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AN INTEGRATED SYSTEM FOR COAL-METHANOL LIQUEFACTION AND SLURRY PIPELINE TRANSPORTATION

Final Report

By
William F. Banks
John K. Davidson
James H. Horton
Claude W. Summers

March 31, 1980

Work Performed Under Contract No. AC03-78CS51884

Engineering Management and Development, Inc.
San Diego, California

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ENGINEERING MANAGEMENT AND DEVELOPMENT, INC
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ABSTRACT

The engineering economics of an integrated coal-to-methanol conversion system and coal-in-methanol transportation system are examined, under the circumstances of the western coalfields, ie, long distances from major markets and scarcity of water in the vicinity of the mines. The transportation economics are attractive, indicating tariffs of approximately 40 cents per million Btu per thousand miles for the coal-methanol pipeline vs 60 cents via coal-water pipelines and upwards of a dollar via rail. Energy consumption is also less in the coal-methanol pipeline than in the coal-water pipeline, and about equal to rail.

It is also concluded that, by a proper marriage of the synthetic fuel (methanolization) plant to the slurrification plant, most, and in some cases all, of the water required by the synthetic fuel process can be supplied by the natural moisture of the coal itself. Thus, the only technology which presently exists and by which synthetic fuel from western coal can displace petroleum in the automotive fuel market is the integrated methanol conversion and transportation system. The key element is the ability of the methanol slurry pipeline to accept and to deliver dry (1 to 5% moisture) coal, allowing the natural coal moisture to be used as synthesis feedstock in satisfaction of the large water requirement of any synthetic fuel plant. By virtue of these unique properties, this integrated system is seen as the only means in the foreseeable future whereby western coal can be converted to synthetic fuel and moved to distant markets.

1.0 Introduction

1.1 Motivation for the Study

The motivation for this study rests upon the axiom that it is essential to the security and economic stability of the United States to achieve independence from foreign energy sources. Therefore, in the time frame of the 1980's and 90's, it is important to accomplish, or at least to make major progress toward accomplishment of a number of measures, including

(a) Conservation of energy,

and

(b) Development of adequate resources within the United States to eliminate the present dependence upon foreign petroleum.

Since coal is the only energy resource presently known to exist in quantities sufficient for the purpose, measure (b) is further defined to mean the use of coal in lieu of petroleum.

While it is of course important that these measures be taken wherever practicable in all areas of the economy, this study examines an integrated system to accomplish both objectives. The known deposits in the western coal fields are sufficient to furnish the nation's energy needs for at least many years at the current consumption rate for both solid and liquid fuels, but in general, the sources are a long distance from the major markets. The system presented here satisfied the requirement for both types of fuel as well as economical transportation to market in terms of both cost and energy conservation. In this study, however, it is primarily the transportation system that is examined.

In simplified terms, measure (a) means that ways must be found to accomplish present results with more energy-conservative methods, eg, new technology, changing consumption patterns, etc. Accomplishment of measure (b) means that in round numbers, the production and consumption of coal should double again in the 90's, which in turn presents two problems:

(1) In the non-transportation markets, in which fuel can be consumed in the solid form, oil-burning plants should convert to coal. This massive conversion constitutes a major problem in itself, and it also presents a major transportation problem in the movement of coal, and in particular in the movement of western coal to distant markets. Problem 1, then is the transport of western coal to distant markets.

(2) In the transportation markets, where fuel can only be consumed if it is in the liquid form, synthetic liquid fuels (synfuels) which are derived from domestic coal should be used in lieu of petroleum fuels. This conversion to synthetic fuels raises a major industrial-environmental problem. Instead of extracting energy resources from foreign ground and refining them on foreign ground, thereby confining the resulting pollution to foreign ground, the resource must be extracted and refined on its home ground. Problem 2, then, is the construction and operation of gigantic new coal mines and synfuel plants in an environmentally acceptable way.

The solution to each of these problems in turn requires the solution of a multitude of sub-problems. In the case of Problem 1, the transportation problem is not only the movement of much greater quantities of coal, but also over much greater distances, because most of the increased coal production must come from the western fields, which are generally a thousand miles and more from their markets. The possible use of pipelines to move some of this coal to market in the form of a water slurry is already the subject of a well-publicized controversy (Banks, 1978).

Turning now to Problem (2), how to build and operate the large industrial complex so that coal can displace petroleum in the automotive fuel market, the principal question to be addressed in this study is whether the slurry pipeline solution to Problem (1) can provide, or at least assist in, the solution of Problem (2), or vice versa.

1.2 Objective

The central question to be addressed in this study can now be stated by paraphrasing what has just been said. It is this: Is there any innovation which solves the transportation problem (Problem 1), and at the same time provides a key to the solution of the industrial-environmental problem (Problem 2)?

The fundamental objective of this study is to develop a preliminary answer to this question through an assessment of the economics, energetics, and potential reduction in petroleum consumption of a combined coal-to-methanol conversion plus coal-in-methanol transportation system. The reasons for the focus upon methanol are given later in Section 1.4 below.

1.3 Limitations

Having said what this study is intended to accomplish, it is also well to note some of the things that it is not intended to do.

First, no original contribution to the technology or the literature of coal conversion is attempted, nor even any in-depth analysis of prior work in this area. This study sifts the work of others for possible keys to synergism between coal conversion and coal transportation.

Second, this study does not attempt to advance the fundamental scientific knowledge of coal or of coal slurries. While the study included a significant experimental program, that program was limited to the generation of engineering information for use in the systems analysis.

Third, this is not a study of technical feasibility. Rather, this study assumes technical feasibility and then asks,

For any given coal mining-conversion-transportation complex, does that system

(1) Save any energy?
(2) Make any money?
(3) Displace any petroleum?

If, and only if, the answer to at least one of these questions is strongly affirmative, then it is to be recommended that feasibility be assessed and the research, development, and demonstration (R, D & D) to bring it to fruition be undertaken.

1.4 Study Plan

At the beginning of this study, it was planned to proceed through the following steps.

(1) Select a reference pipeline system

(2) Select a reference coal

(3) In the laboratory, characterize the rheology of the reference coal in slurries formed with several coal-derived synthetic fuels.

(4) Employ existing mathematical models, presently operational on computers, to estimate the pressure drop for the range of pipe sizes, carrier liquids, and flow regimes of interest.

(5) Develop a pipeline cost model, by updating an earlier model.

(6) Calculate and compare the cost and energy consumption of the various systems.

For comparison purposes, it was necessary to recognize two basic system types. One system (designated type 1 for convenience) transports only boiler fuel. The reference system or comparison baseline for this type is the conventional coal-water slurry pipeline. The other basic system type (designated type 2 system) delivers both boiler fuel and engine fuel. The reference system for this type is a pair of pipelines; a conventional coal-water slurry pipeline, and a conventional petroleum products pipeline.

The fuels of interest are

(1) Alcohols

(2) Synthetic light fuels (gasoline, diesel, jet, and other fuels)

(3) Synthetic crude and the heavier fuels

(4) Liquified gases

As the study progressed, its focus became concentrated on methanol, for several reasons. The first reason is that it is easily separable from coal.

It was soon concluded that, for any system to be interesting, it is necessary to separate the coal from the liquid, so that the liquid can be sold on the premium fuel market. It does not make economic sense to degrade an expensive liquid fueld by contaminating it with coal unless the liquid can be restored to its premium value at the pipeline terminal. The options for consumption and marketing of the delivered fuel are discussed in Section 1.5.

It is necessary to immediately emphasize that this conclusion relates to long-distance pipelining of coal in coal-derived synthetic engine fuels. It does not relate to the introduction of coal into natural fuel which is currently being burned in existing stationary power plants. In the latter case, coal is being substituted for oil which is already being consumed in stationary markets. In the former case, coal-derived engine fuels are restored to their premium state after pipelining and then displace highly refined petroleum derivatives in mobile markets.

The synthetic light fuels may be readily separated thermally. However, nothing is known about their rheological behavior, and therefore their performance as carriers in a slurry are unknown. Also, the process of thermal separation will in effect be a fractional distillation with unknown problems. Therefore, the synthetic light fuels cannot be considered within the scope of this study.

Synthetic crude (syncrude) and other heavy oils may be produced by several coal liquefaction processes now under development, although none has reached a state of development adequate to provide the design basis for a full-scale plant. (A thought treated also under reason two below).) The syncrude may be slurried directly with the coal, or it may be refined to a fuel oil which is then slurried. The slurrification step is similar to the methanol slurrification step, though both capital and operating costs are expected to be higher because of the higher viscosity of the oil.

At the termination of the pipeline, the oil slurry must be burned directly as power plant fuel, because there is no known practical way to separate the coal and the oil. In a search of available literature of the last 30 to 60 years, very little in the way of R and D in this area was discovered. Moreover, there is no program now underway to develop that technology. Therefore syncrude and other heavy oils are not further considered.

The fourth fuel, liquefied gases, would be easily separable, apparently almost ideal in this respect. Also, there may well be some useful applications to heat-absorptive processes such as refrigeration, air conditioning or other cooling requirements in furnishing the heat required to return the liquid fuel to its gaseous state. However, the problems to be expected in cryogenic pipelines, and in particular the development of cost estimates, are beyond the scope of this study. Liquefied gases, therefore, could not be further considered in this study.

The second reason for the early focus upon methanol was that it is the only synthetic fuel for which the conversion techology presently exists.

The third reason was that when unanticipated difficulties were encountered in the program, the additional funding which was needed to treat them could not be obtained. It thus became necessary to narrow the focus in order to develop any conclusive results at all.

Difficulties were encountered in two areas. First, the experimental portion of the program yielded results that were inconsistent among themselves and also inconsistent with some earlier work. Second, the rheological computer model yielded outputs that in some instances did not appear to be reasonable. These two problem areas in turn produced two negative results. The first of these was that much time and money was consumed in iterating between these two problem areas before the nature of the difficulties was fully understood. The second negative result was that it became necessary to broaden the experimental program to include additional coals. This was done, but at great expense to the systems analysis, so that in the end the study addressed only the coal-methanol system. That is the system that is discussed in the remainder of this report.

1.5 Marketing Options

The marketability of a coal slurry is dependent upon the separability of the coal from the carrier liquid. In this respect, the water and oil carriers represent opposite ends of the spectrum. At one extreme, the unseparated water slurry is useless; the coal must be separated from the water before it can be burned. At the other extreme, the oil slurry cannot be separated and hence can only be directly burned as fuel. Between these extremes falls the methanol slurry, which can be burned whole, or its separated components can be burned separately and the degree of separation may be complete or only partial without compromising combustibility. Thus there is a broad spectrum of marketing options available at the methanol pipeline terminal.

1.5.1 Direct Combusion of Methanol Slurry

Many central station boilers which are presently burning petroleum oils are under pressure to convert to coal, which is an expensive process. Recognizing both the incentive and the problem, the ERDA, a DoE predecessor, initiated a rather extensive R, D, and D program in coal-oil slurry combustion to determine whether the slurry can be burned in the existing oil-fired boilers without major modification.

If the necessary combusion R, D, and D is successfully completed, a significant market for combustible slurries will be created. The coal-methanol slurry could very possibly penetrate this market. However, it appears unlikely that the movement to synthetic fuels would benefit.

The slurry could also be used directly as pipeline fuel. When burned in a gas turbine with a bottoming engine, the overall efficiency of the pumping process would then be approximately 50% greater than that of the electrically driven prime movers. The direct use of the slurry as prime mover fuel would render the slurry pipeline the most energy-efficient of all coal transportation modes insofar as the consumption of mechanical pumping energy is concerned. However, because of the significant R and D that would be required, this option was not further considered.

1.5.2 Combustion of Separated Methanol

The slurry may be separated into powdered coal and methanol, and the latter may provide fuel for several applications. As noted earlier, the degree of separation may be complete or only partial.

1.5.2.1 Powdered Coal

The combustion of the pulverized coal, after its separation from the methanol, in power plant boilers is an obviously viable approach. A variation is to slurry the coal in natural oils for combustion in oil burning plants, thereby reducing the petroleum demand of those plants. This, of course, is the option to which the DoE program is directed.

Another option is that the powdered coal, after separation from the slurry, may be used as feedstock for low-Btu gas plants in areas where water for the gasification is available, or for synthetic natural gas plants or ammonia plants.

1.5.2.2 Separated Methanol

The separated methanol constitutes a premium fuel, whose uses depend upon the degree of separation. Four levels of separation and their applications are discussed below.

(1) At the low end of the separation spectrum is the methanol from slurry which has only been subjected to the initial decantation. This methanol contains fine coal, along

with some of the very fine mineral matter and perhaps some of the volatiles which were originally present in the coal. It is not expected that these latter substances will significantly affect the combustion properties of the separated methanol. However, they may have adverse effects in terms of pollutant emission and thus limit the breadth of the available market.

(2) From the marketing point of view, the next level of separation is that at which a sufficient portion of the mineral and coal content has been removed from the methanol to permit its combustion in open-cycle gas turbine engines. It is important to recognize two points about this potential market penetration.

First, gas turbines presently burn only petroleum or natural gas fuels. The penetration of this market by coal-derived methanol thus represents a conversion from consumption of those precious fuel forms to coal. This step will represent a significant achievement.

Second, the gas turbine market is constituted of a larger number of smaller units than the central station boiler market. Moreover, these units are more widely distributed geographically, so that a distribution system will be needed, although it need not be either elaborate or extensive. Only a terminal with tankage and loading pumps, and a small fleet of tanker trucks, will be required.

(3) The next higher level of methanol separation is that at which sufficient mineral matter and potential pollutants have been removed to permit combustion in reciprocating engines. The market opportunity thereby created, ie, the automotive fuel market, is far beyond the capacity of any single pipeline to supply. Since the present purpose is only to identify that market and not to analyze it in depth, only a few descriptive comments are in order.

First, the market possibilities include displacement of gasoline, and possibly diesel, as engine fuel.

Second, as Nierenberg (1976) has observed in the foreword to Barr and Parker (1976) regarding introduction of methanol as a fuel, methanol is the only non-petroleum vehicular fuel which qualifies for both massive and early introduction. It is the United States' sole opportunity for achieving complete independence from OPEC in the twenty-first century. This is not to say that Nierenberg and other methanol proponents, eg, Reed and Lerner (1973), are totally correct in their belief that methanol is ready for immediate and massive introduction. As the opponents, eg, Freeman et al (1976) point out, there are practical obstacles to immediate introduction. But overcoming such obstacles is, or should be, precisely the mission of the DoE and its Division of Transportation Energy Conservation.

Third, if one looks ahead to the time in the twenty-first century when fossil fuels are so depleted that they must be displaced by other sources, there are only three pre-eminent candidates for liquid (vehicular) fuels: hydrogen, methanol and synthetic gasoline. Regardless of which one of these, or some other, ultimately prevails, a great deal of R and D must be performed in order to even make an intelligent decision. Thus, by undertaking now an R, D, and D program on coal-methanol slurries, the nation will simultaneously be developing some of the information needed for that longer-term decision.

(4) The highest level of slurry separation which is of interest is that in which the methanol is purified to the standard for industrial methanol and sold as such rather than as fuel. The spot price was about 40 to 45¢/gallon in early 1980, which may be compared with the approximately 80¢-$1 per gallon for gasoline (see Section 3.2.3.2 below). With an energy content (low heat value) of 18,900 Btu per pound (118,200 Btu per gallon) for gasoline and 8,570 Btu per pound (56,900 Btu per gallon) for methanol, the energy cost ratio of methanol is less than twenty percent above that of gasoline, so that it seems unlikely that the additional cost of purification to industrial grade would be justified.

1.5.3 Levels of Market Penetration

The preceding discussion has identified four levels of market penetration available to methanol after its separation from the coal, ie, boiler fuel, gas turbine fuel, recipricator fuel, and industrial alcohol, and has shown that these progressive levels of market penetration are associated with four progressive levels of separation of the methanol from the coal and its subsequent purification. The market opportunity associated with either of the first two of these levels (boiler fuel and turbine fuel) is sufficient to support several pipelines, each moving 25 million tons/year of coal or more. The potential market associated with the third level of separation, ie, the market for internal combustion engine fuel including the automotive fuel market is vast and far exceeds any of the others, or all of them combined.

1.6 Proprietary Processess

Mr. Leonard J. Keller is the inventor of U.S. Patent 4,045,092, "Fuel Composition and Method of Manufacture," which discusses a coal-methanol mixture that is given the registered proprietary trade name "Mathacoal." The abstract of this patent is shown in Figure 1.6-1. Methacoal is described as distinct from and superior to common slurries, in that it is a "stable suspensoid" which does not settle, ie, the coal does not separate from the methanol during indefinite storage. Table 1.6-1 lists some Keller patents relating to coal.

Mr. Keller is president of the Keller Corporation and the Methacoal Corporation, which are the companies through which he and his associates are promoting the commercialization of Methacoal. The Methacoal Corporation cooperated in many ways with Engineering Management and Development, Inc throughout this program; however, the results which are presented in this report do not relate to Methacoal. To avoid infringement, care was taken to insure that the mixtures that were experimentally characterized in this program were made by conventional grinding and mixing. These common slurries were further distinguishable from Methacoal in not being "critically sized and shaped" and

United States Patent [19]

Keller

[11] **4,045,092**

[45] **Aug. 30, 1977**

---

[54] **FUEL COMPOSITION AND METHOD OF MANUFACTURE**

[75] Inventor: **Leonard J. Keller, Dallas, Tex.**

[73] Assignee: **The Keller Corporation, Dallas, Tex.**

[21] Appl. No.: **615,697**

[22] Filed: **Sept. 22, 1975**

[51] **Int. Cl.**² **B65G 53/30; C10L 1/32**

[52] **U.S. Cl.** **302/66;** 137/13; 44/51

[58] **Field of Search** 44/51; 302/66; 137/13

[56] **References Cited**

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3,926,203	12/1975	Marsden, Jr. et al.	302/66

Primary Examiner—Daniel E. Wyman
Assistant Examiner—Mrs. Y. Harris-Smith
Attorney, Agent, or Firm—James C. Fails

[57] **ABSTRACT**

An economical fuel composition that can be readily transported and stored and that has good nonpollution properties characterized by a combustible, pseudo-thixotropic liquid-solid suspensoid including a critical proportion of coal particles having a critical settling velocity substantially uniformly dispersed in a solution of methyl fuel including methanol, water and other alcohol-soluble constituents of the coal. The critically sized and shaped coal particles are worked in the presence of the methyl fuel to become wet along all surfaces, such that the coal particles are maintained in suspension by even low intensity stirring in storage and do not separate out upon flow through a pipe line. The suspensoid has shear thinning rheological properties so as to be pumpable with a lower apparent viscosity than its at rest viscosity.

13 Claims, 2 Drawing Figures

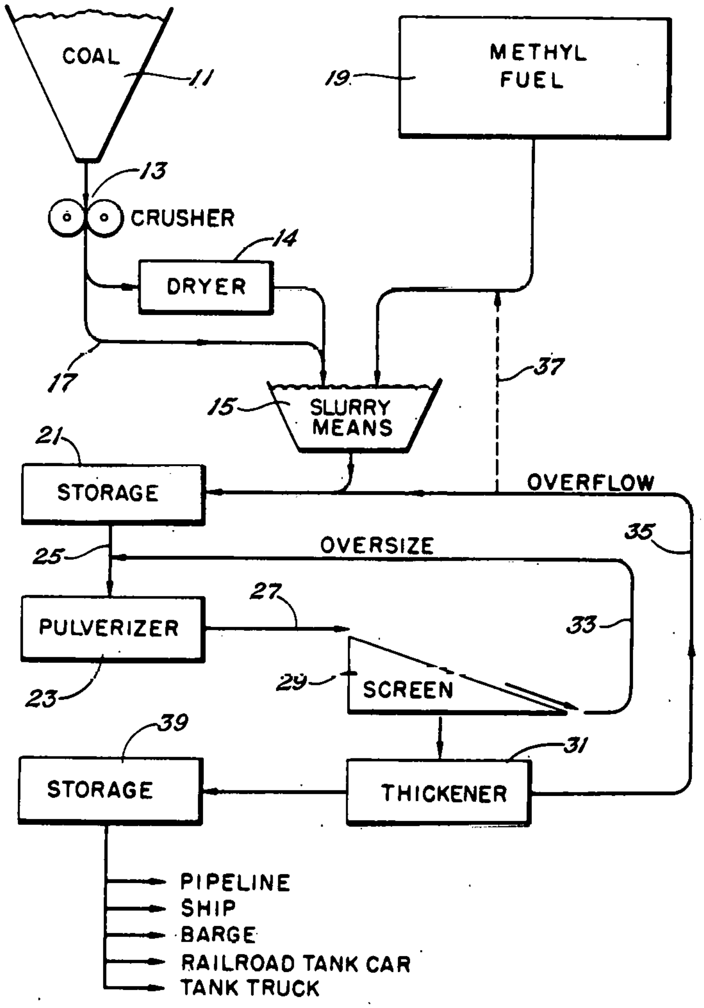

Figure 1.6-1 Abstract of Methacoal Patent

Table 1.6-1

Keller Patents and Disclosures Related to Coal

Number	Date	Title
3,968,999	7/13/76	Method of making available fuels from artic environments
4,030,893	6/21/77	A method of preparing low-sulfur, low-ash fuel
4,045,092	8/30/77	Fuel composition and method of manufacture
4,089,657	5/16/78	Stabilized suspension of carbon in hydrocarbon fuel and method of preparation
4,097,217	6/27/78	Method of converting combustion from hydrocarbonaceous fuel to carbonaceous fuel
4,146,366	3/27/79	Method of removing gangue materials from coal
4,192,651	3/11/80	Method of Producing Pulverulent Carbonaceous Fuel

in that they were not storable; upon standing for a time, the coal settled into a hard plug.

Thus, while strictly speaking the conclusions of this study apply only to common slurries, virtually all of the favorable conclusions can also be drawn with respect to Methacoal, except that they can be stated even more favorably. In other words, when the claimed superior properties of Methacoal have been verified, it can be assumed in general that whatever can be done with the common slurries can be done better with Methacoal. There is one exception to this rule, in that the superior stability of Methacoal can be expected to render it less readily separable by mechanical means than would be the case with a common slurry. However, as the separation plant design turns out, most of the separation is done thermally, which is independent of the mechanical stability of the suspension. Even if the mechanical separative work were doubled in the case of Methacoal, the effect upon the system economics would be small and would tend to be offset by the advantages of the Methacoal's stability.

2.0 Methanol as a Slurry Carrier Liquid

2.1 Superiorities of Methanol as Carrier Liquid

At the outset, it was known from prior work (Banks and Horton, 1977) that methanol possesses a number of attractions, at least in principle, as a slurry carrier liquid for long-distance coal transportation. Therefore, although other candidate liquids had been identified which deserved consideration, first attention was addressed to methanol systems. Methanol deserves this primary emphasis by virtue of several attractions.

First is the ready separability of methanol from coal, at the pipeline terminal, a characteristic which makes it superior to both water and the oils as a carrier.

Second is the ability of methanol to accept bone-dry coal at the head of the pipeline and deliver the coal in the same condition at the terminal. This characteristic also makes it superior to both water and oil as a carrier. The superiority to oil results from the alcohol-water intersolubility, which does not exist between water and oils.

Third is the potential of methanol to permit most of the water requirement for the conversion-transportation complex to be supplied by the native bed moisture of the coal, thus reducing the amount of the scarce western water supply that must be consumed. To convert coal to the hydrocarbon fuels requires a much greater water-to-coal ratio at the conversion plant intake than does methanol conversion. Thus, this characteristic makes methanol superior to both water and to the hydrocarbon fuels as a carrier liquid.

Fourth is the simple fact that the transportation load in the dry-coal methanol pipeline,as compared to other forms of coal transportation, is much less. If, for example, the as-mined moisture is 30 percent, then the dry-coal pipeline must transport only 1400 pounds, whereas the other transportation modes must transport a full ton.

Fifth is the fact that drying the coal in conjunction with the coal-to-methanol conversion process permits conversion of low-grade heat to high-grade heat, in apparent defiance of the second law of thermodynamics. The reason is that the moisture must be thermally evaporated from the coal in the power plant boiler if it has not been removed earlier. While the sensible portion of this heat can be partially recovered in the steam cycle, the latent portion cannot even be made available to the steam cycle if there is any sulfur or other corrosive element in the coal which prevents cooling the stack gas sufficiently to condense the water vapor. Therefore, when the coal is dried in the boiler, more than 90 percent of the energy to dry the coal is unrecoverable in the steam cycle. This penalty is about 300 to 400 BTU per pound, or 3½ to 5 percent of the heat content of the coal itself, for a typical western coal. If the drying were done at the mine with coal which was burned only for that purpose, the penalty would be the same as in the case when the drying is done in the power plant boiler, and there would be no net gain for the total conversion-transportation-power system. But when the coal is slurried in a coal-derivative fuel which is synthesized at the mine-mouth, the drying process can use that heat which would otherwise be wasted from the fuel synthesis plant.

The question may properly be asked whether this energy saving should be credited to the efficiency of the power plant or to the efficiency of the coal conversion plant. The answer is clear: to neither, because the saving cannot be achieved by either of the two acting alone, nor by the two acting together. The saving can only be realized with the methanol slurry pipeline, ie, this saving is only possible when the transportation system is a slurry pipeline in which the carrier liquid is a synthetic fuel derived from coal. Stated differently, the transportation system receives the credit because without the transportation system there is no credit.

It is further interesting to observe that the effect of this is the conversion of low-grade heat into high-grade heat, which, as has been noted, is in apparent defiance of the second law of thermodynamics. Low-grade heat (at a few hundred degrees F) which would otherwise be wasted is taken from the coal liquefaction plant and re-appears a thousand miles away in the power plant boiler at 3000 F. This energy has not only been upgraded but has been transported free.

These attractions make methanol the superior choice for a carrier liquid. They are recapitulated in Table 2.1-1.

2.2 Inferiority of Methanol as Carrier Liquid

Contrary to indications from earlier work (Banks and Horton, 1977), this study finds that pressure drops in coal-methanol pipelines are generally higher than in coal-water systems. However, the advantages of methanol described above more than offset this disadvantage, so that the methanol system is superior to the water system, in terms of both economics and energetics.

Table 2.1-1
Attractions of Methanol as Slurry Carrier Liquid

1. Ready separability from the coal
2. Ability to accept and deliver virtually bone-dry coal
3. Potential reduction/elimination of the system water requirement
4. Reduction of the transportation load
5. Increase of total system thermal efficiency

3.0 The System Model

3.1 The Reference System

As a prelude to discussion of the system model, it is first necessary to identify the system which is being modeled. For this analysis, the reference pipeline system which is summarized in Table 3.1-1 was selected for purposes of comparison and analysis. It accepts typical western sub-bituminous coal and conveys that coal across the relatively gentle terrain of the central great plains to a distant market to the east and/or south. Such markets are usually about 5,000 feet lower in elevation than the coal mine, and the benefit of this significant free fall is recognized in the model. This reference system is similar to the line being promoted by Energy Transportation Systems, Inc. (ETSI) and to several other currently proposed systems.

Studies by several authors have shown that the pipeline is only competitive with the railroad at relatively long distances, approximately a thousand miles, and at large capacities, 20-25 milliontons/year. Accordingly, a throughput of 25 million tons of as-mined coal per year (TAM/yr), equal to 2,000 tons of dry solids per hour (TDS/hr) is used.

The reference methanolization plant is taken to be of the appropriate size to supply the amount of methanol required to carry the 2000 TDS/hr. Thus, the plant output might be as large as 3000 Tons/hr for a slurry concentration of 40% by weight or as low as 1333 Tons/hr for a concentration of 60%. It will be seen later that most cases of interest involve concentrations above the middle of this range, because of the desirability of conserving energy and water. This latter factor is of great importance here, since the western coalfields are in arid regions. This question of conservation of water is discussed further in Section 6.0 below.

Table 3.1-1

Reference Pipeline System

Length	1000 Miles
Free Fall	5000 Feet
Throughput	2000 TDS(1)/hour = 25,000,000 TAM(2)/year

(1) Tons Dry Solids

(2) Tons As-mined

3.2 The Subsystem Models

The complete system model consists of a set of models (submodels), as shown in Figure 3.2-1. In the rheological laboratory, slurries are prepared of a given coal and liquid, and viscometer measurements are made for series of concentrations. The raw laboratory data are processed by the rheological model, which calculates the pressure drop for a specified range of pipe diameters and flow speeds.

The output of the rheological model is input to the pipeline cost model. A set of cases whose speed and Reynolds Numbers are acceptable is selected, and the pipeline cost model calculates the construction and operation costs of the pipeline. In the process, the energy consumption is calculated and printed as a separate output. The pipeline cost model output is input to the tariff model, which calculates the tariff in dollars per million BTU transported per thousand miles.

The synergism model takes as its starting point the methanol plant model which was developed by Badger Plants, Inc. (Badger 1978) (See Section 3.3 below). It also accepts output of the pipeline cost model. The Badger methanol plant is modified in several respects in order to marry it with the pipeline preparation (slurrification) plant. The cost of the methanol from the plant is the output. This model is not computerized; it is a methodology rather than an algorithm. Since it involves design modifications, it is not amenable to computerization.

Each of these models is briefly discussed in the sections to follow.

3.2.1 The Rheological Model

The rheological model used in this study is that which was developed by Dr. Robert Faddick of the Colorado School of Mines. The model accepts as input the raw data generated in the rheological laboratory by the rotational viscometer, ie,

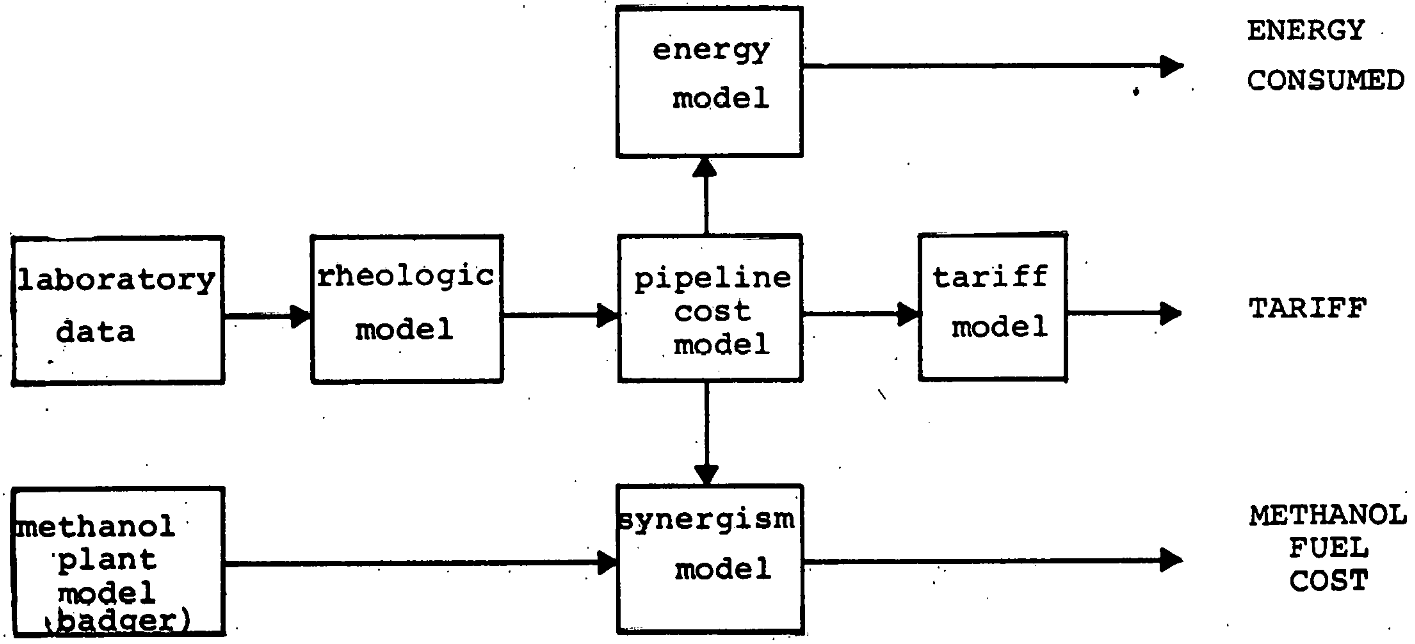
energy model
ENERGY CONSUMED
laboratory data
rheologic model
pipeline cost model
tariff model
TARIFF
methanol plant model (badger)
synergism model
METHANOL FUEL COST

Figure 3.2-1

angular speed of the rotating the element and the angular offset of the stationary element cup against the torque of its retaining spring, along with the quantities which characterize the configuration of the viscometer. Alternatively, measurements of wall shear stress and shear strain rate obtained by other means can be accepted. Measurements are made over a range of concentrations, usually three to five. With the Brookfield viscometer which is in the laboratory at Colorado School of Mines, a range of about ten in shear strain rate is covered.

In the Faddick model, the data are fitted to a yield-pseudoplastic curve, an approach which requires caution to ensure that the shear rates in the pipe do not exceed those in the laboratory instruments. However, in the cases presented here, this was not the case, ie, the shear rates in the pipe fall within range of the laboratory measurements, and use of the pseudoplastic model is justified by the fact that, over the range of shear rates tasted, it gave the best fit to the data. This of course is to be expected, since the yield-pseudoplastic is a three-parameter model, while the other two common models (Power Law and Bingham Plastic) are only two-parameter models.

Next, for a specified pipe diameter and speed of flow, the model calculates the generalized Reynolds number (Metzner and Reed, 1955) and other dimensionless characterizations as needed, determines the flow regime, and calculates pressure drop in the line. The equations and correlations used are taken from the literature. An excellent summary is given in Chapter 5 of Govier and Aziz (1972). There are more than two dozen options in the model, at which selections between alternate correlations are chosen according to criteria which generally respect the opinions of the original experimenter who established the correlation.

This model has some advantages and disadvantages. Its advantages include the fact that it is comprehensive and that it has been validated for a fair number of cases. Its disadvantages include the fact that it has not been validated for the coals which were studied in this program. It has been validated for other mineral slurries in pipes up to 36 inches diameter. Also, the model has not been published and so has not had the benefit of peer review and validation. However, there is nothing else available in the public domain which approaches this model in scope and in extent of validations with other slurries.

3.2.2 The Pipeline Cost Model

The pipeline cost model was first developed by Pipe Line Technologists, Inc. (PLT) in 1976, under an earlier DoE contract. For this study, the earlier model was updated, including escalation to 1979 dollars. As was noted earlier, the model consists of four submodels: line, pump stations, preparation plant and separation plant. They are summarized in Table 3.2.2-1 and are discussed below.

3.2.2.1 The Line Cost Model

Three pipe diameters were selected, 24", 30" and 40", which would bracket the range of interest, and line costs (without pump stations) were estimated. It was recognized that the intermediate sizes, 32", 34", etc., could not be reliably estimated by simple interpolation between the three calculated values, or even by a sophisticated interpolation for that matter. The three baseline sizes were chosen because they are in a sense standard. For example, while there is nothing to distinguish the mill price of 34" pipe from that of 30" in terms of cost as it relates primarily to weight, as well as to other variables such as diameter and thickness, there are important differences in construction methods and construction equipment such as mandrels. The result is that a fair amount of construction-site improvisation is often necessary for the non-standard sizes.

Table 3.2.2-1

Pipeline Cost Model
(1979 $)

Pipeline Proper		
14 Inch	-	$389,600/Mile
30 Inch	-	$513,000/Mile
40 Inch	-	$830,200/Mile
Pump Stations		
5 Pumps	-	$3,863,200/Sta
10 Pumps	-	$7,340,300/Sta
15 Pumps	-	$10,970,300/Sta
Preparation Plant		$93,800,000 (1)
Separation Plant	-	$125,788,000 (1)

(1) Varies with concentration

For this study, it was decided to disregard these subtleties and employ a smoothed cost curve through the three basic points. The rationale for this approach is that for this study it is much more important to properly discern the cost trends than attempt to estimate absolute values with precision.

3.2.2.2 The Pump Station Cost Model

The pump stations were designed around the Wilson-Snyder pump, which is the pump used in Black Mesa pipeline. Quotations were obtained from the Wilson-Snyder division of U.S. Steel Corporation, and stations were costed for 5, 10, and 15 pumps, from which a smoothed cost curve was derived.

The model takes the input characteristics of the slurry, along with the diameter and allowable pressure in the pipe, and calculates the required number of pump stations and the number of pumps per station. A spare pump is added at each station and the cost of the station is then taken from the cost curve.

3.2.2.3 The Separation Plant Cost Model

The separation plant was first designed to separate the coal from the methanol thermally, yielding 99.4% methanol recovery with five flash stages. The energy penalty is 3.1% of the slurry content, which can however be reduced to 0.4% when the hot (freshly separated) coal is fed immediately to the power plant boiler, as would ordinarly be the case, since the separation plant would be located next to the power plant. This economy cannot be achieved 100% of the time, however, because there are times when some of the arriving coal is being stockpiled. At those times, the heat in the stockpiled coal will be lost. Further study showed that significant economies could be achieved by initial centrifugation followed by flash evaporation, and that design was adopted. The estimated cost of the separation plant is $125,788,000 for a slurry with solids concentration of 60% by weight. At other concentrations, this figure is scaled according the six-tenths-power law.

3.2.2.4 The Preparation Plant Cost Model

The preparation plant was designed in two stages. First the basic wet-rodmilling slurry preparation process of the Black Mesa Pipeline was modified to include hoods for retension and recovery of methanol vapors. The modification, though simple in concept, involves significant expense. The requirement is not simply the economic one of the preventing loss of valuable vapor, but also one of protecting against serious hazard. The basic design approach is to provide good ventilation and extensive automation so that human operators are near the mills during operation only for occasional maintenance, for which they are adequately protected.

The second stage of preparation plant design is its marriage with the methanolization plant. This requires that hot methanol vapors from the methanolization plant be taken from the process stream at the intake to the methanol dryers, conducted to the slurrification plant, passed through the incoming coal to remove its moisture and returned to the methanol plant, where it enters a second battery of dryers and continues on through the process-stream path. The estimated cost is $93,800,000.

3.2.3 The Methanolization Plant Cost Model

The basis of the methanolization plant model is the design study of a coal methanoliztion plant which was done by Badger Plants, Inc. (Badger 1978), and upon two reviews of their results (Salmon et al 1979 and Kermode et al 1980). For the purpose of this study, it was necessary to make adjustments in the physical design of the Badger plant and in the calculation of the price of methanol.

3.2.3.1 Design Changes and Capital Cost Adjustments

The two adjustments which involve changes in the capital cost result from changes in the design of the plant so that it forms a proper mate for the pipeline system. One such design change has been described in the preceding section, ie, use of the raw methanol process stream to dry the incoming coal, and thereby conserving coal and using the natural moisture in the coal to satisfy a part or all of the plant water requirement. This change adds $382 million to plant cost.

The second adjustment involving design change is the change from wet cooling towers to the dry type, thereby eliminating by far the largest element of the plant water requirement. The Badger design employs the wet type because its northern Alabama site possessed plentiful water and the wet towers are cheaper. However, the Badger report points out that for a western site the dry type would be preferred and that the plant design could be modified accordingly. This change adds $208 million to the plant cost.

The Badger cost estimate was $3105 million. A validation study of this estimate was performed by the Army Corps of Engineers, resulting in a figure of $3489 million. Both figures are in the late 1977 dollars. For conservatism the higher figure was used for this analysis, so that the adjusted baseline capital cost becomes $4079 million.

3.2.3.2 Methanol Price Adjustments

The Badger study included sensitivity calculations and curves, which were used in this analysis to adjust the price of methanol to the conditions of this study.

An important element in the economics is plant life. The fundamental limitation upon the life of a slurry pipeline is the corrosion allowance. The pipeline was designed for a thirty-year life, while in the Badger study the methanol plant life was taken as twenty years. Accordingly, adjustments must be made in the methanol plant depreciation, bond life, and maintenance set-aside to adjust to a thirty-year life. This latter element was calculated by assuming that maintenance cost during the ten-year life extension would be double the value used by Badger in the twenty-year calculations. When a twenty-year sinking fund at 12% (the internal rate of return for all the calculations) is established, the price of methanol over the thirty-year plant life is increased by 0.09¢/gallon.

For this analysis, the interest rate was increased to 15% to better reflect conditions in 1980, as contrasted with the 1977 conditions (9% interest) used in the Badger study.

The Badger study used 25 $/ton for the cost of coal, a figure which was fixed by the contract. For this analysis several mines in the Powder River basin of Wyoming were asked for quotations for 25 million tons/year on a thirty-year contract. The consensus was that a buyer of 25 million tons per year on a long-term contract would obtain a price well below 6 $/ton. For conservatism, 8 $/ton was used in the analysis.

The effect of scale upon the price of the product is recognized by adjusting the capital cost in the ratio of plant capacities, taken to the power 0.73, which is the exponent suggested for this purpose by Kermode (1979). The Badger sensitivity ratios are then used to correct for the increased cost per gallon from the smaller plant.

The Badger study concluded that the price of methanol at the plant gate would be 33.6¢/gal in 1987, the first full year of full production, based upon an annual inflation rate of 6% during the ten years from 1977. Deflating that price back ten years at an annual rate of six percent yields a price of 18.8¢/gal in 1977, which is the base price that is used in the Badger presentations. However, the price calculated in this way is not in terms of truly constant 1977 dollars. The dollars which flow into the project in 1986 for example, are inflated only once to bring them up to 1987, but then they are deflated ten times to bring them back to 1977. Thus, the contribution of these dollars to the 18.8¢/gal price is too low by a factor of $(1.06)^{-9}$ = 0.592, or 41 percent,

Salmon et al (1979) and Kermode et al (1980) have recalculated the price of methanol from the Badger plant in truly constant 1977 dollars, arriving at 24.5¢/gal and 24.2¢/gal respectively. This latter value is obtained by logarithmic interpolation of Table IV in the reference. For this analysis, the higher of these two figures was taken as the baseline price of methanol at the plant gate in constant 1977 dollars. This baseline figure is then adjusted for inflation by a factor of 1.225, which turns out to be almost identical to the inflation effect shown by Kermode et al in their Table IV. Then, using the Badger sensitivity curves to allow for the factors listed in Table 3.2.3.2-1, the coefficients and adjustment amounts shown there were derived. The final adjusted price is seen to be 26.6 ¢/gallon.

On the basis of BTU content, this is equivalent to about 60¢/gal for gasoline, without taking credit for the improvement in engine efficiency which is realized with methanol as compared to gasoline. For comparison, spot prices for unleaded gasoline at the end of February 1980 were quoted in the Oil and Gas Journal as follows:

New York	81.00-98.50 ¢/gal
Los Angeles	91.25-101.00¢/gal
Chicago	91.50-96.00 ¢/gal

It must, of course, be recognized that spot prices do not reflect contract prices, but it seems clear that the technology is at hand to produce engine fuel from western coal at prices that are competitive. The remaining major unknowns are:

(1) How to obtain the large quantity of water that is needed for the coal-to-methanol conversion process, and

(2) How to reach the market.

Table 3.2.3.2-1

Adjustments to Methanol Price

Adjustment Factor	Baseline Value	Adjusted Value	Adjustment Coeff/Amount
Capital Cost, 10^6\$	3489	4079	1.056
Scale, 10^6 T/yr	19.4	15.6	1.0792
Price of coal, \$/Ton	25	8	-7.2 ¢/gal
Interest rate, %	9	15	1.102
Inflation from	Nov 77	to March 80	1.225
Plant life, yrs	20	30	0.915
Bond life, yrs	20	30	0.983
Maintenance, 10^6 \$/yr	11.3	16.95	+0.09¢/gal

$$\begin{aligned} \text{Adjusted price} &= (24.5 \times 1.056 \times 1.102 \times 1.225 \times 1.0792 \times \\ &\quad 0.915 \times 0.983) - 7.2 + 0.1 \\ &= 26.8\ \text{¢/gal} \end{aligned}$$

The coal-methanol slurry Pipeline provides a large part of the answer to each of these questions, provided of course that the pipeline itself proves to be economic. The economics will be treated later, in Section 4.0.

3.3 The Tariff Model

The inputs to the tariff model are the outputs of the rheological model and of the pipeline cost model along with the same system specification that was input to those models. The principal output of the tariff model is, of course, the tariff, calculated in dollars per million BTU of net heat value (lower heating value) for a thousand-mile distance. In the course of this calculation, the pumping energy consumed is calculated and printed. An annual capital charge of twenty percent of total initial investment is used. The cost of electric power is taken as 3¢/kwhr. Operations and maintenance expenses are taken as 3% of the initial investment.

3.4 The Synergism Model

The concept of pipelining coal as a slurry in synthetic fuels immediately raises the question of the relationship between the two basic processes of coal liquefaction and coal transportation. It may not be obvious to all readers that the cost of a liquefaction plant cannot be justified solely as part of a transportation system, but earlier studies (Banks and Davidson, 1978) have shown that it quickly becomes apparent upon analysis. For example, the cost of a thousand-mile pipeline to convey 25 million tons/year of coal is of the order of a billion dollars. The cost of a liquefaction plant to provide the liquid synfuel to pipeline the coal is about five times as much. Thus, if the liquefaction process were regarded as only a part of the transportation process, ie, if the slurry were to be sold as boiler fuel just as though it were coal, then the capital cost of the system would be increased by a factor of about six. Although there are offsetting benefits from the use of non-water carrier liquids, they do not approach the magnitude of this large capital cost penalty.

It follows that the total system will only be economically viable if the liquefaction subsystem and the transportation subsystem are each economically viable in their own right. That is, each system must compete successfully in its own market, independently of the other.

The next question, then, is whether there is any fundamental interaction between the two processes such that the benefits of the whole system are greater than the sum of the benefits of the two separate systems when operated independently of each other. That is, given for example a coal-to-methanol plant that undersells competing fuels, is there any further advantage in transporting the product to market as a slurry carrier liquid, as opposed to simply pipelining the neat methanol? The existence of such an advantage would constitute what is meant by the term synergism in this discussion.

In addressing this question of the possible existence of synergism, several rather obvious observations can be made at the outset. First, to exploit the potential superiorities of methanol as the carrier liquid which were discussed in Section 2.1 above, it is necessary to dry the coal, using otherwise wasted heat from the methanolization plant and to use the native water from the coal in the methanolization process. This means that the pipeline slurrification facility must be located immediately adjacent to, and may be viewed as a part of, the methanolization plant. This marriage of the two systems has been recognized in the models of the methanolization plant and of the pipeline, as has been described above.

Second, having also concluded that the concept is viable only if the output of the methanol plant is strongly competitive in the engine fuel market, the question arises as to the effect upon the methanol fuel properties of the passage through the pipeline. This means that the deslurrification facility at the pipeline terminal must return the methanol to acceptable fuel-grade quality. As discussed in Section 3.2.2.3, it was necessary to include this capability in the separation plant model.

Thus, if synergism exists, it must involve a marriage of the methanolization plant with the slurrification plant at the pipeline, and it must impose a purification penalty upon the pipeline terminal facilities. Between the two ends, the design of the pipeline proper and of its pumping stations are unaffected by the source of the methanol.

4.0 System Economics

4.1 Analytical Procedures

The point of departure for discussion of the analysis will be the laboratory data. The analytical procedure will be described, using an example set of calculations for the particular coal upon which more experimentation was done than upon any other single type.

By definition, a fluid is a substance which cannot resist shear stress and remain at rest. The slurries considered in this program, when allowed to come to rest, do not meet this criterion. Like fresh concrete made with very little water, they initially resist shear stress without flowing. However, when the applied shear stress exceeds some value, called the yield stress, the slurry begins to flow. As it flows, it undergoes shear strain and the time rate at which it is being strained during the flow is referred to as the strain rate. In simple liquids such as water, which are called Newtonian fluids, the stress and the strain rate are linearly proportional to each other, but in a slurry (Non-Newtonian fluid) they have a more complicated relationship. The nature of this relationship is called the rheological behavior of the substance and the study of such behavior is a branch of knowledge called rheology. One of the ways in which the relationship is often represented (mathematically modeled) is:

$$T - T_Y = KG^N$$

or, in computer language

```
TAU - TAUY = KY*GDOT**NYP
```

where

T = TAU = Shear Stress
T_Y = TAUY = Yield Stress
K = KYP = Flow Consistency Index
G = GDOT = Shear Strain Rate
N = NYP = Flow Behavior Index

This relationship is called the yield-pseudoplastic flow model. It is the form to which the experimental data was fitted, as was discussed in Section 3.2.1 above.

The first step in the analysis, then is to fit the laboratory data to this flow model. Figure 4.1-1A presents an example output of such a calculation. This calculation is the first part of the rheological model that was described in Section 3.2.1 above. The first column of numbers, headed RPM, gives the angular speed of the rotating element of the viscometer. The second column, headed DIAL, gives the dial reading of the viscometer. This reading gives the spring force necessary to hold the stationary element of the viscometer against the shearing stress which is transmitted to it through the fluid from the rotating element. The third column, headed STRESS, is the shear stress, in dynes /cm^2, which is calculated from those two readings. The other columns are strain rates and related quantities which are calculated by several of the various formulae which have been developed for the viscometer. Two of these yield-pseudoplastic parameters, KYP and NYP, are printed in the last line. The other parameter, the yield stress (TAUY) is printed directly above the column headed OMEGA.

The information from Figure 4.1-1A is then used to calculate the pressure drop that would be expected if the fluid were flowing through a pipe. Example results are shown in Figures 4.1-1 through 4.1-5. Sheet A of each figure displays the information just discussed, sheet B presents properties, and sheet C presents the results of the calculations. At the top of sheet C is a notation that throughput is the same for all cases at 2000 tons of dry solids (TDS) per hour. The first column on sheet C is the inside pipe diameter in inches. The diameters of interest are listed below.

```
FOUR DATA POINTS
SLURRY:  EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 53%  1-22-79
  I RC(CM) RS(CM)  RAT(I) LN(RAT(I)) CW(%) CV(%)
  2 4.0000 0.5128  7.8003   2.0542   53.3  37.1

TEMP(C)    S      SL   TAUK(I)    SM  YIELD(DYNES/CM/CM)
 24.6   1.527 0.789  0.1407 1.063        52.52

RPM  DIAL    STRESS     BROGAM    ALVGAM    OMEGA  LN(OMEGA) LN(STRESS)
 10. 18.2    129.50      6.73      6.73    1.0472   0.0461     4.8636
 20. 25.2    179.25     13.46     13.46    2.0944   0.7393     5.1888
 50. 32.9    233.69     33.65     33.65    5.2360   1.6556     5.4540
100. 37.6    267.24     67.30     67.30   10.4720   2.3487     5.5881

K = 75.34  N = 0.311  KYP = 36.58  NYP = 0.438  RYP = 0.9769


LAST THREE DATA POINTS
SLURRY:  EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 53%  1-22-79
  I RC(CM) RS(CM)  RAT(I) LN(RAT(I)) CW(%) CV(%)
  2 4.0000 0.5128  7.8003   2.0542   53.3  37.1

TEMP(C)    S      SL   TAUK(I)    SM  YIELD(DYNES/CM/CM)
 24.6   1.527 0.789  0.1407 1.063        52.52

RPM  DIAL    STRESS     BROGAM    ALVGAM    OMEGA  LN(OMEGA) LN(STRESS)
 10. 18.2    129.50      6.73      6.73    1.0472   0.0461     4.8636
 20. 25.2    179.25     13.46     13.46    2.0944   0.7393     5.1888
 50. 32.9    233.69     33.65     33.65    5.2360   1.6556     5.4540
100. 37.6    267.24     67.30     67.30   10.4720   2.3487     5.5881

K = 75.34  N = 0.311  KYP = 54.50  NYP = 0.331  RYP = 0.9925
```

Figure 4.1-1A Rheological Data and Calculations

53.3% CW (Laboratory Data)

```
                                        SYSTEM PROPERTIES

MINERAL --- EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 53%  1-22-79
AVERAGE SOLID          SPECIFIC GRAVITY (S ) --- 1.527
LIQUID PHASE           SPECIFIC GRAVITY (SL) --- 0.789
SLURRY                 SPECIFIC GRAVITY (SM) --- 1.063
SLURRY CONCENTRATION BY WEIGHT               --- 0.533
SLURRY CONCENTRATION BY VOLUME               --- 0.371
ABSOLUTE PIPEWALL ROUGHNESS (E), FEET        --- 0.00015000
GRAVITATIONAL ACCELERATION                   --- 32.1573 FEET/SEC/SEC
SLURRY TEMPERATURE (TEMP), DEGREES CELSIUS   --- 24.6
PIPE TYPE                                    ---
PIPE SLOPE                                   --- HORIZONTAL


    MESH       PERCENT     SUM %

    1/PAN        0.00         0.0
 TOTAL =    0.0

WEIGHTED MEAN DIAMETER =0.0000E+00
COEFFICIENT OF VARIATION =    0.00000      SETTLING REGIME =
DRAG COEFF OF WEIGHTED MEAN DIA =   0.000  VISCOSITY FACTOR =  0.8
REYNOLDS NUMBER OF SETTLING =    0.00
ROSIN - RAMMLER EQUATION:  R = 100 * EXP(-(D/  0.000000) **  0.000000)
SLOPE =  0.000000     INTERCEPT B =  0.00000000000  MILLIMETERS
CORRELATION COEFF. = 0.000000    D50 =  0.00 MILLIMETERS

KYP =  36.58     NYP =  0.438     TAUY =   52.516
SM THEORY
```

Figure 4.1-1B Rheological Data and Calculations

53.3% CW (System Properties)

```
  DIA    RELRUF   VCL    VCT    VLCTY    SHRATE   REYNOLDS   FM       PSI      KILW-HR
  IN.     E/DIA   FPS    FPS     FPS      1/SEC    NUMBER    MIX       MI      TON-MI

THROUGHPUT =2000. SHORT  TONS/HR

23.124 0.00008  6.91 10.44  10.80       59.23    4764.   .0380   87.019    0.2670
23.750 0.00008  6.86 10.36  10.24       54.67    4434.   .0388   77.732    0.2390
24.125 0.00007  6.83 10.32   9.92       52.16    4252.   .0393   72.760    0.2238
24.625 0.00007  6.79 10.26   9.53       49.05    4024.   .0399   66.734    0.2052
25.124 0.00007  6.75 10.20   9.15       46.18    3813.   .0406   61.331    0.1886
25.500 0.00007  6.73 10.16   8.88       44.17    3664.   .0410   57.618    0.1772
26.000 0.00007  6.69 10.10   8.54       41.67    3477.   .0417   53.107    0.1639
27.062 0.00007  6.61  9.99   7.89       36.96    3123.   .0431   44.906    0.1381
27.500 0.00007  6.58  9.95   7.64       35.22    2991.   .0436   41.990    0.1291
28.000 0.00006  6.55  9.90   7.37       33.36    2850.   .0443   38.946    0.1198
28.500 0.00006  6.52  9.85   7.11       31.64    2717.   .0449   36.174    0.1112
29.000 0.00006  6.49  9.80   6.87       30.03    2593.   .0456   33.646    0.1035
29.500 0.00006  6.46  9.75   6.64       28.53    2477.   .0463   31.336    0.0964
30.000 0.00006  6.43  9.71   6.42       27.13    2096.   .0000   26.841    0.0825
30.500 0.00006  6.40  9.66   6.21       25.81    2005.   .0000   26.008    0.0800
30.876 0.00006  6.37  9.63   6.06       24.88    1940.   .0000   25.387    0.0781
31.500 0.00006  6.34  9.57   5.82       23.43    1838.   .0000   24.447    0.0752
32.000 0.00006  6.31  9.53   5.64       22.35    1762.   .0000   23.721    0.0730
32.500 0.00006  6.28  9.49   5.47       21.34    1690.   .0000   23.002    0.0707
32.876 0.00005  6.26  9.46   5.34       20.61    1639.   .0000   22.514    0.0692
33.500 0.00005  6.23  9.41   5.15       19.48    1558.   .0000   21.730    0.0668
34.000 0.00005  6.20  9.37   5.00       18.63    1497.   .0000   21.134    0.0650
34.375 0.00005  6.19  9.34   4.89       18.03    1454.   .0000   20.697    0.0636
34.750 0.00005  6.17  9.31   4.78       17.45    1412.   .0000   20.276    0.0624
35.125 0.00005  6.15  9.29   4.68       16.90    1372.   .0000   19.882    0.0611
36.000 0.00005  6.11  9.22   4.46       15.70    1284.   .0000   18.986    0.0584
36.375 0.00005  6.09  9.20   4.37       15.22    1249.   .0000   18.609    0.0572
36.750 0.00005  6.07  9.17   4.28       14.76    1215.   .0000   18.254    0.0561
37.375 0.00005  6.04  9.13   4.13       14.03    1161.   .0000   17.695    0.0544
38.000 0.00005  6.01  9.08   4.00       13.35    1111.   .0000   17.157    0.0528
38.625 0.00005  5.99  9.04   3.87       12.71    1063.   .0000   16.637    0.0512
38.750 0.00005  5.98  9.03   3.85       12.59    1054.   .0000   16.532    0.0508
39.625 0.00005  5.94  8.98   3.68       11.77     993.   .0000   15.875    0.0488
40.000 0.00004  5.93  8.95   3.61       11.44     968.   .0000   15.604    0.0480
40.375 0.00004  5.91  8.93   3.54       11.13     944.   .0000   15.346    0.0472
40.624 0.00004  5.90  8.92   3.50       10.92     928.   .0000   15.181    0.0463
```

Figure 4.1-1C Rheological Data and Calculations

53.3% CW (Calculations)

```
FOUR DATA POINTS
SLURRY:  EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 51%  1-22-79
  I RC(CM) RS(CM)  RAT(I) LN(RAT(I)) CW(%) CV(%)
  2 4.0000 0.5128  7.8003   2.0542   50.7  34.7

TEMP(C)    S      SL  TAUK(I)    SM  YIELD(DYNES/CM/CM)
 25.4    1.527 0.789  0.1407 1.045         19.38

RPM  DIAL    STRESS     BROGAM    ALVGAM    OMEGA  LN(OMEGA) LN(STRESS)
 10. 11.6     82.30      6.36      6.36    1.0472   0.0461     4.4104
 20. 15.8    112.15     12.72     12.72    2.0944   0.7393     4.7199
 50. 20.7    147.33     31.81     31.81    5.2360   1.6556     4.9927
100. 25.0    177.68     63.61     63.61   10.4720   2.3487     5.1800

K = 46.41  N = 0.329  KYP = 31.97  NYP = 0.394  RYP = 0.9911
```

Figure 4.1-2A Rheological Data and Calculations

50.7% CW (Laboratory Data)

```
                                             SYSTEM PROPERTIES

MINERAL --- EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 51%  1-22-79
AVERAGE SOLID          SPECIFIC GRAVITY (S ) --- 1.527
LIQUID PHASE           SPECIFIC GRAVITY (SL) --- 0.789
SLURRY                 SPECIFIC GRAVITY (SM) --- 1.045
SLURRY CONCENTRATION BY WEIGHT               --- 0.507
SLURRY CONCENTRATION BY VOLUME               --- 0.347
ABSOLUTE PIPEWALL ROUGHNESS (E), FEET        --- 0.00015000
GRAVITATIONAL ACCELERATION                   --- 32.1573 FEET/SEC/SEC
SLURRY TEMPERATURE (TEMP), DEGREES CELSIUS   --- 25.4
PIPE TYPE                                    ---
PIPE SLOPE                                   --- HORIZONTAL


    MESH        PERCENT      SUM %

    1/PAN        0.00          0.0
 TOTAL =     0.0

WEIGHTED MEAN DIAMETER =0.0000E+00
COEFFICIENT OF VARIATION =     0.00000      SETTLING REGIME =
DRAG COEFF OF WEIGHTED MEAN DIA =    0.000  VISCOSITY FACTOR =  0.8
REYNOLDS NUMBER OF SETTLING =     0.00
ROSIN - RAMMLER EQUATION:  R = 100 * EXP(-(D/  0.000000) **  0.000000)
SLOPE =  0.000000     INTERCEPT B =  0.00000000000  MILLIMETERS
CORRELATION COEFF. = 0.000000     D50 =  0.00 MILLIMETERS

KYP =  31.97     NYP =  0.394     TAUY =   19.384
SM THEORY
```

Figure 4.1-2B Rheological Data and Calculations

50.7% CW (System Properties)

```
  DIA     RELRUF   VCL     VCT     VLCTY     SHRATE     REYNOLDS    FM       PSI      KILW-HR
  IN.      E/DIA   FPS     FPS      FPS       1/SEC      NUMBER     MIX       MI      TON-MI

THROUGHPUT =2000. SHORT  TONS/HR

23.124 0.00008   5.88    8.78    11.55        66.42     7061.    .0340    87.655    0.2883
23.750 0.00008   5.84    8.73    10.95        61.30     6549.    .0347    78.295    0.2575
24.125 0.00007   5.82    8.69    10.61        58.49     6266.    .0352    73.285    0.2411
24.625 0.00007   5.79    8.65    10.19        55.00     5914.    .0357    67.213    0.2211
25.124 0.00007   5.76    8.61     9.79        51.79     5589.    .0363    61.770    0.2032
25.500 0.00007   5.74    8.58     9.50        49.53     5360.    .0367    58.029    0.1909
26.000 0.00007   5.71    8.54     9.14        46.73     5074.    .0373    53.485    0.1759
27.062 0.00007   5.66    8.45     8.44        41.44     4533.    .0386    45.223    0.1488
27.500 0.00007   5.64    8.42     8.17        39.49     4332.    .0391    42.286    0.1391
28.000 0.00006   5.61    8.38     7.88        37.41     4118.    .0396    39.220    0.1290
28.500 0.00006   5.59    8.35     7.61        35.48     3917.    .0402    36.429    0.1198
29.000 0.00006   5.56    8.31     7.35        33.67     3730.    .0408    33.883    0.1115
29.500 0.00006   5.54    8.28     7.10        31.99     3555.    .0414    31.557    0.1038
30.000 0.00006   5.52    8.24     6.86        30.42     3390.    .0420    29.428    0.0968
30.500 0.00006   5.50    8.21     6.64        28.94     3236.    .0426    27.477    0.0904
30.876 0.00006   5.48    8.18     6.48        27.90     3126.    .0430    26.116    0.0859
31.500 0.00006   5.45    8.14     6.23        26.27     2955.    .0438    24.040    0.0791
32.000 0.00006   5.43    8.11     6.03        25.06     2826.    .0444    22.525    0.0741
32.500 0.00006   5.41    8.08     5.85        23.92     2705.    .0450    21.128    0.0695
32.876 0.00005   5.40    8.06     5.72        23.11     2619.    .0454    20.149    0.0663
33.500 0.00005   5.37    8.02     5.50        21.84     2484.    .0462    18.647    0.0613
34.000 0.00005   5.35    7.99     5.34        20.89     2096.    .0000    13.980    0.0460
34.375 0.00005   5.34    7.97     5.23        20.22     2032.    .0000    13.684    0.0450
34.750 0.00005   5.32    7.95     5.12        19.57     1971.    .0000    13.396    0.0441
35.125 0.00005   5.31    7.93     5.01        18.95     1912.    .0000    13.115    0.0431
36.000 0.00005   5.28    7.88     4.77        17.60     1784.    .0000    12.495    0.0411
36.375 0.00005   5.26    7.86     4.67        17.06     1733.    .0000    12.251    0.0403
36.750 0.00005   5.25    7.84     4.57        16.55     1683.    .0000    12.009    0.0395
37.375 0.00005   5.23    7.81     4.42        15.73     1605.    .0000    11.613    0.0382
38.000 0.00005   5.21    7.78     4.28        14.97     1532.    .0000    11.245    0.0370
38.625 0.00005   5.19    7.75     4.14        14.25     1463.    .0000    10.886    0.0358
38.750 0.00005   5.18    7.74     4.11        14.11     1450.    .0000    10.833    0.0356
39.625 0.00005   5.15    7.70     3.93        13.20     1361.    .0000    10.358    0.0341
40.000 0.00004   5.14    7.68     3.86        12.83     1326.    .0000    10.177    0.0335
40.375 0.00004   5.13    7.66     3.79        12.48     1291.    .0000    10.007    0.0329
40.624 0.00004   5.12    7.65     3.74        12.25     1269.    .0000     9.882    0.0325
```

Figure 4.1-2C Rheological Data and Calculations

50.7% CW (Calculations)

```
FOUR DATA POINTS
SLURRY:  EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 47%  1-22-79
 I RC(CM) RS(CM)  RAT(I) LN(RAT(I)) CW(%) CV(%)
 1 4.0000 0.9421  4.2458   1.4459   47.1  31.5

TEMP(C)    S      SL  TAUK(I)   SM  YIELD(DYNES/CM/CM)
 24.9   1.527 0.789  0.5814 1.022          8.67

RPM  DIAL    STRESS     BROGAM     ALVGAM    OMEGA  LN(OMEGA) LN(STRESS)
 10. 34.0     58.45      11.90      11.90    1.0472   0.0461     4.0681
 20. 38.2     65.70      23.81      23.81    2.0944   0.7393     4.1852
 50. 46.1     79.34      59.52      59.52    5.2360   1.6556     4.3738
100. 50.4     86.69     119.04     119.04   10.4720   2.3487     4.4623

K = 37.86  N = 0.176  KYP = 30.39  NYP = 0.200  RYP = 0.9964
```

Figure 4.1-3A Rheological Data and Calculations

47.1% CW (Laboratory Data)

```
                                            SYSTEM PROPERTIES

MINERAL --- EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 47%  1-22-79
AVERAGE SOLID          SPECIFIC GRAVITY (S ) --- 1.527
LIQUID PHASE           SPECIFIC GRAVITY (SL) --- 0.789
SLURRY                 SPECIFIC GRAVITY (SM) --- 1.022
SLURRY CONCENTRATION BY WEIGHT               --- 0.471
SLURRY CONCENTRATION BY VOLUME               --- 0.315
ABSOLUTE PIPEWALL ROUGHNESS (E), FEET        --- 0.00015000
GRAVITATIONAL ACCELERATION                   --- 32.1573 FEET/SEC/SEC
SLURRY TEMPERATURE (TEMP), DEGREES CELSIUS --- 24.9
PIPE TYPE                                    ---
PIPE SLOPE                                   --- HORIZONTAL


    MESH       PERCENT     SUM %

    1/PAN       0.00         0.0
 TOTAL =     0.0

WEIGHTED MEAN DIAMETER =0.0000E+00
COEFFICIENT OF VARIATION =    0.00000      SETTLING REGIME =
DRAG COEFF OF WEIGHTED MEAN DIA =   0.000  VISCOSITY FACTOR =  0.8
REYNOLDS NUMBER OF SETTLING =    0.00
ROSIN - RAMMLER EQUATION:  R = 100 * EXP(-(D/  0.000000) **  0.000000)
SLOPE =  0.000000      INTERCEPT B =  0.00000000000  MILLIMETERS
CORRELATION COEFF. = 0.000000     D50 =  0.00 MILLIMETERS

KYP =  30.39     NYP =  0.200     TAUY =    8.669
SM THEORY
```

Figure 4.1-3B Rheological Data and Calculations

47.1% CW (System Properties)

```
 DIA    RELRUF   VCL    VCT    VLCTY     SHRATE    REYNOLDS    FM       PSI      KILW-HR
 IN.     E/DIA   FPS    FPS     FPS      1/SEC      NUMBER     MIX       MI      TON-MI

THROUGHPUT =2000. SHORT  TONS/HR

23.124 0.00008  4.13   5.91   12.71      105.38    18227.    .0267    81.216     0.2939
23.750 0.00008  4.12   5.89   12.05       97.27    16645.    .0272    72.653     0.2629
24.125 0.00007  4.11   5.88   11.68       92.80    15782.    .0276    68.066     0.2463
24.625 0.00007  4.10   5.87   11.21       87.26    14719.    .0281    62.485     0.2261
25.124 0.00007  4.09   5.86   10.77       82.16    13749.    .0286    57.493     0.2081
25.500 0.00007  4.09   5.85   10.45       78.58    13072.    .0289    54.061     0.1956
26.000 0.00007  4.08   5.83   10.05       74.14    12237.    .0294    49.888     0.1869
27.062 0.00007  4.06   5.81    9.28       65.75    10681.    .0305    42.293     0.1531
27.500 0.00007  4.05   5.80    8.99       62.65    10113.    .0309    39.590     0.1433
28.000 0.00006  4.04   5.79    8.67       59.36     9513.    .0314    36.765     0.1330
28.500 0.00006  4.04   5.77    8.37       56.29     8957.    .0319    34.183     0.1237
29.000 0.00006  4.03   5.76    8.08       53.43     8443.    .0324    31.833     0.1152
29.500 0.00006  4.02   5.75    7.81       50.76     7967.    .0329    29.685     0.1074
30.000 0.00006  4.01   5.74    7.55       48.26     7524.    .0334    27.717     0.1003
30.500 0.00006  4.01   5.73    7.31       45.93     7113.    .0339    25.912     0.0938
30.876 0.00006  4.00   5.72    7.13       44.27     6823.    .0343    24.652     0.0892
31.500 0.00006  3.99   5.71    6.85       41.69     6375.    .0350    22.728     0.0822
32.000 0.00006  3.98   5.70    6.64       39.77     6042.    .0355    21.322     0.0772
32.500 0.00006  3.98   5.69    6.43       37.96     5732.    .0360    20.025     0.0725
32.876 0.00005  3.97   5.68    6.29       36.67     5513.    .0364    19.115     0.0692
33.500 0.00005  3.96   5.67    6.06       34.66     5171.    .0371    17.718     0.0641
34.000 0.00005  3.96   5.66    5.88       33.15     4917.    .0376    16.691     0.0604
34.375 0.00005  3.95   5.66    5.75       32.08     4737.    .0380    15.971     0.0578
34.750 0.00005  3.95   5.65    5.63       31.05     4566.    .0385    15.290     0.0558
35.125 0.00005  3.94   5.64    5.51       30.07     4402.    .0389    14.645     0.0530
36.000 0.00005  3.93   5.63    5.24       27.93     4049.    .0398    13.270     0.0480
36.375 0.00005  3.93   5.62    5.14       27.07     3909.    .0402    12.732     0.0461
36.750 0.00005  3.92   5.61    5.03       26.25     3775.    .0407    12.221     0.0442
37.375 0.00005  3.92   5.60    4.87       24.96     3565.    .0414    11.426     0.0413
38.000 0.00005  3.91   5.59    4.71       23.75     3370.    .0421    10.696     0.0387
38.625 0.00005  3.90   5.58    4.56       22.61     3188.    .0428    10.025     0.0363
38.750 0.00005  3.90   5.58    4.53       22.39     3153.    .0429     9.897     0.0358
39.625 0.00005  3.89   5.57    4.33       20.94     2923.    .0439     9.059     0.0328
40.000 0.00004  3.89   5.56    4.25       20.36     2830.    .0444     8.728     0.0316
40.375 0.00004  3.88   5.55    4.17       19.80     2742.    .0448     8.412     0.0304
40.624 0.00004  3.88   5.55    4.12       19.44     2685.    .0451     8.210     0.0297
```

Figure 4.1-3C Rheological Data and Calculations

47.1% CW (Calculations)

```
FOUR DATA POINTS
SLURRY:  EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 45%  1-22-79
  I RC(CM) RS(CM)  RAT(I) LN(RAT(I)) CW(%) CV(%)
  1 4.0000 0.9421  4.2458   1.4459   45.2  29.9

TEMP(C)    S      SL  TAUK(I)    SM  YIELD(DYNES/CM/CM)
 25.3   1.527 0.789  0.5814 1.010         4.35

RPM  DIAL   STRESS    BROGAM    ALVGAM    OMEGA   LN(OMEGA) LN(STRESS)
 10. 23.0    39.59    12.51     12.51    1.0472    0.0461     3.6787
 20. 26.2    45.12    25.02     25.02    2.0944    0.7393     3.8092
 50. 29.5    50.69    62.54     62.54    5.2360    1.6556     3.9257
100. 34.3    59.08   125.09    125.09   10.4720    2.3487     4.0789

K = 25.98  N = 0.167  KYP = 22.20  NYP = 0.184  RYP = 0.9949
```

Figure 4.1-4A Rheological Data and Calculations

45.2% CW (Laboratory Data)

```
                                      SYSTEM PROPERTIES

MINERAL --- EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 45%  1-22-79
AVERAGE SOLID        SPECIFIC GRAVITY (S ) --- 1.527
LIQUID PHASE         SPECIFIC GRAVITY (SL) --- 0.789
SLURRY               SPECIFIC GRAVITY (SM) --- 1.010
SLURRY CONCENTRATION BY WEIGHT             --- 0.452
SLURRY CONCENTRATION BY VOLUME             --- 0.299
ABSOLUTE PIPEWALL ROUGHNESS (E), FEET      --- 0.00015000
GRAVITATIONAL ACCELERATION                 --- 32.1573 FEET/SEC/SEC
SLURRY TEMPERATURE (TEMP), DEGREES CELSIUS --- 25.3
PIPE TYPE                                  ---
PIPE SLOPE                                 --- HORIZONTAL


    MESH       PERCENT     SUM %

    1/PAN       0.00        0.0
 TOTAL =    0.0

WEIGHTED MEAN DIAMETER =0.0000E+00
COEFFICIENT OF VARIATION =    0.00000      SETTLING REGIME =
DRAG COEFF OF WEIGHTED MEAN DIA =   0.000  VISCOSITY FACTOR =  0.8
REYNOLDS NUMBER OF SETTLING =    0.00
ROSIN - RAMMLER EQUATION:  R = 100 * EXP(-(D/  0.000000) **  0.000000)
SLOPE =  0.000000     INTERCEPT B =  0.0000000000  MILLIMETERS
CORRELATION COEFF. = 0.000000     D50 =  0.00 MILLIMETERS

KYP =  22.20     NYP =  0.184     TAUY =    4.351
SM THEORY
```

Figure 4.1-4B Rheological Data and Calculations

45.2% CW (System Properties)

```
 DIA    RELRUF   VCL    VCT    VLCTY     SHRATE   REYNOLDS    FM      PSI     KILW-HR
 IN.    E/DIA    FPS    FPS    FPS       1/SEC    NUMBER      MIX     MI      TON-MI

THROUGHPUT =2000. SHORT  TONS/HR

23.124 0.00008  3.41   4.86   13.40      117.25   28965.    .0239   79.925   0.3049
23.750 0.00008  3.40   4.84   12.70      108.22   26417.    .0244   71.414   0.2724
24.125 0.00007  3.39   4.84   12.31      103.25   25028.    .0247   66.859   0.2551
24.625 0.00007  3.38   4.83   11.82       97.09   23319.    .0251   61.377   0.2342
25.124 0.00007  3.38   4.82   11.35       91.42   21761.    .0255   56.428   0.2153
25.500 0.00007  3.37   4.81   11.02       87.43   20674.    .0258   53.035   0.2023
26.000 0.00007  3.37   4.80   10.60       82.49   19336.    .0263   48.898   0.1865
27.062 0.00007  3.35   4.78    9.78       73.15   16843.    .0272   41.396   0.1579
27.500 0.00007  3.35   4.77    9.47       69.71   15936.    .0275   38.727   0.1477
28.000 0.00006  3.34   4.76    9.14       66.04   14976.    .0279   35.931   0.1371
28.500 0.00006  3.34   4.76    8.82       62.63   14090.    .0284   33.394   0.1274
29.000 0.00006  3.33   4.75    8.52       59.44   13270.    .0288   31.078   0.1186
29.500 0.00006  3.32   4.74    8.23       56.47   12510.    .0292   28.963   0.1105
30.000 0.00006  3.32   4.73    7.96       53.70   11806.    .0297   27.026   0.1031
30.500 0.00006  3.31   4.72    7.70       51.10   11152.    .0301   25.250   0.0963
30.876 0.00006  3.31   4.72    7.52       49.25   10691.    .0304   24.011   0.0916
31.500 0.00006  3.30   4.71    7.22       46.38    9978.    .0310   22.120   0.0844
32.000 0.00006  3.30   4.70    7.00       44.24    9451.    .0314   20.740   0.0791
32.500 0.00006  3.29   4.69    6.78       42.23    8959.    .0319   19.462   0.0742
32.876 0.00005  3.29   4.69    6.63       40.80    8611.    .0322   18.569   0.0708
33.500 0.00005  3.28   4.68    6.38       38.56    8070.    .0328   17.200   0.0656
34.000 0.00005  3.28   4.67    6.20       36.89    7668.    .0332   16.193   0.0618
34.375 0.00005  3.27   4.67    6.06       35.69    7384.    .0336   15.488   0.0591
34.750 0.00005  3.27   4.66    5.93       34.55    7113.    .0339   14.820   0.0565
35.125 0.00005  3.27   4.66    5.81       33.45    6854.    .0343   14.189   0.0541
36.000 0.00005  3.26   4.64    5.53       31.07    6297.    .0351   12.844   0.0490
36.375 0.00005  3.25   4.64    5.42       30.12    6076.    .0354   12.318   0.0470
36.750 0.00005  3.25   4.63    5.31       29.21    5865.    .0358   11.818   0.0451
37.375 0.00005  3.24   4.63    5.13       27.77    5533.    .0364   11.042   0.0421
38.000 0.00005  3.24   4.62    4.96       26.42    5226.    .0370   10.330   0.0394
38.625 0.00005  3.23   4.61    4.80       25.16    4940.    .0376    9.675   0.0369
38.750 0.00005  3.23   4.61    4.77       24.92    4885.    .0377    9.550   0.0364
39.625 0.00005  3.23   4.60    4.56       23.30    4523.    .0386    8.733   0.0333
40.000 0.00004  3.22   4.60    4.48       22.65    4379.    .0389    8.410   0.0321
40.375 0.00004  3.22   4.59    4.40       22.03    4240.    .0393    8.103   0.0309
40.624 0.00004  3.22   4.59    4.34       21.62    4151.    .0395    7.906   0.0302
```

Figure 4.1-4C Rheological Data and Calculations

45.2% CW (Calculations)

```
OUR DATA POINTS
LURRY:  EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 43%  1-22-79
 I RC(CM) RS(CM)  RAT(I) LN(RAT(I)) CW(%) CV(%)
 1 4.0000 0.9421  4.2458   1.4459   42.7  27.8

EMP(C)    S      SL   TAUK(I)    SM  YIELD(DYNES/CM/CM)
25.4    1.527 0.789  0.5814 0.994          2.61

PM  DIAL    STRESS     BROGAM     ALVGAM     OMEGA  LN(OMEGA) LN(STRESS)
10. 15.0     25.85      12.15      12.15    1.0472    0.0461     3.2524
20. 16.7     28.69      24.29      24.29    2.0944    0.7393     3.3565
50. 19.2     33.06      60.74      60.74    5.2360    1.6556     3.4983
00. 22.5     38.70     121.47     121.47   10.4720    2.3487     3.6558

 = 16.64   N = 0.172   KYP = 14.38   NYP = 0.188   RYP = 0.9958
```

Figure 4.1-5A Rheological Data and Calculations

42.7% CW (Laboratory Data)

```
                                      SYSTEM PROPERTIES

MINERAL --- EMD-WYO-BA-S2 COAL(MC= 1.4%)-METHANOL- 43%  1-22-79
AVERAGE SOLID          SPECIFIC GRAVITY (S ) --- 1.527
LIQUID PHASE           SPECIFIC GRAVITY (SL) --- 0.789
SLURRY                 SPECIFIC GRAVITY (SM) --- 0.994
SLURRY CONCENTRATION BY WEIGHT               --- 0.427
SLURRY CONCENTRATION BY VOLUME               --- 0.278
ABSOLUTE PIPEWALL ROUGHNESS (E), FEET        --- 0.00015000
GRAVITATIONAL ACCELERATION                   --- 32.1573 FEET/SEC/SEC
SLURRY TEMPERATURE (TEMP), DEGREES CELSIUS --- 25.4
PIPE TYPE                                    ---
PIPE SLOPE                                   --- HORIZONTAL


    MESH        PERCENT      SUM %

    1/PAN        0.00         0.0
 TOTAL =     0.0

WEIGHTED MEAN DIAMETER =0.0000E+00
COEFFICIENT OF VARIATION =    0.00000      SETTLING REGIME =
DRAG COEFF OF WEIGHTED MEAN DIA =   0.000  VISCOSITY FACTOR =  0.8
REYNOLDS NUMBER OF SETTLING =    0.00
ROSIN - RAMMLER EQUATION:  R = 100 * EXP(-(D/  0.000000) **  0.000000)
SLOPE =  0.000000     INTERCEPT B =  0.00000000000  MILLIMETERS
CORRELATION COEFF. = 0.000000     D50 =  0.00 MILLIMETERS

KYP =  14.38     NYP =  0.188     TAUY =    2.614
SM THEORY
```

Figure 4.1-5B Rheological Data and Calculations

42.7% CW (System Properties)

```
 DIA    RELRUF   VCL    VCT    VLCTY     SHRATE    REYNOLDS    FM       PSI     KILW-HR
 IN.     E/DIA   FPS    FPS     FPS      1/SEC      NUMBER     MIX      MI      TON-MI

THROUGHPUT =2000. SHORT  TONS/HR

23.124 0.00008  2.72   3.88   14.43     124.53   49531.   .0212    81.014    0.3329
23.750 0.00008  2.71   3.87   13.68     114.94   45187.   .0216    72.275    0.2969
24.125 0.00007  2.71   3.87   13.26     109.67   42820.   .0219    67.604    0.2777
24.625 0.00007  2.70   3.86   12.72     103.12   39906.   .0222    61.952    0.2545
25.124 0.00007  2.70   3.85   12.22      97.10   37248.   .0225    56.890    0.2337
25.500 0.00007  2.69   3.84   11.87      92.87   35395.   .0228    53.403    0.2194
26.000 0.00007  2.69   3.84   11.41      87.61   33110.   .0231    49.190    0.2021
27.062 0.00007  2.68   3.82   10.54      77.70   28856.   .0239    41.543    0.1707
27.500 0.00007  2.67   3.81   10.20      74.04   27307.   .0242    38.820    0.1595
28.000 0.00006  2.67   3.81    9.84      70.15   25668.   .0245    35.992    0.1479
28.500 0.00006  2.66   3.80    9.50      66.52   24154.   .0249    33.411    0.1373
29.000 0.00006  2.66   3.79    9.17      63.14   22753.   .0252    31.077    0.1277
29.500 0.00006  2.65   3.79    8.87      59.98   21455.   .0256    28.931    0.1188
30.000 0.00006  2.65   3.78    8.57      57.03   20251.   .0259    26.972    0.1108
30.500 0.00006  2.64   3.77    8.29      54.27   19133.   .0263    25.170    0.1034
30.876 0.00006  2.64   3.77    8.09      52.31   18344.   .0266    23.917    0.0983
31.500 0.00006  2.63   3.76    7.78      49.27   17126.   .0270    22.008    0.0904
32.000 0.00006  2.63   3.75    7.53      46.99   16224.   .0274    20.615    0.0847
32.500 0.00006  2.63   3.75    7.30      44.86   15382.   .0277    19.326    0.0794
32.876 0.00005  2.62   3.74    7.14      43.34   14786.   .0280    18.427    0.0757
33.500 0.00005  2.62   3.74    6.88      40.96   13861.   .0285    17.048    0.0700
34.000 0.00005  2.61   3.73    6.67      39.18   13173.   .0288    16.035    0.0659
34.375 0.00005  2.61   3.73    6.53      37.91   12686.   .0291    15.326    0.0630
34.750 0.00005  2.61   3.72    6.39      36.70   12222.   .0294    14.656    0.0602
35.125 0.00005  2.61   3.72    6.25      35.53   11779.   .0297    14.022    0.0576
36.000 0.00005  2.60   3.71    5.95      33.00   10825.   .0303    12.673    0.0521
36.375 0.00005  2.60   3.70    5.83      31.99   10446.   .0306    12.145    0.0499
36.750 0.00005  2.59   3.70    5.71      31.02   10084.   .0309    11.645    0.0478
37.375 0.00005  2.59   3.69    5.52      29.49    9517.   .0314    10.868    0.0446
38.000 0.00005  2.58   3.69    5.34      28.06    8990.   .0318    10.153    0.0417
38.625 0.00005  2.58   3.68    5.17      26.72    8500.   .0323     9.499    0.0390
38.750 0.00005  2.58   3.68    5.14      26.46    8406.   .0324     9.374    0.0385
39.625 0.00005  2.57   3.67    4.91      24.75    7785.   .0331     8.559    0.0352
40.000 0.00004  2.57   3.67    4.82      24.06    7537.   .0334     8.238    0.0338
40.375 0.00004  2.57   3.66    4.73      23.40    7299.   .0337     7.931    0.0326
40.624 0.00004  2.57   3.66    4.68      22.97    7147.   .0339     7.736    0.0318
```

Figure 4.1-5C Rheological Data and Calculations

42.7% CW (Calculations)

Inside Diameter, Inches	Outside Diameter, Inches
29.000	30
30.876	32
32.876	34
34.750	36
36.750	38

The fifth column of each C figure, headed VLCTY, is the speed of flow. The sixth column (SHRATE) is the maximum shear rate, which occurs at the pipe wall. The seventh column is the generalized (Metzner-Reed) Reynolds number. The ninth column is the pressure drop in psi per mile, and the tenth column is the friction work done on the fluid.

The example calculations in the figures were done on sub-bituminous coal from the Belle Ayr mine of the Amax Coal Company near Gillette, Wyoming. From the figures designated -B, it is seen that concentrations by weight vary from 0.533 down to 0.427. The laboratory procedure is to first make the slurry as thick as the viscometer can measure, and take a measurement. After each of a succession of dilutions, another measurement is taken. Thus, Figure 3.4-1 shows laboratory data and rheoglocial calculations for the stiffest mixture, while 4.1-6 is for the most dilute.

For each pipe size, these results are cross-correlated against concentration, and concentrations are identified by interpolation which yield Reynolds numbers of 2100 (laminar flow) and 4200 (turbulent flow). Simultaneously, the associated pressure drops are also identified from these correlations.

The value of the Reynolds number of the lower bound of turbulent flow is usually taken as 4000. However, it has been pointed out by Hanks (1979) that the Metzner-Reed generalized number is not valid for transitional or turbulent flow if the fluid possesses a yield stress, as is the case with the slurries which were tested in this program. Accordingly, it was judged that some small margin of conservatism was warranted, and the upper-transition criterion of 4200 was used.

From the total 1000-mile pressure drop and the allowable pipe pressure, the number of pump stations and the number of pumps per station are calculated, and the total cost of pumps and stations is found from the pump station cost model. This result is combined with the results of the line cost model for the particular pipe size and of the end-of-line facilities cost which is appropriate to the slurry being pumped to yield the total investment cost in 1979 dollars.

This cost is that of what is called the instant plant, ie, the effects of inflation during construction are not taken into account. The interest cost during construction is included however; it is only the effect of inflation that has been disregarded. If, for example, inflation during construction should double the capital and operating costs of the system, then the calculated tariffs would approximately double. One then must estimate whether the prices of competing systems will also double over the same period, or will grow by some other factor. The reader who is concerned with such questions is left to apply his/her own favorite factors to the results.

Returning now to the calculation sequence, the capital cost estimate is used by the tariff model to calculate the tariff, ie, cost to the shipper. Table 4.1-1 presents the results for the set of cases which was displayed in Figures 4.1-1 through 4.1-5.

It is seen first that, over a range of several percentage points of concentration, the tariff varies less than does the concentration. Between the 32-inch and 38-inch pipe diameters, concentration varies over a range of 6.9% and 5.6% for the laminar and turbulent cases, respectively, while the corresponding tariff variations are only 1.0% and 4.7%. In the turbulent regime, in which it is possible to choke the flow into the smaller pipes, the tariff rises rapidly to the limiting concentration for turbulent flow. In this case, the

Table 4.1-1

Tariffs(1) for Belle Ayr Coal(2)

Pipe Dia(3) In	Laminar Flow		Turbulent Flow	
	Weight Conc(4)	Tariff(1)	Weight Conc(4)	Tariff(1)
28	(5)	(5)	0.511	0.403
30	(5)	(5)	0.501	0.379
32	0.529	0.383	0.493	0.369
34	0.519	0.382	0.483	0.362
36	0.504	0.386	0.475	0.379
38	0.495	0.383	0.467	0.373

(1) \$ per 10^6 BTU net heat value for a 1000-mile pipeline

(2) Dried, ground, then mixed into methanol

(3) Nominal (outside) diameter

(4) Fraction of dry solids (DS)

(5) Not pumpable at 2000 TDS/hr

cutoff diameter is between 28 and 26 inches. In laminar flow, the limiting concentration is reached somewhere between 32-inch and 30-inch pipes, but the tariff is virtually constant, ie, variations are in the third significant figure, even when closely approaching the limiting concentration. The conclusion emerges that once a decision is made (in the face of the known operating difficulties) to operate in the laminar region, the economic incentive is to operate at high concentrations, near the maximum. In turbulent flow, the economics favor a concentration farther below the limit.

This insensitivity of tariff to concentration is due to the fact that by far the largest element of capital cost is in the pipe. For the fixed dry-solids throughput, smaller pipe requires higher concentration and consequently higher cost of pump stations. However, in the high-concentration region, this higher cost is offset by the reduction in pipe cost. To examine the effect of higher pump station cost, the calculations for the turbulent flow cases were repeated for pump station costs which were increased by 20 percent from the previous case, the results being shown in Table 4.1-2. Over the range of diameters from 32 to 38 inches, the same insensitivity is seen. However, as the limit of pumpability is approached, the rise in tariff is slightly steeper than for the base case.

Another observation to be made is that there is not a single minimum-tariff (economically optimum) point in either laminar or turbulent flows, because of the near-balance of pipe cost against pumping cost which occurs as the maximum pumpable concentration is approached, as has just been discussed. As also noted, these variations are so small that they are not regarded as significant. However, the effect is seen with all of the coals that were experimentally characterized in the program, as Table 4.1-2 shows, and thus it is not merely an idiosyncrasy of the model. Thus, the general form of the tariff function is as shown in Figure 4.1-6.

Table 4.1-2

Sensitivity to Pump Station Cost

Pipe Dia In	Wt Conc	Tariff	
		Cost x 1	Cost x 1.2
28	0.511	0.403	0.423
30	0.501	0.379	0.393
32	0.493	0.369	0.379
34	0.483	0.362	0.370
36	0.475	0.379	0.385
38	0.467	0.373	0.378

Coal: Belle Ayr, dry-mixed, turbulent flow

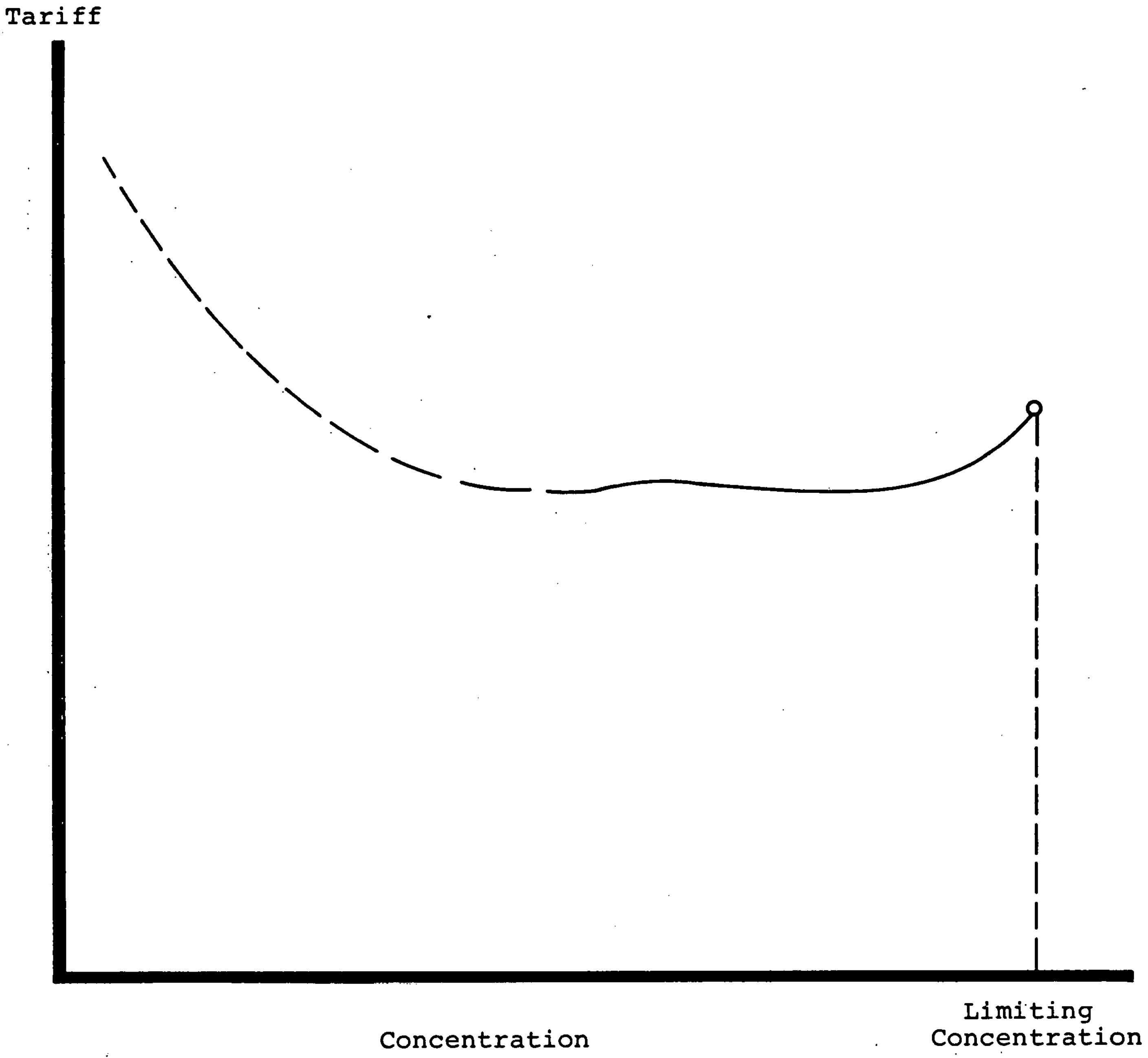

Figure 4.1-6 General Form of Tariff vs Concentration (Not to Scale)

Table 4.1-3

Tariffs for Several Western Coals in Methanol

Coal	Weight conc, DS(2)	Flow Regime, L/T(3)	Tariff(1)
Belle Ayr, WM(4)	0.434	L	0.360
Belle Ayr, WM(4)	0.437	T	0.492
Belle Ayr, DM(5)	0.529	L	0.383
Belle Ayr, DM(5)	0.511	T	0.403
Thunder Basin	0.474	L	0.413
Thunder Basin	0.474	T	0.450
Thunder Basin	0.417	L	0.366
Thunder Basin	0.408	T	0.395
Black Mesa	0.506	L	0.365
Black Mesa	0.488	T	0.384
Knight	0.583	L	0.386
Knight	0.563	T	0.386
Carbon King	0.590	L	0.387
Carbon King	0.588	T	0.405

(1) \$ per 10^6 Btu net heat value per thousand miles

(2) Dry Solids

(3) L = Laminar, T = Turbulent

(4) Wet mixed, ie, rodmilled in MeOH

(5) Dry mixed, ie, ground dry then mixed into MeOH

Although the tariffs shown in Table 4.1-2 appear to favor operating in the laminar flow regime, it should be recognized that there are operating complexities associated with this mode. Whenever there is any settling in laminar flow, there is no way that the fluid can recover the settled material and re-introduce it into the slurry. Therefore, the system must be cleaned occasionally, possibly by pigging or perhaps by reducing concentration and operating in the turbulent flow regime for a while. This, of course, is an annoyance at least and probably an additional cost. In this study however, no assessment is made of these operating complexities.

Returning now to the analysis leading to Tables 4.1-1 and 4.1-2, when that analysis is extended to the other coals that were rheologically characterized, the results are as summarized in Table 4.1-3. In the case of the Belle Ayr coal, two pairs of values are presented. The coal for the wet-mixed (WM) slurry was crushed, dried, and then rodmilled in the methanol to emulate the Black Mesa slurrification process. The coal for the dry-mixed (DM) slurry was crushed, ground, dried, and then simply mixed into the methanol.

The tariffs shown in Table 4.1-3 are not those which correspond to the maximum pumpable concentration, but to somewhat lower concentrations approximately relating to the the local minimum tariff, although no claim is made to having optimized any of the systems. The model is not, as yet, sufficiently refined, nor are the inputs sufficiently precise for the results to have any significance in the third significant figure except to indicate probable trends.

Each pair of values in the table was selected by first taking the local-minimum value for laminar flow. Then, the turbulent case having the concentration nearest to that of the laminar flow case was taken for comparison. In almost all cases, lower tariffs for the turbulent cases can be realized by further reducing the concentration into the region indicated on Figure 4.1-6 by the dashed line to the left end of the curve. This effect is because it is cheaper to move Btu's in the form of MeOH than in the form of the thicker slurry. However, these dilute slurries are not of interest in this study for reasons that will be developed in Section 5.0 below. There, it will be seen that a major obstacle to the liquefaction of western coal is the scarcity of water in the west, and the integrated coal methanolization and coal-in-methanol pipeline system offers a unique opportunity to solve that problem. But the solution requires relatively highly concentrated slurries. Hence it is of primary interest to compare the laminar and turbulent cases on the basis of equal or near-equal concentrations.

The approximate magnitude of the difference in tariffs between the lower and higher concentrations may be seen from the second pair of values for the Thunder Basin coal.

Two significant conclusions emerge from the information just presented. First, it is seen that the cost of transporting a million BTu over a thousand miles in the form of a coal-methanol slurry lies in the range of 35 to 40 cents. Moreover, this cost is not sensitive to either concentration or to type of coal, ie, bituminous or sub-bituminous.

It is well to elaborate, lest this statement regarding sensitivity be misinterpreted. If, for example, a type of coal, pipe diameter, and flow regime are fixed, it will be found that the tariff results are indeed rather sensitive to solids concentration. However, and this is the observation that is being made here, the optimum concentration and pipe size for a given type of coal will result in a tariff that is not greatly different between laminar and turbulent regimes nor from the optimum result for another coal.

4.2 Economic Comparisons

The fundamental economic variable in the economic comparison is, of course, the tariff, ie, the cost to the shipper for transporting energy via the coal-methanol slurry pipeline vs the cost via coal-water pipeline or via rail.

This comparison embraces two types of systems. The first, (Type 1 System) transports both a boiler fuel (coal) and an engine fuel (methanol). This product mix may be accommodated in either of two ways. The first way is via the coal-methanol slurry pipeline, which represents the innovation that is the subject of this study. The other way is the conventional way, ie, transporting the coal via a water slurry pipeline and transporting the methanol via a neat methanol pipeline.

The Type 2 System is a system which delivers boiler fuel only. The conventional Type 2 System is the coal-water slurry pipeline, which delivers only coal for boiler fuel. The innovative Type 2 System is the coal-methanol slurry pipeline, with the slurry being directly fired in the boiler without separation. As has been noted earlier in Section 1.4 above, a clean, premium engine fuel such as methanol is not an economic boiler fuel. Coal, at a price of 8$/ton (Section 3.2.3) and a net heating value of about 17,000,000 Btu/ton costs about $0.47/million Btu. Methanol, which can be sold as a premium fuel for about $0.30/gal (Section 3.2.3) and has a net heating value of 56,900 Btu/gal costs about $5.17/million Btu. Also, the energy consumed by the methanolization process is a penalty against the system. Type 2 Systems thus receive no further consideration here.

Turning now to the economics of the water system, Belle Ayr coal was used as the reference water-system coal for comparison with the methanol system, for the reason that of the five coals experimentally characterized, more experimentation and more analysis was done with it than with the others. Typical results are shown in Table 4.2-1, for three values of dry solids concentration and five pipe diameters. The general conclusion which emerges is that the cost to the shipper is about sixty cents per million Btu for a thousand-mile coal-water pipeline.

Table 4.2-1

Tariffs(1) for Belle Ayr Coal in Water

Pipe Diameter 36"

Conc, % DS(2)	Tariff(1) $\$/10^6$Btu-$10^3$Mi
0.456	0.595
0.430	0.590
0.405	0.590

Solids Concentration 0.456

Pipe Dia In	Tariff(1) $\$/10^6$Btu-$10^3$Mi
30	0.560
32	0.555
34	0.557
36	0.595
38	0.597

(1) \$ per 10^6 Btu net heat value for a 1000-mile pipeline

(2) Dry solids

Although this study did not address the costs of transporting coal by rail, it is of interest to compare rail tariffs with the costs via pipeline. Rail tariffs vary a great deal, but in view of the experience of the city of San Antonio (1976) and others, it seems extremely unlikely that any future contracts will be signed for less than a dollar per million Btu for a thousand miles. Thus, a good first order estimate of the comparative economics of coal transport via rail, water slurry and methanol slurry is obtained by comparing the thousand-mile tariffs per million Btu of net heat value.

Taking for this comparison the above rail tariff and the pipeline tariffs shown in Tables 4.1-3 and 4.2-1 yields:

Rail	Coal-Water Pipeline	Coal-Methanol Pipeline
$1.00+	$0.60	$0.40

The economic attractiveness of the methanol system is clear.

5.0 System Energetics

5.1 Energy Consumption in Coal-Water Pipelines

Coal that is transported by rail or other conventional means is normally burned in the boiler in its as-received condition, so that its moisture content entering the boiler is the same as it was when it came out of the ground except as modified by weather or other conditions incidental to its transportation and storage. Its moisture content when consumed may be higher or lower than as-mined, but unless it is just too wet to burn, it is simply dried in the boiler and, as mentioned earlier in Section 2.1, the evaporation of the moisture by the boiler is a loss of energy. Much coal is routinely burned at its native bed moisture content of about 30%, although many coals are much dryer. In any case, an energy loss that is inherent to the nature of the transport system is a penalty that must be charged to that system, and therefore, an increase in moisture content in the as-received condition over the as-mined condition because of the treatment which it receives by the transportation system is a penalty that must properly be assessed against the transportation system.

To appreciate the many ways in which a slurry pipeline consumes energy requires some rather detailed discussion (Banks, 1977). It is to be noted that the total pipeline system, including its end-of-line (EoL) facilities, consumes energy in a great many ways other than in simply pumping the fluid through the pipeline. Moreover, at the head of the line, energy is consumed in providing the water and in the slurrification process. Additionally, energy is consumed at the terminal in the deslurrification process.

Some of this deslurrification energy is mechanical and some is thermal. An appreciation for the diversity and complexity of the mechanical processes may be acquired by perusal of Table 5.1-1, which lists the power consuming equipment which partially separates the coal from the water at the terminal of the Black Mesa Pipeline.

Table 5.1-1

Energy-Consuming Deslurrification Equipment
(Black Mesa Pipeline)

Active Storage

Booster pumps to active storage
Agitators
Slurry transfer pumps
Water pump to primary treatment
Water pump to evaporation pond

Boiler Fuel Preparation

Centrifuges
Pulverizer mills
Clariflocculator agitators
Underflow pump
Underflow injection pump

Reslurry from Inactive Storage

Conveyor motors
Vibrator motors
Reslurry pump, primary
Reslurry pump, final

The thermal energy of separation is the heat that is necessary to dry the coal until its moisture content is the same as it was when the coal came out of the ground. Taking again the Black Mesa Pipeline as an example, the moisture content of the as-mined coal is about 11%, but when it enters the power plant boiler, it contains about 32% moisture. The 21% difference must be thermally removed by the boiler, and the heat required to do this cannot be used to generate electricity, so that the transportation process must be charged with that lost energy.

In the case of the Black Mesa, this energy penalty is large because of the large difference in moisture contents between the slurrification feedpoint and the boiler feedpoint. If the as-mined moisture of the Black Mesa coal were 32%, as is in fact the case with some western coals, there would be no penalty for thermal separation.

Table 5.1-2 illustrates how these factors work out for the Black Mesa Pipeline, which is the only operating coal slurry pipeline in the U.S.

It is seen that the largest element of energy consumption is the moisture correction that has just been discussed. As noted above, this element is large because the as-mined Black Mesa coal with eleven percent moisture is one of the driest western coals. This, of course, is partly responsible for the energy intensity (EI) being so high. The other reason that the EI is high is that the pipeline is relatively short and the largest energy consumption is at the terminal and, thus, is a fixed quantity, independent of pipeline length. The effect of stretching the line to a thousand miles in length will be seen shortly.

Table 5.1-2

Energy Consumption in the Black Mesa Pipeline
(Btu/Ton of Fuel)

Slurry Water Supply		24,000
Pipeline Operation		
Pumping Energy	135,000	
Other Operations	30,000	
		165,000
Deslurrification		
Initial Separation	205,000	
Moisture Correction	710,000	
		915,000
Total		1,104,000
Length of Pipeline, mi		273
Energy Intensity, Btu/Ton-mi		4,040

5.2 Energy Consumption in the Synergistic System

The methanol system enjoys a double advantage over the water system in regard to coal moisture. First, since the methanol system does not add any water to the coal, it does not have to take any away, so that the moisture correction to return the coal to its as-mined moisture is zero. Even more significant, however, is the fact that virtually all of the as-mined moisture itself can be removed and used in the methanolization process, as has been discussed earlier.

The energy benefit of this utilization of otherwise wasted heat from the methanolization process is realized in the power plant boiler, where the energy that is normally wasted in evaporating the native moisture in the coal, and is thus lost in the stack effluent, instead goes into steam which generates electricity. Thus, besides not suffering the penalty for moisture correction, the methanol system also reaps a large additional benefit from the dry coal.

Table 5.2-1 shows how all the factors discussed above may work out for three systems. The first system is the Black Mesa, water-slurry pipeline, stretched to a thousand mile length. The second system is the water-slurry pipeline that is being promoted by Energy Transportation Systems, Inc. (ETSI). Its main trunk will be approximately a thousand miles. It will transport Wyoming coal whose moisture content at the slurrification facility is expected to be about 26 percent, so that the moisture correction is much less than was the case with Black Mesa. The third system is the reference coal-methanol system which was described earlier in Section 3.1.

Table 5.2-1 does not present the three systems upon an unbiased comparative basis, for the obvious reason that they are different in important respects other than the water-methanol difference. Table 5.2-2 presents results for water and methanol systems (the Reference Systems discussed earlier), which are otherwise the same.

Table 5.2-1

Comparison of Energy Consumption

(Btu/Ton of Fuel in 1000-Mile Pipeline)

		Stretched Black Mesa		ETSI		MeOH
Slurry Water Supply		24,000		25,000		10,000
Pipeline Operation						
Pumping Energy	441,000(1)		539,000		300,000	
Other Operations	47,000(2)		47,000		30,000	
		488,000		586,000		330,000
Deslurrification						
Initial Separation	205,000		65,000		240,000	
Moisture Correction	710,000		136,000		-0-	
Credit for Dry Coal	-0-		-0-		(580,000)	
		915,000		201,000		(340,000)
Total		1,427,000		812,000		-0-
Energy Intensity, Btu/Ton-Mile		1,427		812		-0-
Energy Intensity, Btu/10^6 Btu-Mile		67		51		-0-

(1) Adjusted for 1000-mile length and 5000-foot free fall

(2) Adjusted for 1000 mile length

Table 5.2-2

Summary of Energy Consumption, H_2O vs MeOH
(Btu/Ton of Fuel in 1,000-Mile Pipeline)

	H_2O		MeOH	
Slurry Water Supply		25,000		10,000
Pipeline Operation				
Pumping Energy	400,000		300,000	
Other Operations	40,000		30,000	
		440,000		330,000
Deslurrification				
Initial separation	100,000		240,000	
Moisture Correction	-0-		-0-	
Credit for Dry Coal	-0-		(580,000)	
		100,000		(340,000)
Total		665,000		-0-
Energy Intensity Btu/Ton-Mile		665		-0-
Energy Intensity Btu/10^6 Btu-Mile		42		-0-

It is apparent from this table, of course, that the methanol system is potentially an extremely attractive system from the viewpoint of energy conservation. The conclusion is that the energy materials, coal and methanol can be transported for long distances, ie, hundreds of miles and sometimes a thousand miles and more, with energy that would otherwise be wasted.

Now, having arrived at this pleasantly surprising conclusion, it is necessary immediately to add and to emphasize two reservations. First, the comparison is grossly unfair in that it repeats the usual practice of comparing paper systems with steel-and-concrete systems. Unfortunately, when studying concepts with limited resources, the situation cannot be avoided; nevertheless, it must be continually recognized as a deterrent to premature over-optimism. Black Mesa exists, and the values presented here are based upon operating information which was provided by the Black Mesa Pipeline, owner and operator of the system. The ETSI system is not yet steel and concrete, of course, but its preliminary design is based upon the currently operating equipment in Black Mesa. Additionally, the Bechtel engineering staff has devoted much more effort to the design of the system than could be accomplished in this study. Thus, the comparison just presented suffers from a weakness which, unfortunately, can only be cured by designing and building the system. It must be remembered that as systems move from concept to reality they inevitably lose a significant portion, and sometimes all, of their initial attractiveness.

The second reservation is that the amount of the credit for dry coal, which represents energy that would otherwise be wasted, is a sensitive function of two variables - the concentration of the slurry and the moisture in the coal when it enters the system. These variables work against each other, in that coals which have a high bed moisture content generally have lower limiting concentrations beyond which they become unpumpable. Thus, there are systems in which the dry coal credit is not large enough under any circumstances to achieve zero net energy consumption. However, if the net energy consumption is not zero for a 1000 miles it is still zero for some hundreds of miles, so that some saving as compared with other systems is always available, and it is always significant in magnitude as compared to the other energy uses in the system.

6.0 System Water Usage

6.1 The Politics of Western Water

In the controversy between the proponents and the opponents of federal eminent domain for slurry pipelines, the issue of water usage has been exploited by the opposition. The opposition disregards the fact that, even in the arid states, some allocation is made of water for industrial use. To the outside bystander, it would seem best that it be left to the people of the affected state to decide whether they want to assign some portion of that industrial allocation to slurry pipelines or to some other industrial use. Seen in this light, the question of water usage by slurry pipelines would appear to be completely independent of the eminent domain issue. It is sometimes argued by the slurry pipeline proponents that water problems should not even be considered in debating the issue of federal eminent domain in slurry lines. The states historically managed their own water, so the argument goes, and there is no reason why they should not do so in the case of slurry pipelines. Parenthetically, it may be noted that that is precisely what happened in the case of the ETSI line. ETSI made arrangements with Wyoming for the necessary water. Therefore, the argument continues, there is no reason for the federal government to take a position one way or another regarding the propriety of using water for slurry pipelines vis-a-vis using the same water in some other industry.

However, the question still has some bearing upon the issue of federal eminent domain. If the Congress, with full knowledge of the problems and issues surrounding water supply, endows the slurry lines with federal eminent domain without any recognition of the water issue, that action could be construed by many, including the courts, to whom the question of congressional intent is always a central question, as a congressional endorsement of the principle of using water for slurry lines in the arid West. The only way to avoid such an implied endorsement and thereby settle the political question would appear to be by an explicit statement in the act that the water questions must be resolved by the state involved in each case, and that has not been proposed. In the absence of such a provision in the act, water will remain a political issue that every proposed western pipeline must face and overcome. And any system, such as the coal-methanol system, which requires less water than the coal-water system will enjoy a political advantage. It is well to further observe that political opposition has probably killed far more projects than technical obstacles. Political advantages should not be disparaged.

6.2 Water Requirements for Coal-Water Slurries

When water is cheap, coal-water slurries generally operate most economically at mixtures of about half water and half dry solids by weight. At this concentration, every million tons of dry solids that is slurried requires 736 acre-feet of water. If the coal going into the slurrifier has a total moisture content of 30 percent, 515 acre-feet of water are required. Since water is held by coal in three different ways, it is necessary to identify the retention mode to which reference is being made.

The first mode is called surface moisture and, as the name implies, it is the moisture which is on the exterior surface of the coal. In dry air, this moisture readily evaporates. Usually about ten percent or less by weight of freshly mined coal is surface moisture.

The moisture which is so closely held inside the coal chunks that it does not produce wetness on the surface is called by several names, ie , bed moisture, seam moisture, inherent moisture, etc. In Section 5.0 above, pending the explanation which is now to be presented, this moisture was referred to as the as-mined or native moisture. This moisture consists of water which is contained in the interstices, as minute droplets or adsorbed film, and does not readily evaporate, although in dry air at room temperature, this water migrates slowly to the surface of the chunk and is evaporated. Conversely, dry coal in saturated air gradually takes moisture from the air until it attains its natural bed moisture content. The bed moisture is measured by a process (ASTM Specification D1412) of equilibration in saturated air, and it is therefore also referred to as equilibrium moisture.

The third mode of retention is by water of crystallization and other weak chemical bonds which can be broken with gentle heat, as for example breakdown of carboxyl radicals or oxidation of hydroxl radicals. Under the ASTM test procedures, any moisture that is released at a temperature of 105 C or less is considered bed moisture. Thus, in discussing coal-water slurries, reference to dry solids means coal without the moisture that is released below 105 C under the prescribed ASTM conditions.

Taking now an example, if a million tons of dry coal, bereft of its 30% bed moisture, were mixed with 736 acre-feet of water, the resulting slurry would be 50 percent dry solids by weight. Three hundred fifteen acre-feet would be absorbed by the coal in reaching its equilibrium (bed) moisture content of 30 percent and 421 acre-feet of water would be carrying the 1,429,000 tons of wet coal. Thus, depending upon the bed moisture content, each million tons of as-mined coal requires between 500 and 700 acre-feet of water so that if a 100 million tons of coal per year were exported from the coal fields of Wyoming and Montana, via water slurry pipeline, something like 60,000 acre-feet of water per year would also be exported. Quite naturally, there is widespread concern about the prospect of long-term commitments for such export quantities.

6.3 Water Economics

The influence of water cost upon slurry pipeline water requirements has been examined by Palmer et al (1977). Their results are presented in Table 6.3-1. If the water were free, the economic optimum for their particular reference system would operate at about 52 percent concentration. If the water cost were $2500 per acre-foot, the optimum design would operate at about 58.5 percent concentration and consume 76.5 percent as much water as would the free-water system. There is little of what the economists term elasticity of demand in this situation. The water slurry pipeline is a thirsty system, and even quite high prices for the water do not modify that habit pattern very much.

6.4 Water Requirements for Coal-Methanol Slurries

In Section 5.0 above, it was seen that if the coal-methanol pipeline and the coal methanolization plant are integrated into a single system, so that waste heat from the methanolization plant is used to dry all of the incoming coal, then otherwise-wasted energy is released in the power plant boiler and used to generate electricity. If additionally the water that is driven from the coal in the drying process is collected and fed into the methanolization process, the water feedstock that is required for that process is reduced proportionately.

The concept that was originated in this study for accomplishing this reduction of both energy and water requirements is summarized below. The flow of the raw methanol stream in the methanolization process is interrupted after passing through the drying columns which remove the water that has survived the process to that point. This hot methanol is then conducted out of the methanolization plant to the coal dryers in the next-door slurrification plant, where the vapor is passed through the incoming coal, absorbing its moisture. The

Table 6.3-1

Water Demand Function for Water Slurry Pipelines

Cost of Water ($/acre-foot)	Relative Quantity of Water Demanded
$0	1.000
$25	0.994
$50	0.988
$100	0.982
$500	0.926
$1,000	0.876
$1,500	0.829
$2,000	0.788
$2,500	0.765

Source: Palmer et al (1977)

now-wet methanol vapor is returned to the methanolization plant, passed through an additional, identical set of dryers which remove the water that was taken from the coal. Like the other water that is processed elsewhere in the methanolization plant, this water is recovered and used in the plant. For environmental reasons, the methanolization plant is already designed to recover and reuse virtually all of its water, rather than release it to the environment.

Basically, the water feedstock to the methanolization process supplies the four atoms of hydrogen that combine with an atom of carbon from the coal and an atom of oxygen to form a molecule of methanol. Stoichiometrically, 12 pounds of carbon combine with 4 pounds of hydrogen and 16 pounds of oxygen to form 32 pounds of methanol. If the coal contained no hydrogen, 36 pounds of water would be required to produce the 32 pounds of methanol. However, the coal contains some inherent hydrogen, typically five or six percent on a dry basis, and this hydrogen is reacted in the gasifier and so contributes toward the satisfaction of the total hydrogen requirement. The remainder of the requirement is supplied in the form of water.

The only native (coal-bound) hydrogen that can contribute to the methanol-hydrogen requirement is that hydrogen contained in the coal which enters the gasifier. However, in the integrated-system (synergistic) concept described here, all of the coal which enters the plant is dried and the collected water contributes this hydrogen to the methanol synthesis process, so that coal which is consumed in the methanolization plant but outside of the gasifier also contributes its water to the methanolization process. Likewise, the coal which is destined to move down the pipeline also contributes its water. The result is that the water requirement of the system is greatly reduced and in some cases eliminated.

Some general insight into the magnitude and sensitivity of the potential water reduction is provided by Figure

6.4-1, which displays the excess hydrogen above the stoichiometric water requirement which is contained in typical western coals. Dry-basis carbon and hydrogen contents are taken as 70% and 5% respectively, and the hydrogen excess is plotted for the 30% and 15% moistures which typically characterize sub-bituminous and bituminous western coals. The excess is plotted against weight concentration of dry solids in the slurry. The results are sensitive to this variable, since a high concentration means that a large quantity of pipeline coal contributed its natural water to the methanolization process.

The postulated conversion efficiencies are shown on the figure, and are approximately equal to those of the Badger design. The postulated 90% efficiency for water recovery is, of course, only a guess, since as noted earlier the drying facility could not be designed within the resources of this study. However, the reader will recall from Section 3.2.3 that a generous allowance for the cost of the facility was included in the economic analysis.

The conclusion which emerges from Figure 6.4-1 is that from 50 to 100% and more of the required water may be taken from the coal itself. To test this hypothesis, calculations were performed for the actual constitutions of the six coals which were analyzed in the laboratory as a part of this study. Figure 6.4- presents the results for the three sub-bituminous coals and Figure 6.4-3 presents the results for the three bituminous results. Within the significance of the sample size, the hypothesis is indeed confirmed, although it must be recognized that constitution of coals varies and the generality of the conclusion is accordingly limited. At the same time, it is clear that the concept has great merit in many situations.

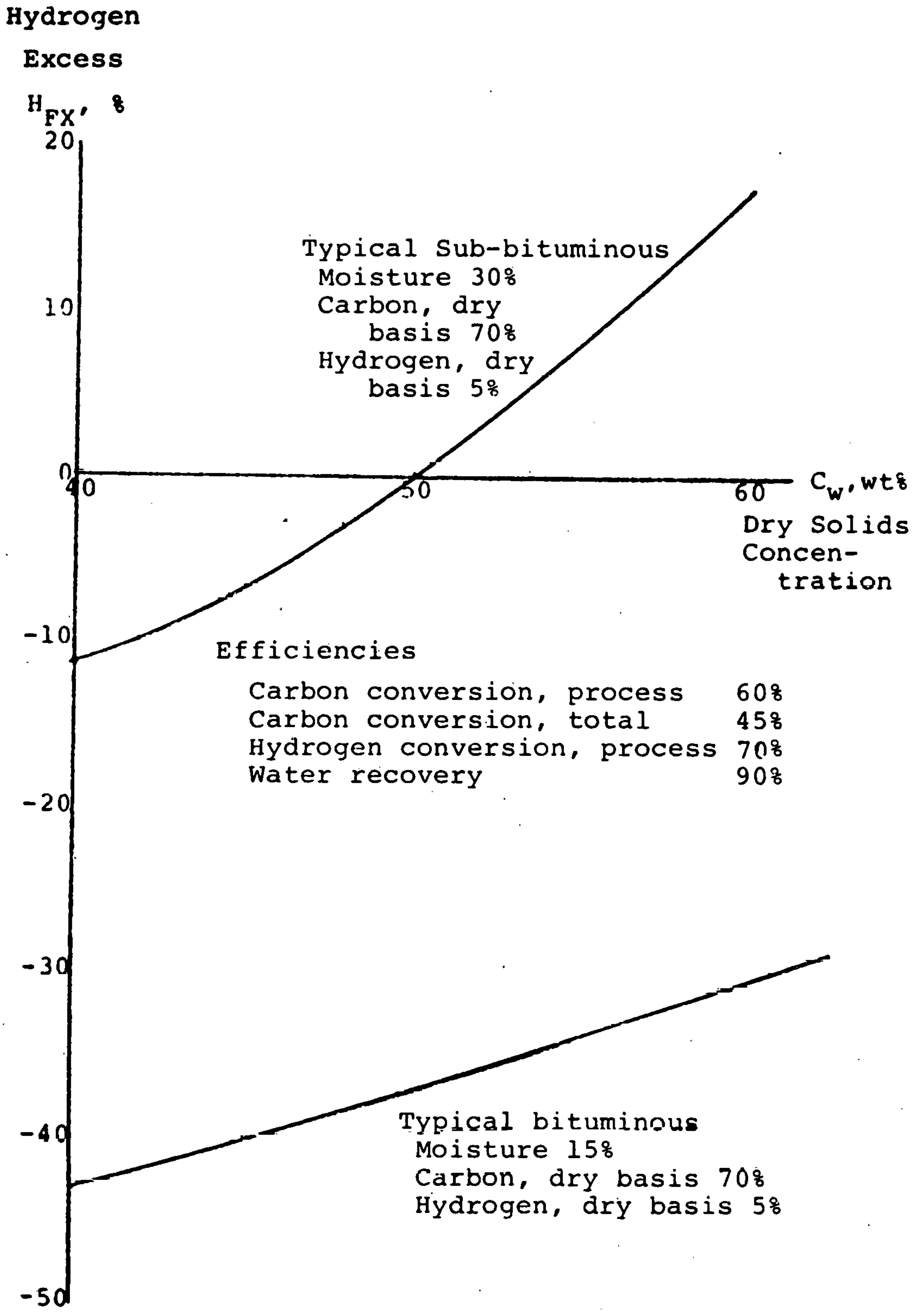

Figure 6.4-1 Hydrogen Excess for Typical Western Coals

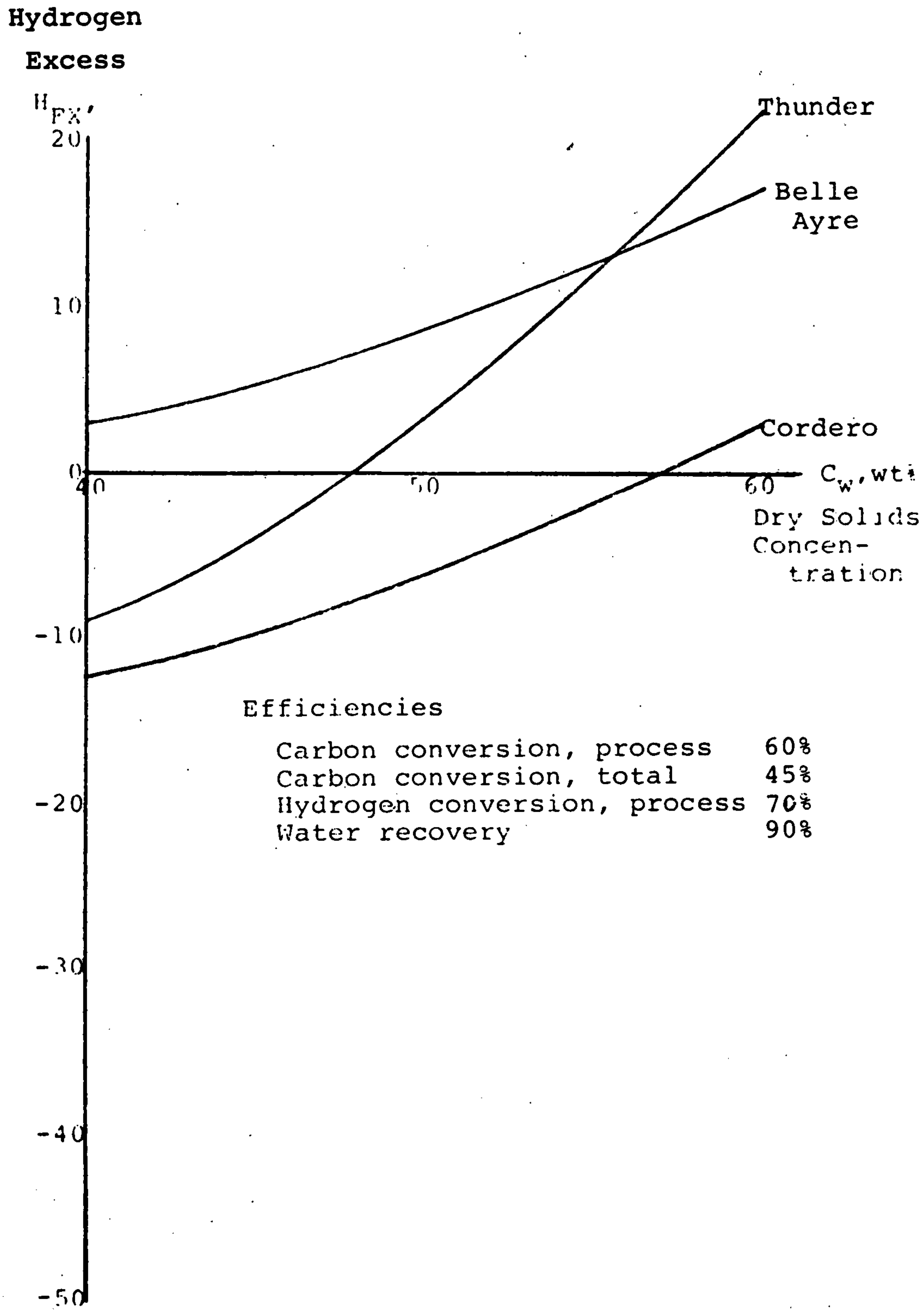

Figure 6.4-2 Hydrogen Excess for Three Sub-bituminous Western Coals

7.0 Summary of the Experimental Program

This is a study of the engineering economics of an integrated coal methanolization and transportation system. It was never the intent of this study to engage in either basic research or engineering development. As has been explained earlier, technical feasibility has been assumed because the overriding question is the economics. Only if the economics appear favorable will it be worthwile to begin any research and development.

Now, this approach is straightfoward when the physical constants characterizing the system are available in engineering handbooks or elsewhere in the open literature. However, it was not possible to perform this study without laboratory experimentation, because some necessary basic elements of engineering information did not exist, ie, information characterizing the rheological behavior in methanol of the various coals of interest. Accordingly, from the inception of the project an experimental program was planned.

The planned approach was to select a reference coal and develop rheograms experimentally from which the Faddick pipeline model described in Section 3.2.1 above, could be used to calculate the pressure drop. This was to be done over a range of concentrations. The coal from the Belle Ayr mine of the Amax Coal Company was selected for several reasons, one being that it was thought to be typical of the subbituminous coals from the Powder River basin of Wyoming, another being that Amax generously provided abundant samples of their coal. The laboratory measurements in methanol and in water were conducted at the Colorado School of Mines (CSM) under the supervision of Professor Robert Faddick, a well-known slurry specialist, using a Brookfield viscometer.

The results were disappointing in that they failed to confirm prior expectations which had been based upon some very limited measurements of the behavior of Utah coal in methanol. Moreover, the results displayed wide variability and some inconsistencies among themselves. To resolve the difficulty, the experimental program was expanded to include several additional coals and additional variables, and work was stopped on all systems other than methanol. Additional measurements were made of the behavior of the same coal under different conditions of preparatory treatment, eg, moist vs dry, air-dried vs oven-dried, washed vs dirty, dry-mixed vs wet-mixed, and of different coals vis-a-vis one another. Additional Powder River (sub-bituminous) coals were provided by the Thunder Basin Coal Company of Arco and by the Cordero mine of Sunedco. Also, three bituminous coals were measured. Some of these coals were shipped to the Texas A & M University chemical engineering laboratory, where measurements were made on the rheogoniometer under the supervision of Dr. Ronald Darby, Professor of Chemical Engineering. In some cases, measurements were made in the two different laboratories on the identical slurry. The results were widely variable and sometimes inconsistent between themselves, and it became clear that the experimental program would have to be expanded again if resolution was to be achieved. An attempt was made to obtain the necessary funding, but the attempt was unsuccessful, and the remaining resources were then applied to simply doing only those things which were necessary to develop some definitive conclusions for this report.

8.0 Conclusions

The general conclusion that emerges from this study is that an integrated coal methanolization and transportation facility offers an extremely attractive opportunity to accomplish several very beneficial results:

(1) An import-balance benefit in the displacement of petroleum imports by clean, premium-quality engine fuel from coal.

(2) A financial benefit by the transportation of the energy contained in western coal to distant markets at much lower tariffs than can be achieved in any other way.

(3) An energy benefit in that the net energy cost of transportation is far less than by any other mode, and can in some cases even be reduced to zero or below. That is, by this system approach, and only by this approach, significant amounts of energy that would otherwise be wasted can be recovered as useful electric power at the busbar of the generating station. This energy recovery may be as much as is required to transport the coal and liquid fuel for a thousand miles or more.

(4) A social benefit in that most and sometimes all, of the water that is required by the system can be taken from the fresh as-mined coal itself, reducing or eliminating the need for imposition upon the scarce western water resource.

(5) An environmental benefit in that large amounts of bulk commodity freight can be taken off the surface rail system and moved underground, where it is out of sight and its environmental impact is negligible (Faddick 1979).

9.0 Recommendations

The recommendations which emerge from the conclusions just stated are of two kinds: those relating to policies of the DoE and the nation, and those relating to the technical program of research, development, and demonstration (R, D & D) which is necessary to realize the potential benefits which have been identified.

9.1 Technical Recommendations

As with other DoE development programs, the end purpose of the technical program recommended here is a demonstration of the concept which will lead to commercialization. To that end, the following recommendations are made.

(1) Jointly with Badger Plants, Inc., the systems integration of the methanolization plant and the slurrification plant which has been proposed here should be assessed in depth. This integration is the only serious question that remains unanswered, but it is critical. If that answer is affirmative, then the additional work to be described below should be performed.

(2) Additonal coals should be characterized rheologically, using tube-flow measurements in addition to viscometry.

(3) The relationship between rank of a coal and its rheological behavior is a mystery. While the only major variables discernible from the standard laboratory analyses that correlate with rank are moisture and oxygen content, this study has shown that rheological behavior in methanol correlates rather well with rank, but not at all with moisture content. The effects of oxygen content have not been examined. These relationships should be explored and explained.

(4) An engineering model of coal slurry pipeline pressure drop is needed in the public domain.

(5) The pipeline cost model, particularly the end-of line facilities, should be refined.

(6) Engine tests should be conducted on methanol which has been slurried and passed through a simulated pipeline. It seems quite certain that there will be no discernible effect upon engine performance. The effect upon emissions, however, could be detrimental and should be determined.

(7) Although the economics do not vary much between pipelines operating in the laminar and turbulent regimes, the former is much more attractive for conservation of both energy and water. Accordingly, the techniques for maintaining clean pipe in laminar flow under actual pipeline operating conditions need to be verified.

9.2 Policy Recommendations

It is recommended that U.S. energy policymakers

(1) Recognize the attraction of transporting energy a thousand miles for forty cents per million Btu.

(2) Recognize the several attractions of slurry pipelines as supplemented energy carriers.

(3) Recognize the importance of water conservation in the arid west.

(4) Recognize the attraction of transporting energy over long distances, possibly a thousand miles, with zero net energy consumption, ie, with energy that would otherwise be wasted.

(5) Recognize the attraction of methanol as an engine fuel. It is the only synthetic fuel which is technologically ready for early and massive introduction to the market.

(6) Initiate and support the technical program of R, D, and D on the integrated methanolization-pipeline system.

(7) Because methanol is the only synthetic fuel that is technologically ready, maintain the methanol program as the baseline against which all other approaches are to be assessed.

(8) Recognize the desirability of resolving the remaining questions that were presented in the preceeding section, in order to have a proven and practical plan of action for immediate implementation, once a decision has been made or the necessity has been forced upon us by external forces.

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