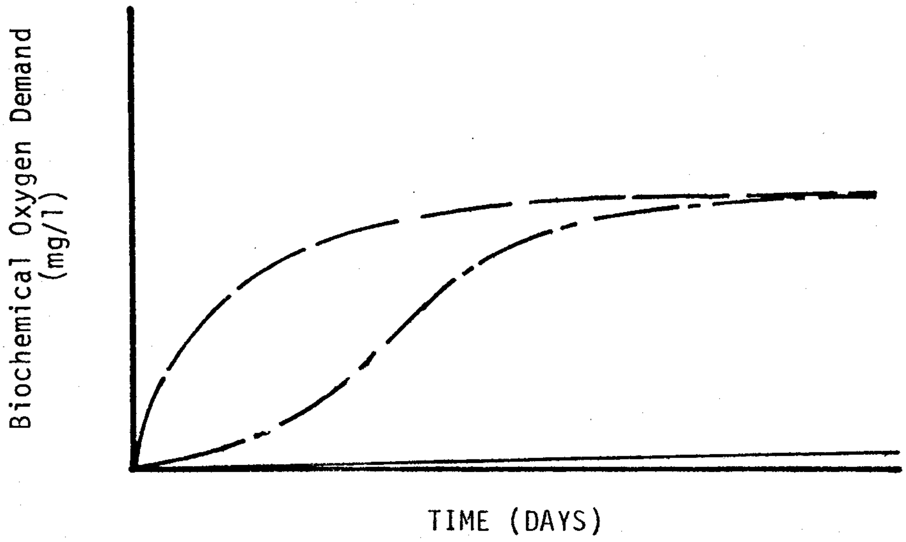


Figure 12. Biochemical Oxygen Demand Curves Representing Various Degrees of Treatability

Figure 13. As shown on this figure, some of the biochemical oxygen demand is readily exertable with additional demand exerted in stages. The significance of this curve cannot be generalized because site specific factors will largely determine its significance. Slurry wastewater treated by conventional biological treatment would not necessarily remove the biochemical oxygen demand. If the wastewater were discharged to a surface watercourse following conventional biological treatment, the biochemical oxygen demand would be exerted in the watercourse. Conversely, if the site conditions were such that no discharge from the plant site, occurred, little significance would be attached to the curve. Should the slurry wastewater be used in the circulating water system, the high biochemical oxygen demand could cause difficulty. These factors are discussed more completely in the Phase III results.

Figure 14 shows the five-day biochemical oxygen demand curve for one coal source at 50 percent solids concentration with an anaerobic environment. As shown by the figure, the five-day biochemical oxygen demand decreases with increasing residence time in the pipeline. The generally decreasing five-day biochemical oxygen demand concentrations may result from stabilization of the biochemical oxygen demand, from adsorption of the biochemical oxygen demand by the coal, from the increasing concentration of a toxic material, or a combination of these factors. Figure 15 shows the five-day biochemical oxygen demand concentrations for the 40 and 50 percent solids concentrations sluries under aerobic conditions with municipal wastewater used as the slurry media. These show the same general tendencies as did the anaerobic data shown on Figure 14. Figure 16 provides a comparison of five-day

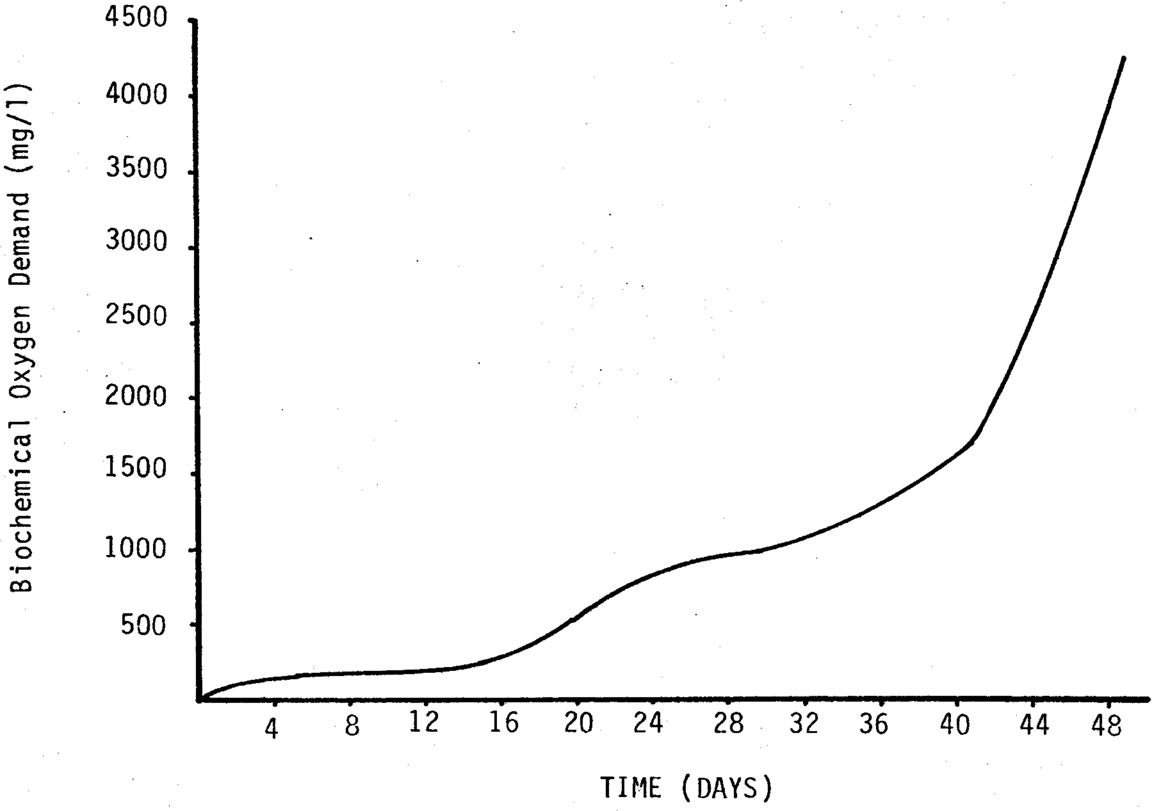


Figure 13. Ultimate Biochemical Oxygen Demand Curve for Slurry Wastewater

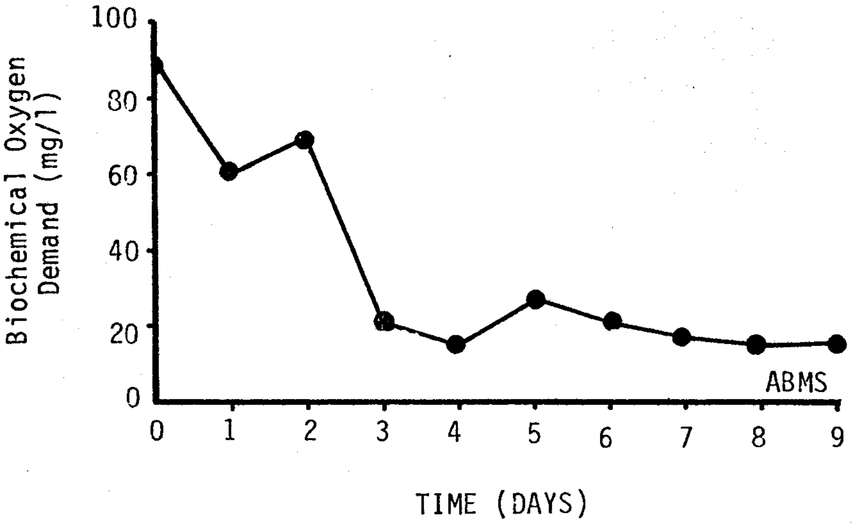


Figure 14. Biochemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time

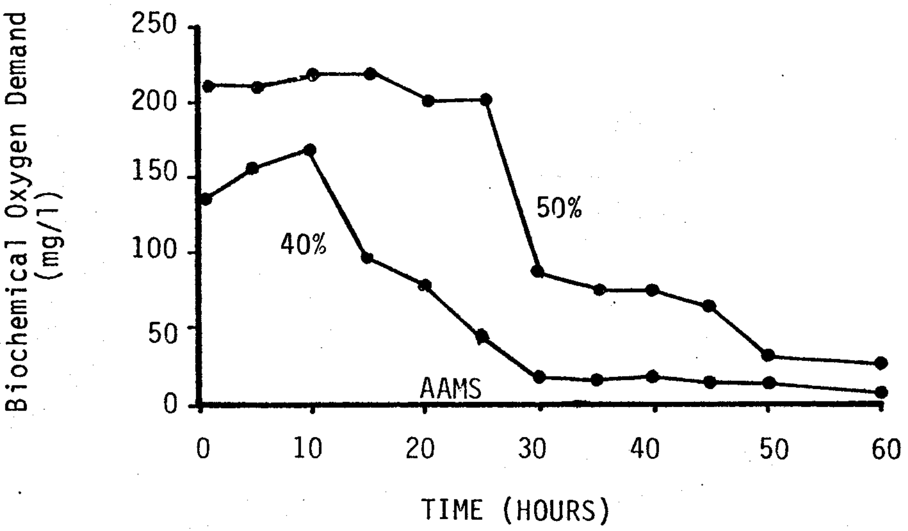


Figure 15. Biochemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time and Slurry Solids Concentration

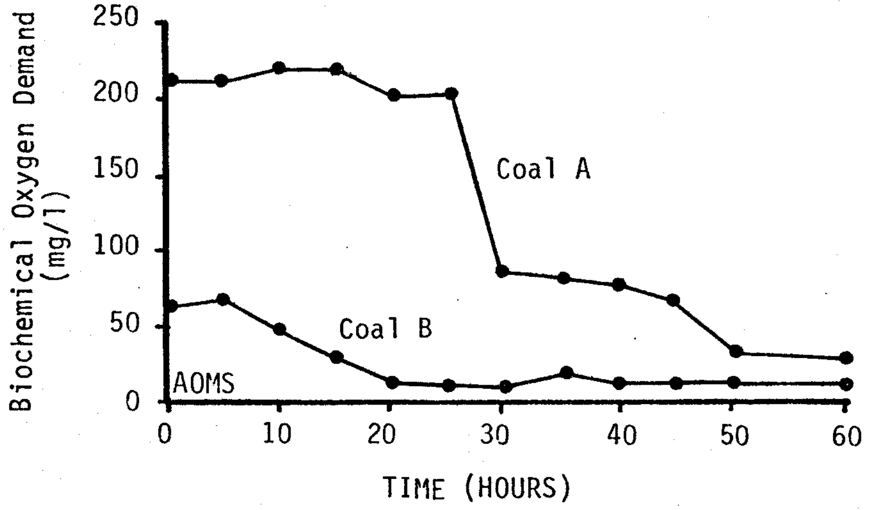


Figure 16. Biochemical Oxygen Demand Concentrations as a Function of Residence Time and Coal Source

biochemical oxygen demand for the slurry wastewaters from two coals with treated municipal wastewater used as the slurry media. As indicated by Figure 16, the differences in the initial five-day biochemical oxygen demand concentrations for the two coals were significant, but the concentrations were about the same after a residence time of about 36 hours.

Chemical Oxygen Demand. The chemical oxygen demand test also provides a measure of the organic material present in a wastewater. This test used a strong oxidant (potassium dichromate) in the presence of a strong acid (sulfuric) to oxidize the organic materials present. Because the chemical oxygen demand test measures both non-biodegradable and biodegradable organic material, the chemical oxygen demand concentration is greater than the biochemical oxygen demand concentration for a sample except when certain specific chemicals which interfere with the test are present. Figure 17 shows the chemical oxygen demand concentrations in a slurry wastewater under anaerobic conditions with municipal wastewater effluent used as the slurry media. Figure 18 provides a comparison of the chemical oxygen demand concentrations for two slurry solids concentrations under aerobic conditions with distilled water used as the slurry media. Figure 19 shows the chemical oxygen demand concentration for slurry wastewaters from two coals under aerobic conditions with distilled water used as the slurry media.

The chemical oxygen demand concentrations for 40 and 50 precent solids slurries under aerobic conditions with municipal wastewater effluent used as the slurry media are shown on Figure 20.

Calcium and Total Hardness. The term "hardness" refers to the divalent metal cations present in water. For most waters, the concentrations

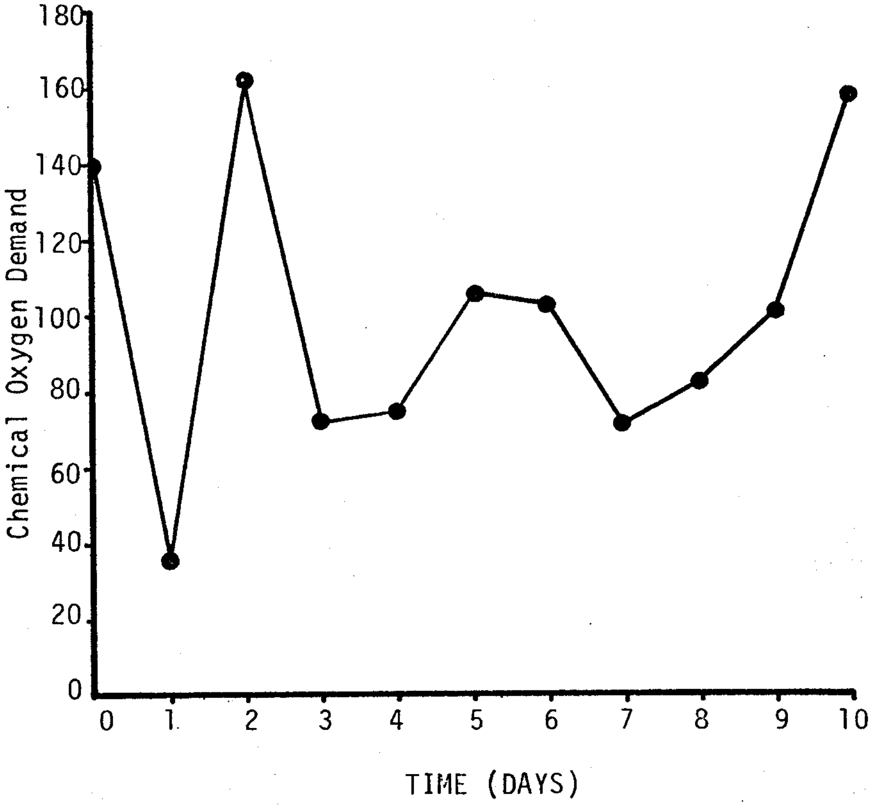


Figure 17. Chemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time

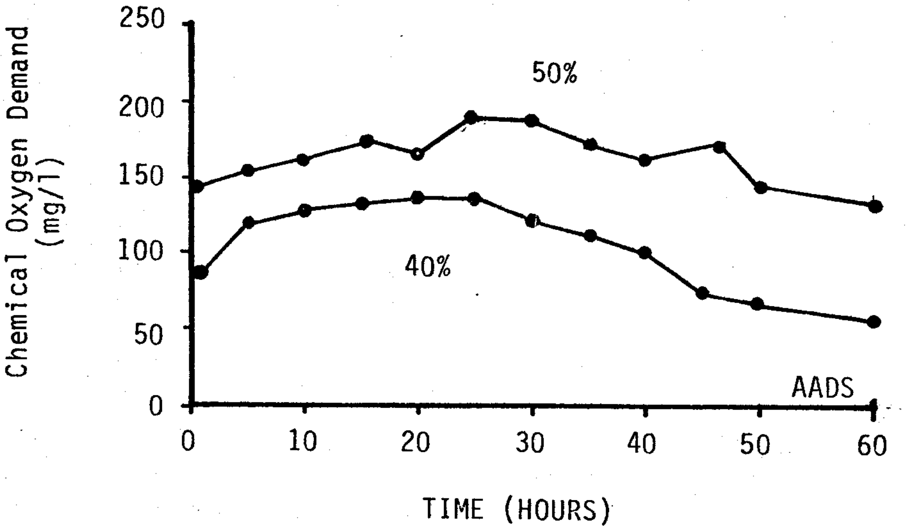


Figure 18. Chemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time and Solids Concentration

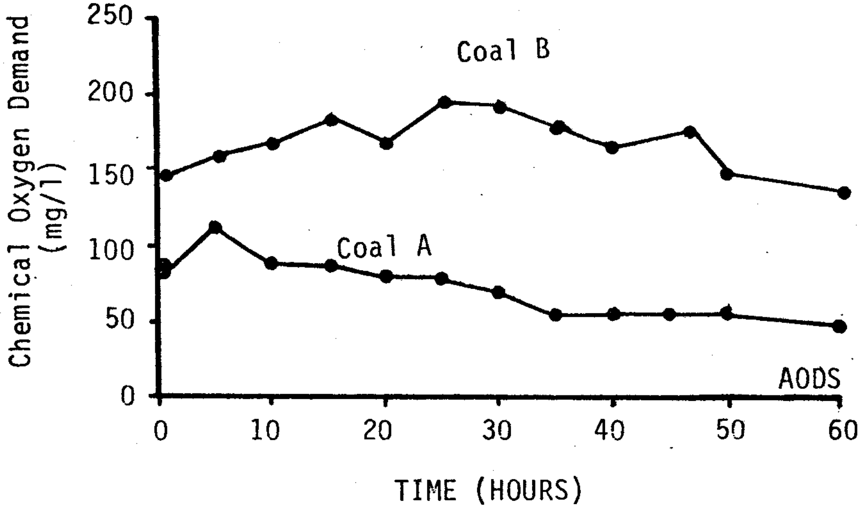


Figure 19. Chemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time and Coal Source

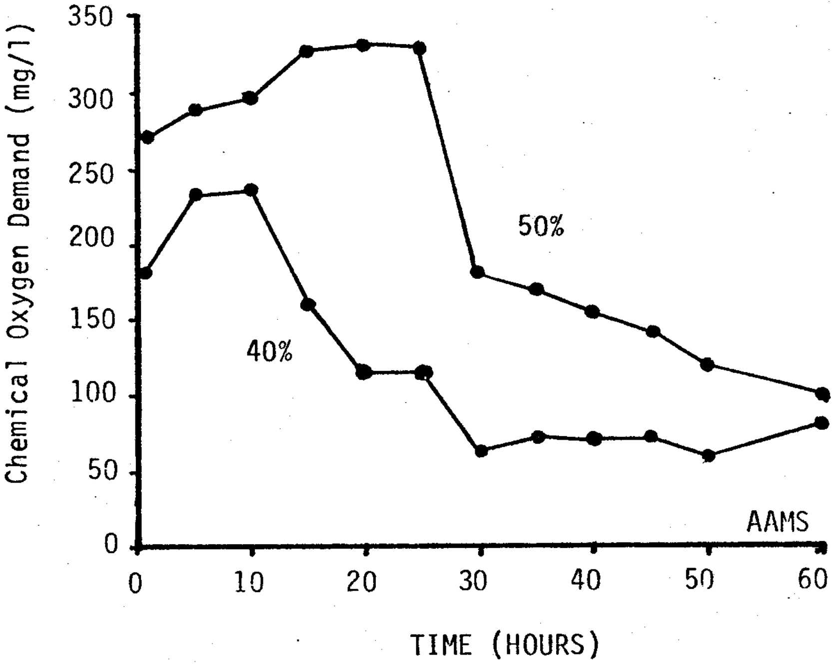


Figure 20. Chemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time

of iron, manganese and strontium are sufficiently low that the term usually refers to the ions of calcium and magnesium. The significance of hardness in water is related primarily to non-physiological properties. Water treated for domestic consumption usually is softened (i.e., some of the hardness removed) if the hardness exceeds 150-175 milligrams per liter. Such treatment is provided to reduce soap consumption, to minimize calcium carbonate precipitation on heat exchange surfaces and other more limited reasons.

The technology of hardness removal from water is well developed. Consequently, the presence of hardness in the slurry wastewater is primarily an economic consideration. Hot and cold lime-soda ash softening, hot phosphate softening and ion exchange all may be used with minimal difficulty for hardness removal. For installations utilizing the slurry wastewater in heat exchange equipment without dilution, softening may be required to avoid significant reduction in heat exchange rates because of calcium carbonate precipitation on the heat exchange surfaces.

The calcium and total hardness concentrations in the slurry wastewater may be substantial as shown on Figure 21. This curve represents the hardness resulting from an anaerobic environment with municipal wastewater effluent used as the slurry medium. Figure 22 shows the calcium and total hardness concentrations in slurry wastewater with distilled water used as the slurry medium. Figure 23 shows the relationship of calcium and total hardness with residence time with muncipal wastewater effluent used as the slurry make-up water. These curves represent the same coal used for developing Figure 22.

<u>Chloride</u>. The chloride concentrations in the slurry wastewater are relatively low and are a function of both the coal quality and the slurry

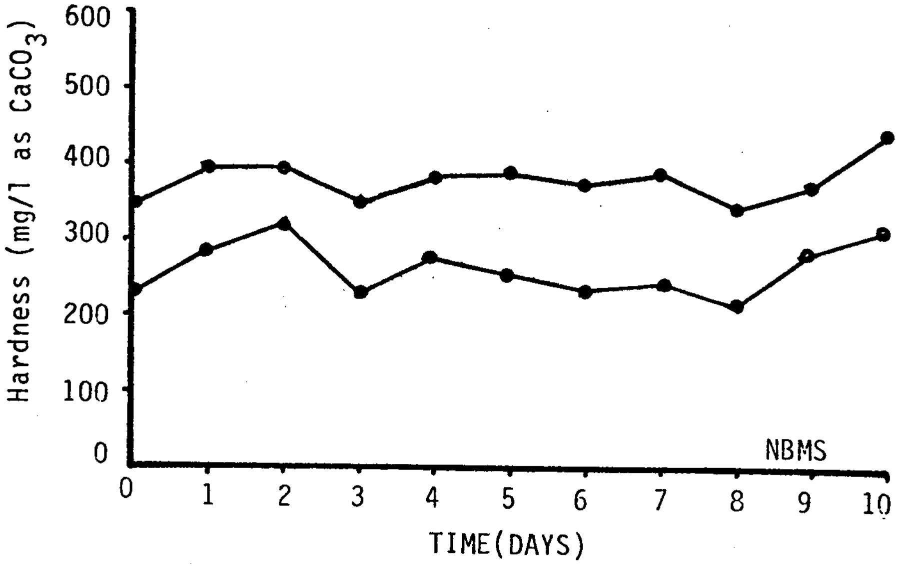


Figure 21. Calcium and Total Hardness Concentrations in Slurry Wastewater as a Function of Residence Time

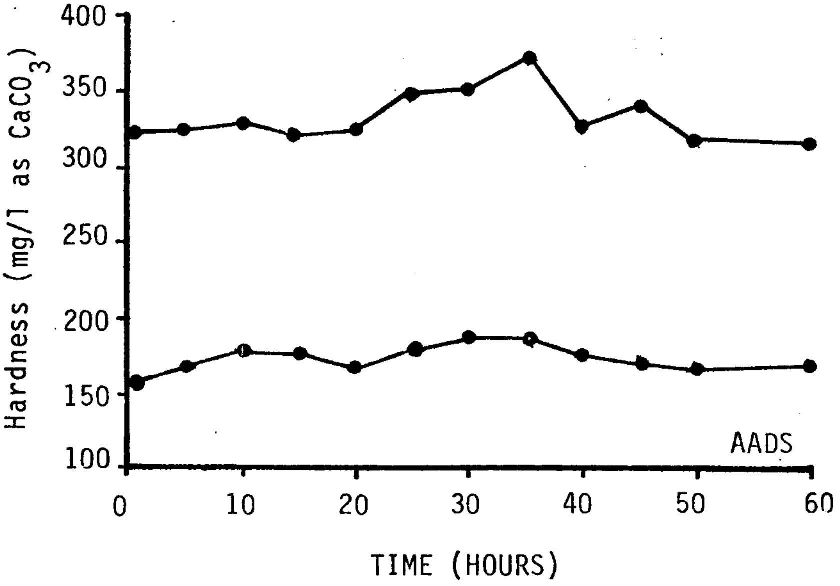


Figure 22. Calcium and Total Hardness of the Slurry Wastewater as a Function of Residence Time

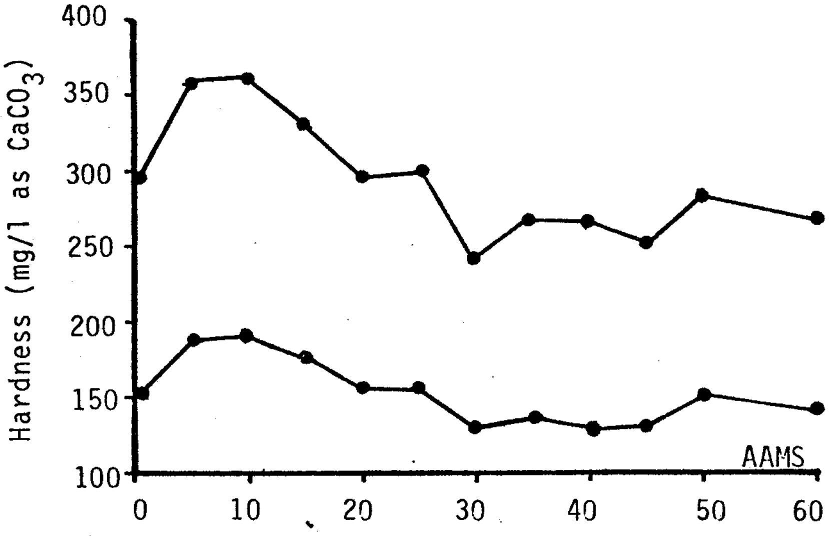


Figure 23. Calcium and Total Hardness Concentrations in Slurry Wastewater as a Function of Residence Time

media water quality. Figure 24 provides a comparison of the chloride concentrations in slurry wastewaters from 40 and 50 percent solids slurries with distilled water used as the slurry media. A comparison of the chloride concentrations resulting from two different coals with distilled water used as the slurry media is shown on Figure 25. The effect of slurry media water quality on the chloride concentrations in the slurry wastewater is shown on Figure 26. The chloride concentration in the traded municipal wastewater was 35.0 milligrams per liter.

Nitrate. The primary significance of nitrate in water supplies is that nitrates have been linked with methemoglobinemia and death in infants and cattle. The nitrate concentrations in the slurry wastewater were relatively low. Because a nitrogen blanket is being used to obtain an anaerobic environment, the nitrate test is not being conducted for the anaerobic studies. Figure 27 provides a comparison of the nitrate concentrations in slurry wastewaters representing two coals with distilled water used as the slurry media. The effect of slurry media water quality on the nitrate concentrations in the slurry wastewater is shown to some extent on Figure 28. A raw water with substantial concentrations of nitrate would be expected to yield higher nitrate concentrations in the slurry wastewater.

pH. The pH of a solution is a measure of the hydrogen ion concentration in the solution. By definition it is the negative logarithm of the reciprocal of the hydrogen ion concentration. Thus, pH serves as a measure of the acidity or alkalinity of a water or wastewater. Figure 29 shows the fluctuations in the pH values measured under anaerobic conditions with municipal wastewater effluent used as the slurry media.

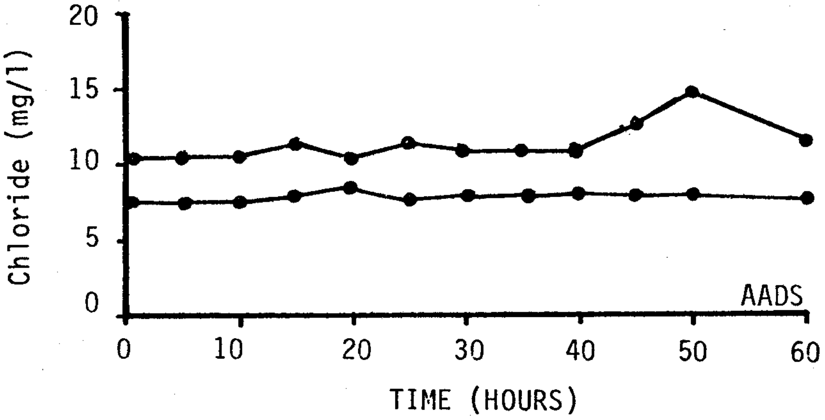


Figure 24. Chloride Concentrations in the Slurry Wastewater as a Function of Residence Time

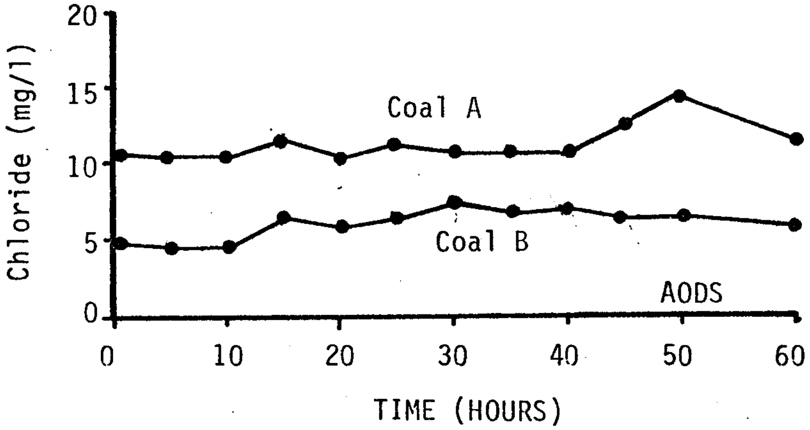


Figure 25. Chloride Concentration in the Slurry Wastewater as a Function of Residence Time and Coal Source

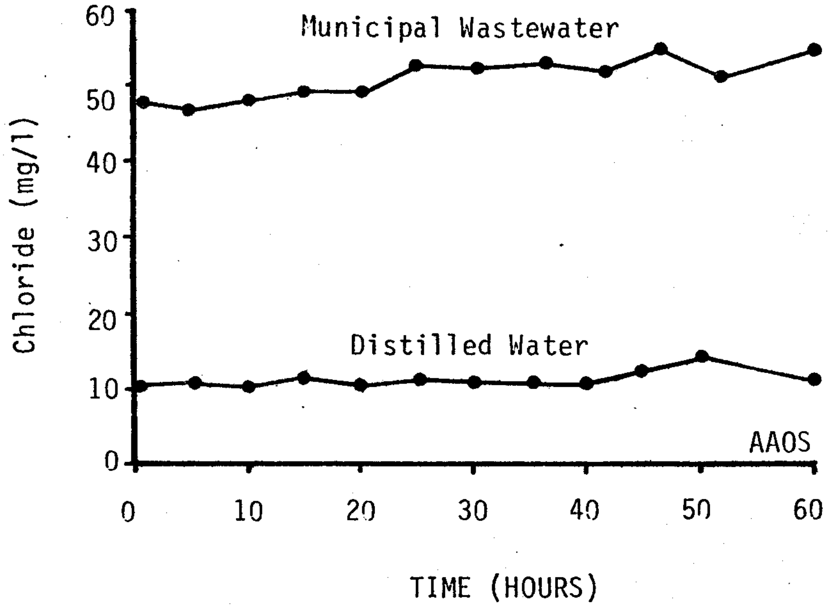


Figure 26. Chloride Concentrations in Slurry Wastewater with Distilled Water and Municipal Wastewater Effluent Used as the Slurry Media

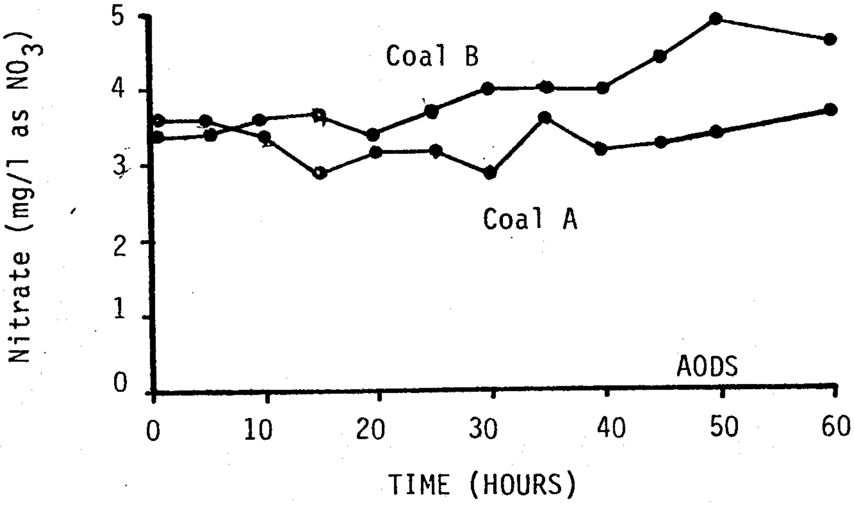


Figure 27. Nitrate Concentrations in the Slurry Wastewater as a Function of Residence Time and Coal Source

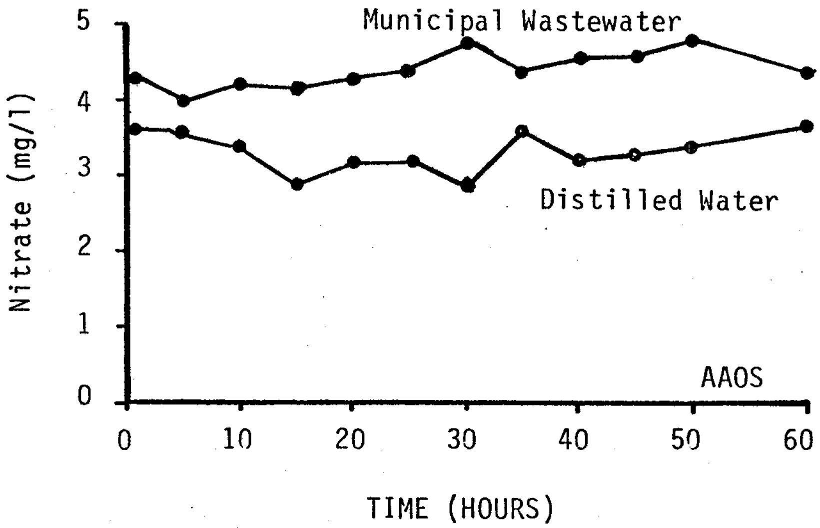


Figure 28. Nitrate Concentrations in the Slurry Wastewater as a Function of Residence Time and Slurry Media

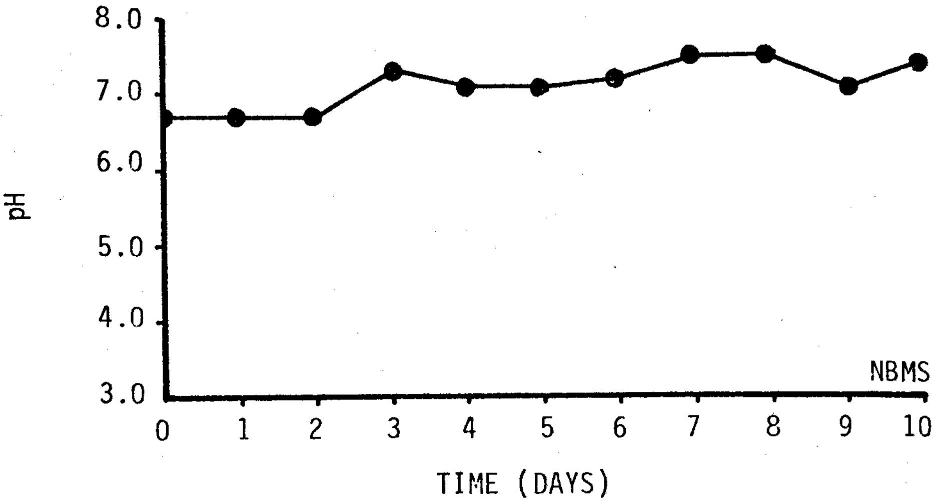


Figure 29. pH of Slurry Wastewater at Various Residence Times

The pH values for the slurry wastewaters from two coals under aerobia conditions with distilled water used as the slurry media are shown on Figure 30.

Potassium. Figure 31 shows a comparison of the potassium concentrations in slurry wastewaters from two coals with distilled water used as the slurry media water quality. The potassium concentrations were low in the slurry wastewater for all experimental work. Consequently, other then the contribution to total dissolved solids, this parameter is not significant.

Silica. Figure 32 shows a comparison of the silica concentrations in the slurry wastewater from two coals under aerobic conditions with distilled water used as the slurry media. The primary significance of silica in water is that it can form a hard dense scale on heat exchange surfaces and can severely impede heat transfer.

Sodium. The primary significance of sodium in public water supplies is related to cardiovascular problems, that is, persons with cardiovascular difficulties are usually assigned a low-sodium diet. A comparison of the sodium concentrations in slurry wastewater from 40 and 50 percent solids slurries under aerobic conditions with distilled water used as the slurry media is shown on Figure 33. These concentrations are only moderately high and should not create significant problems. The sodium concentrations in slurry wastewaters from two coals under aerobic conditions are shown on Figure 34. The chloride concentrations in slurry wastewaters under aerobic conditions with both distilled water and treated municipal wastewater used as the slurry media are shown on Figure 35. The sodium concentration in the municipal wastewater was 7.8 milligrams per liter.

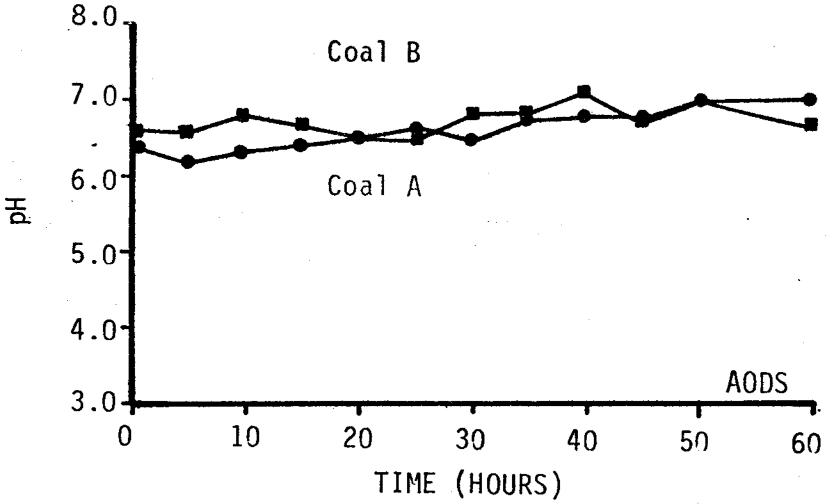


Figure 30. Variation in pH with Residence Time for Slurry Wastewater

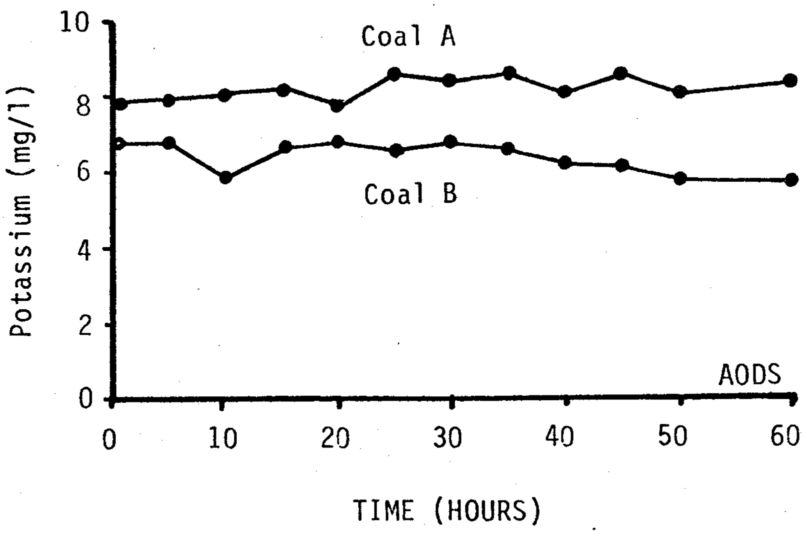


Figure 31. Potassium Concentrations in the Slurry Wastewater as a Function of Residence Time and Coal Source

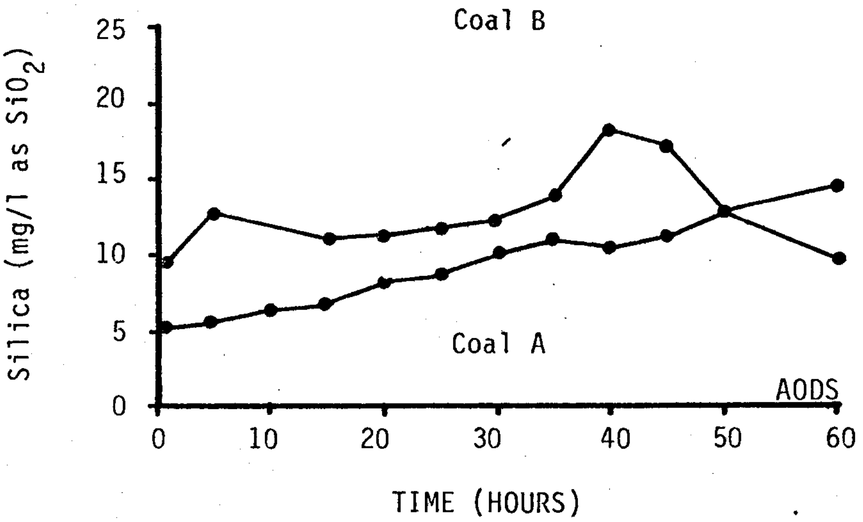


Figure 32. Silica Concentrations in the Slurry Wastewater as a Function of Coal Source and Residence Time

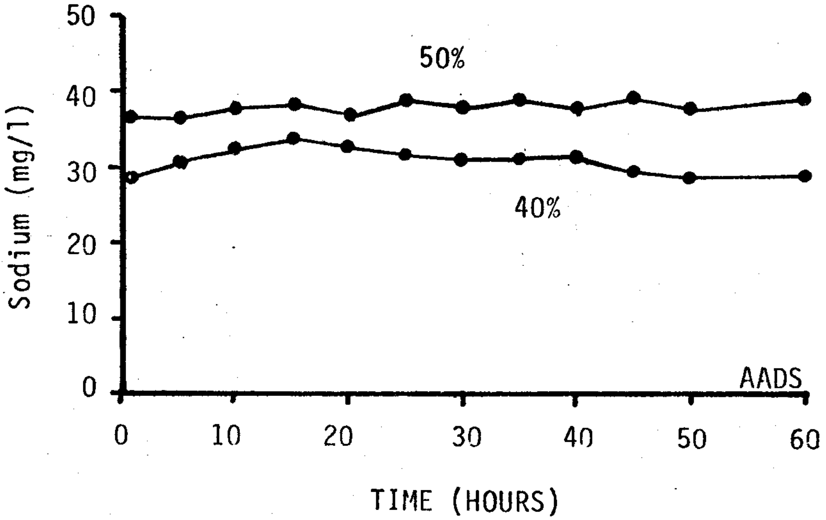


Figure 33. Sodium Concentrations in the Slurry Wastewater as a Function of Percent Solids and Residence Time

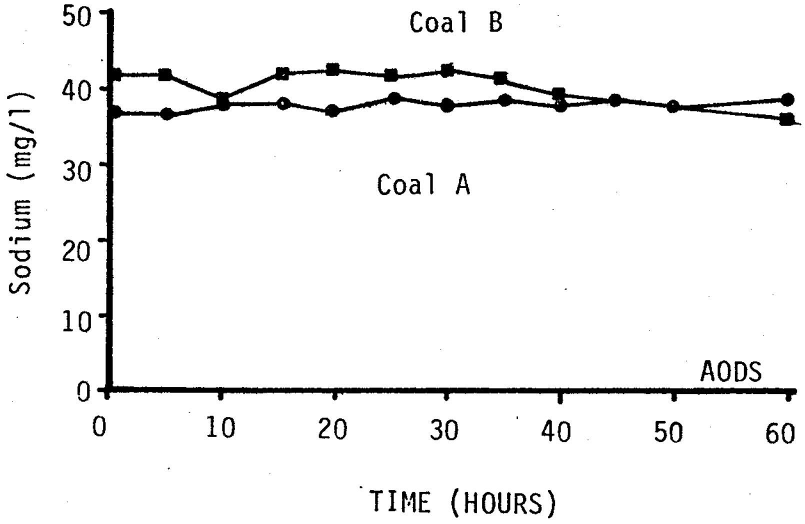


Figure 34. Sodium Concentrations in the Slurry Wastewater as a Function of the Coal Source and Residence Time

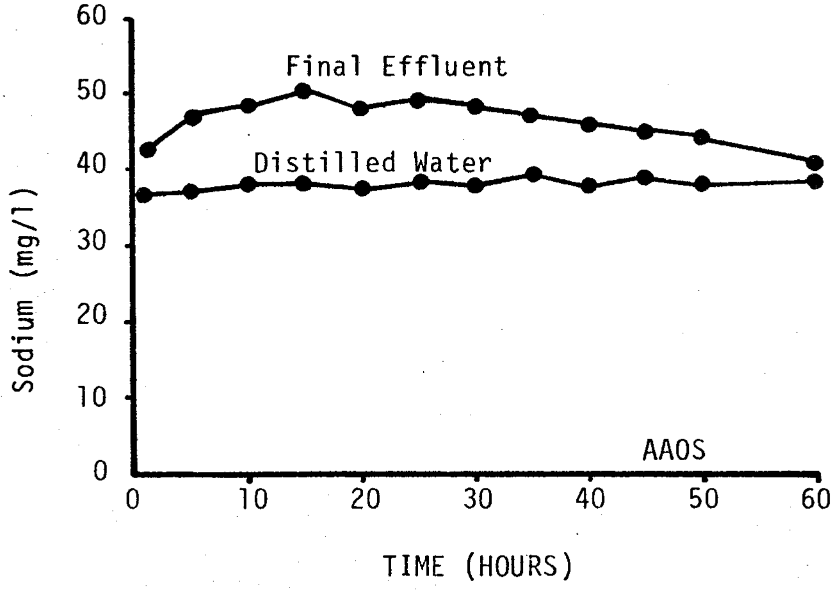


Figure 35. Sodium Concentration in Slurry Wastewater as a Function of Residence Time and Water Source

Sulfate. A comparison of the sulfate concentrations resulting from two coals under aerobic conditions with distilled water used as the slurry media is shown on Figure 36. As would be expected, the sulfate concentrations in the slurry wastewater are a function of coal source, that is, coal quality. Figure 37 shows the slurry wastewater sulfate concentrations over a longer residence time.

Titanium. The titanium concentrations in slurry wastewater were relatively low. Figure 38 shows the titanium concentrations as a function of residence time and slurry solids concentration.

Anaerobic-Aerobic Environment Comparisons. Figures 40, 41, 42, 43 and 44 provide comparisons of the parameter concentrations for pH, total alkalinity, calcium and total hardness, five-day biochemical oxygen demand and chemical oxygen demand, respectively, under anaerobic and aerobic-anaerobic environments has been taken and is currently being evaluated.

Phase II Results

The objective of this phase of the research program was to determine the feasibility of utilizing poor-quality water (impaired water) such as municipal and industrial effluents as the slurry medium. The impaired water phase was included for two reasons. First, if the impaired water would be acceptable for use as slurry media, the higher quality water in the state of origin could be reserved for other purposes, thus avoiding the duplicate cost of quality restoration of the impaired water. Second, the use of the impaired water would undoubtedly be more acceptable in the state of origin.

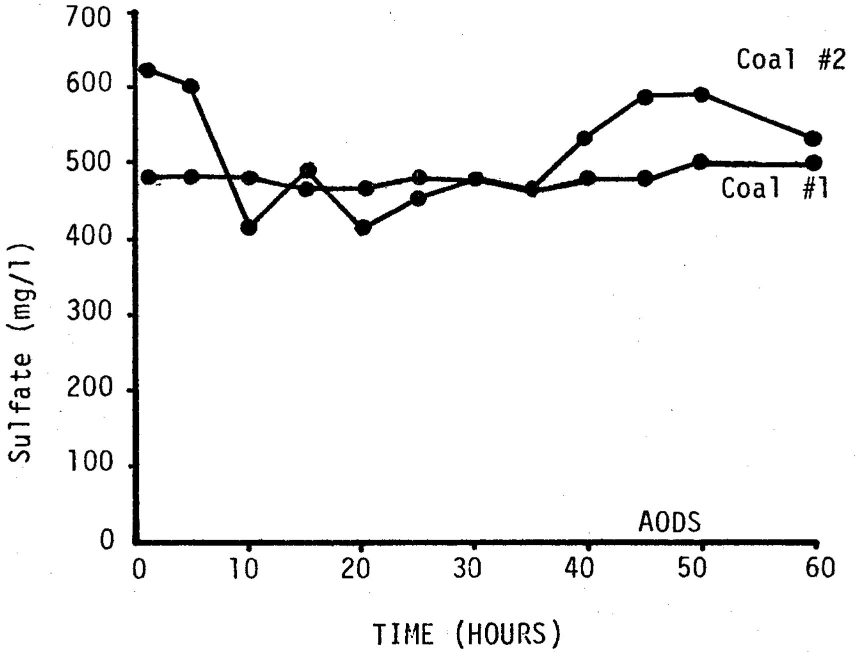


Figure 36. Sulfate Concentration in Slurry Wastewater as a Function of Residence Time and Coal Source

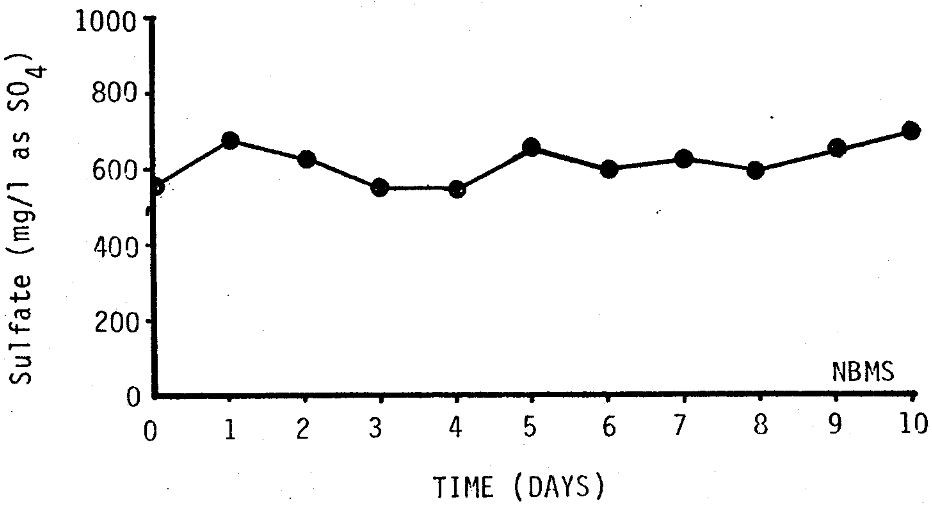


Figure 37. Sulfate Concentrations in the Slurry Wastewater as a Function of Residence Time

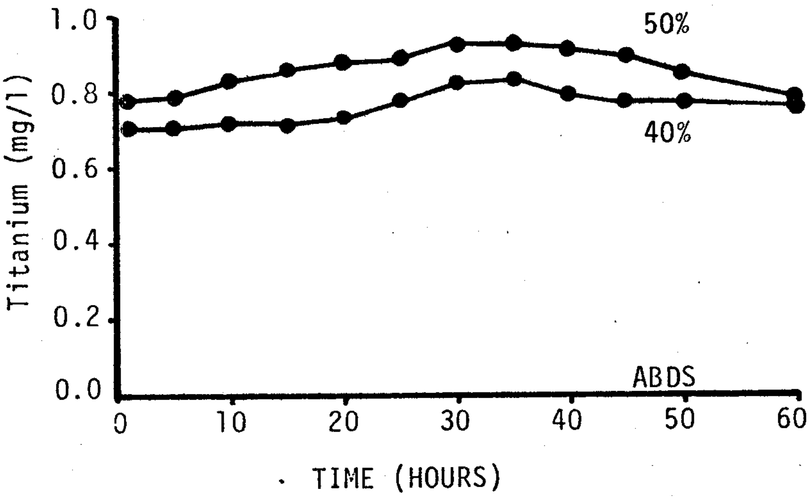


Figure 38. Titanium Concentration in Slurry Wastewater as a Function of Residence Time and Solids Concentration

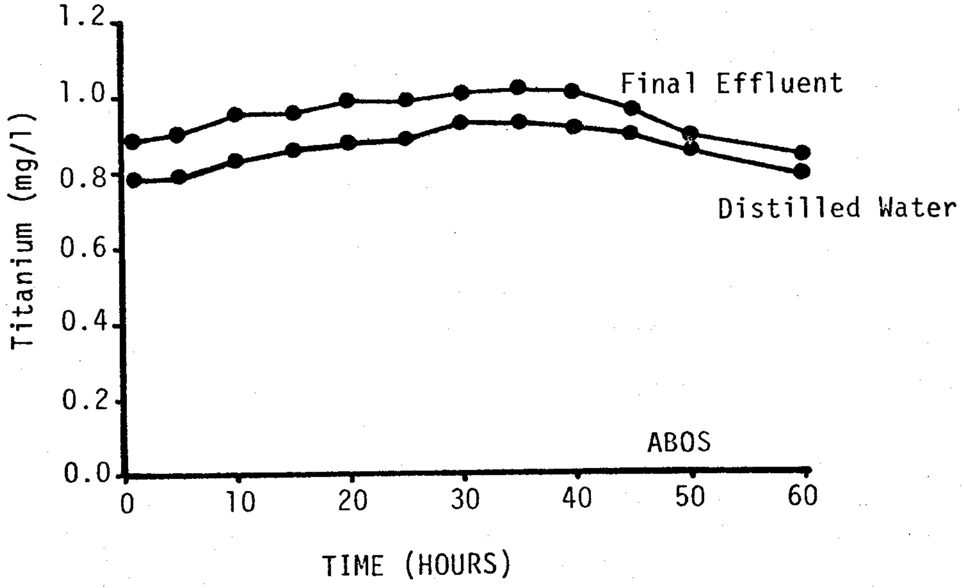


Figure 39. Titanium Concentration in Slurry Wastewater as a Function of Residence Time and Solids Concentration

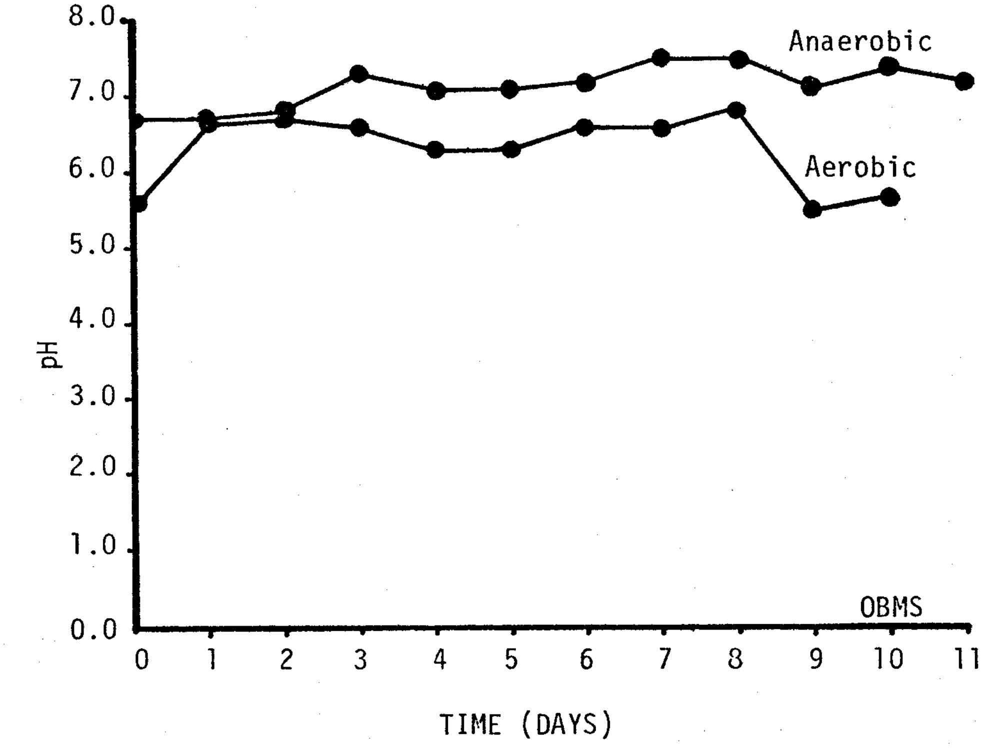


Figure 40. pH of the Slurry Wastewater as a Function of Residence Time

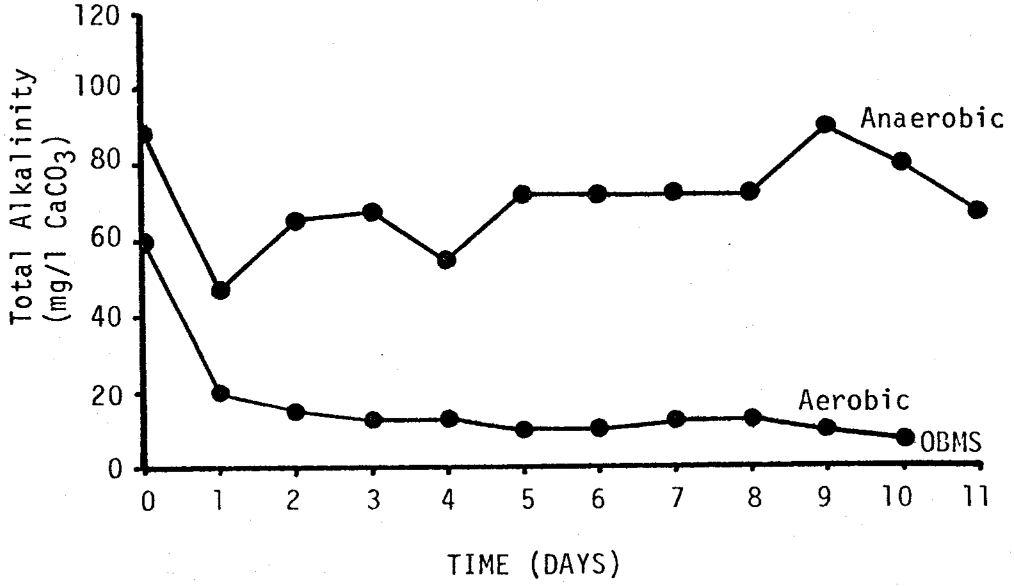


Figure 41. Total Alkalinity Concentrations in the Slurry Wastewater as a Function of Residence Time

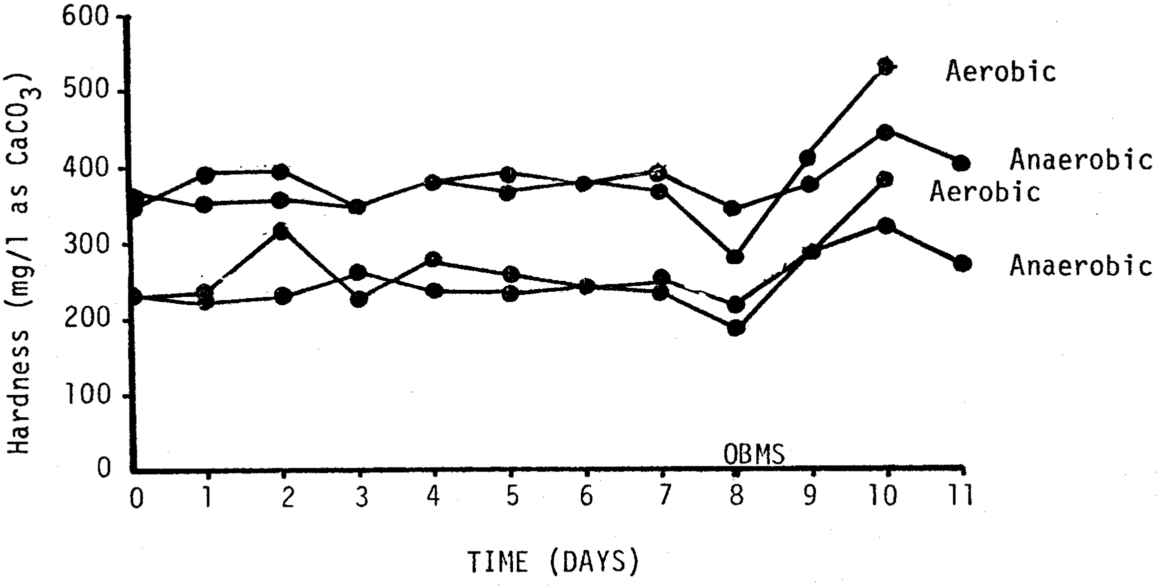


Figure 42. Calcium and Total Hardness Concentrations in the Slurry Wastewater as a Function of Residence Time

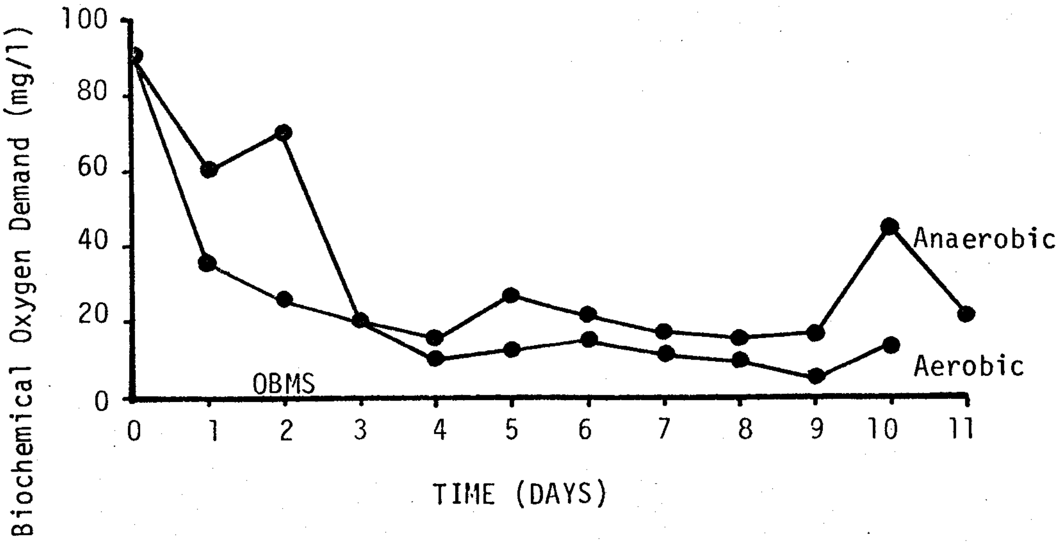


Figure 43. Biochemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time

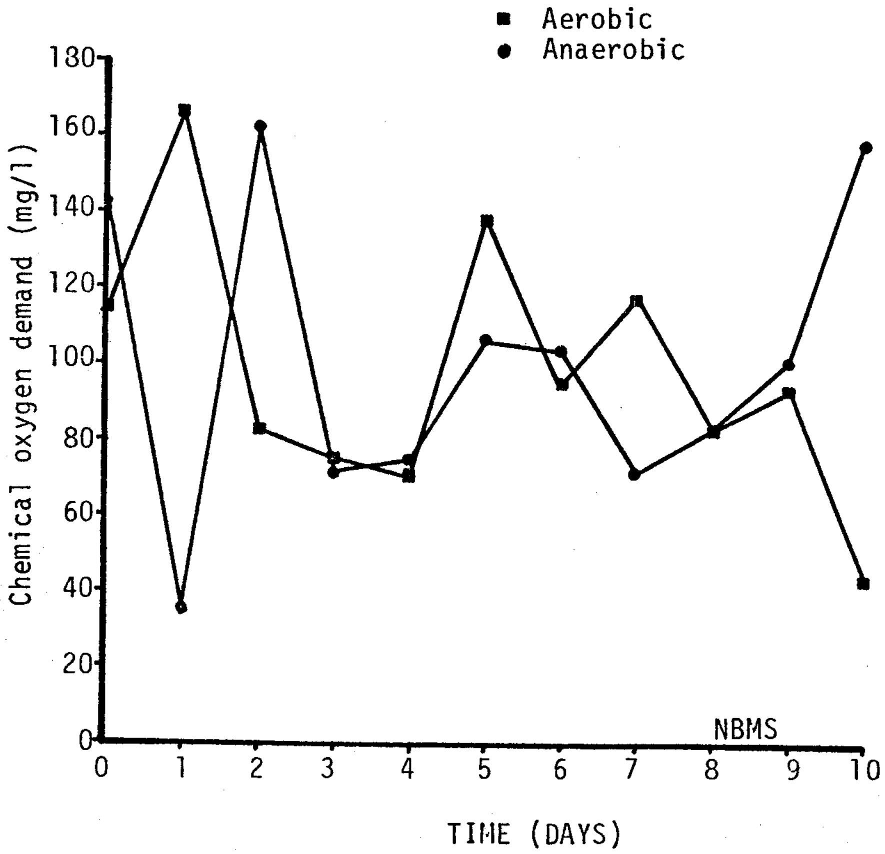


Figure 44. Chemical Oxygen Demand Concentrations in the Slurry Wastewater as a Function of Residence Time

Some of the Phase II results were included with the Phase I results for ease of comparison. In general, the use of impaired water does increase the contaminant concentrations in the slurry wastewater. However, the resulting contaminant concentrations are not necessarily additive, that is, the concentration of the contaminants in the slurry wastewater are not equal to the sum of the concentrations of the contaminant in the distilled water and the treated municipal and industrial wastewaters. These data are currently being analyzed in detail to establish the relationships that do occur.

In general, wastewater treatment costs are not linear because of economies of scale and other factors. Consequently, although the cost of water quality restoration would be increased by the use of impaired water, the increase should not be prohibitively large except possibly when very poor quality water is used. For example, if lime-soda ash softening were required for reducing the hardness concentration, the size of the treatment facilities (basin, etc.) is ordinarily not a function of the hardness concentration. The chemical costs, however, are dependent on the hardness as are the sludge handling facilities. Thus, the cost of removing the additional hardness resulting from the use of impaired water would largely reflect the additional chemical and sludge handling and treatment costs. This relationship does not strictly hold true for those concentration intensive processes such as biochemical oxygen demand removal where oxygen transfer represents a major cost. However, even in these cases the treatment costs are not linear with concentration. A much more detailed discussion of this aspect of the research program will be included in the final report.

Phase III Results

The objective of this phase of the on-going research program was to determine the treatment measures applicable for restoring the slurry wastewater quality to acceptable levels, if required. The approach taken in this phase of the program was to identify those treatment measures applicable for restoring all parameters to acceptable levels. All of the treatment measures would not necessarily be required at each liquid-solids separation site. Similarly, the entire wastewater stream would not necessarily be treated. For example, a power generation station firing slurry pipeline delivered coal would have the option of using the wastewater as part of the circulating water makeup. Thus, both wastewater streams (the slurry wastewater and circulating water blowdown) could be treated on a combined basis, if and when required. The cooling water makeup requirements are substantially greater than the slurry media water requirement. For example, a 1600 megawatt (gross) power station requires about 45 cubic feet per second of makeup water for the cooling system, whereas the water requirement for the slurry pipeline delivering the coal required by the station would be about 10 to 15 percent of the cooling water requirement.

The presence of the significant biochemical and chemical oxygen demand concentrations in the slurry wastewater indicated that biological treatment for stabilization of the organic material should be investigated. As previously indicated in the biochemical oxygen demand section of the Phase I results, the ultimate biochemical oxygen demand curve is unusual. Substantial acclimation of the microorganisms is apparently required before a major fraction of the organic material can be stabilized. However, a portion of the biochemical oxygen demand (that represented by the first 12-14 days of the ultimate biochemical oxygen demand curve) was relatively easy to stabilize in the biochemical oxygen demand bottle. Consequently, this portion of the biochemical oxygen demand would be expected to be relatively easy to stabilize by biological treatment. Laboratory activated sludge treatment studies, however, indicated that the biochemical oxygen demand could not be readily stabilized, at least without remedial measures. To date, the reason for this treatment difficulty has not been identified. Figure 44 shows the response of a labor atory activated sludge treatment unit to the slurry wastewater as reflected by the mixed liquor suspended solids concentration in the activated sludge aeration basin. Several studies have been conducted to determine the source of the treatment difficulty without success. These include addition of the trace elements added in the biochemical oxygen demand test to the laboratory units, acclimation studies including growth of microorganisms on synthetic media with gradual addition of the slurry wastewater, and others. There are several possible reasons for the treatment difficulty including the lack of a required trace element, insufficient food supply, and the presence of a toxic material in the wastewater. Laboratory tests which included the trace elements added in the biochemical oxygen demand test eliminated the first possibility, that is, if the required trace elements were present in the biochemical oxygen demand test and were added to the laboratory activated sludge units in the same concentration, as was done, the biochemical oxygen demand should have been stabilized in the laboratory units. The mixed liquor suspended solids concentration may be used as an indicator of the status of an activated sludge unit.

Studies were conducted to determine if the decreasing suspended solids concentrations were caused by an insufficient food supply. These studies were negative. Consequently, the presence of a toxic element or material is the most likely source of the treatment difficulty. In theory, the toxic material could be either inorganic or organic. Concentrations of the inorganic materials measured all appear to be within acceptable ranges for activated sludge treatment. Although it is possible that one of the metals, for example, could be concentrated sufficiently to be toxic, the most likely source of toxicity is an organic compound in the coal.

Studies have been and are being conducted for determination of the treatment measures suitable for water quality restoration. The results to date indicate that current technology is adequate for treatment of the inorganic contaminants. Additional investigation may be required concerning the effectiveness of organic contaminant treatment methods

Summary

The current project should provide sufficient data by which the water quality aspects of coal slurry pipelining can be assessed including the use of certain categories of impaired water. The use of very poor quality water, such as raw or primary treated municipal wastewater was not included in the investigation because of the presence of substantial concentrations of pathogenic microorganisms present. Although these could be deactivated, the work involved in such a program exceeded the resources of the current project. The use of saline water was not investigated because the requirement for installing flue gas desulfurization systems on new electric power plants firing coal appears imminent. Chloride corrosion is a severe problem in most cases because of the chloride present in the coal and in the raw water. The additional chlorides from the saline water that is retained by the coal solids following liquid-solids separation would undoubtedly have severe effects on the sulfur dioxide scrubbing equipment.

The use of secondary-treated municipal and certain industrial wastewaters appears to be technically feasible. Treatment for removal of the inorganic contaminants can be accomplished by current technology. Some increase in treatment costs can be expected but the increase should not adversely affect a proposed project unless the project economics are marginal. More complete treatment cost data will be included in the final project report.

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