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TRANSPORTATION RESEARCH FORUM

1. INTRODUCTION

THERE HAS BEEN an almost fourfold increase in the ton-mile capacity of commercial slurry pipeline systems over the last four years. This is due in large part to the commercial operation in late 1970 of the Black Mesa Coal Pipeline in Arizona. Current projections indicate that this trend will continue at an ever-accelerating rate. For instance, systems now in engineering or under construction will double the capacity of iron concentrate pipelines. Considering only three or four of the systems now being seriously planned, the ton-mile capacity of slurry pipelines will easily increase by an order-of-magnitude before the end of this decade.

This presentation will be limited to those materials that have been proven, both technically and economically, as feasible for long-distance pipeline transportation. It is further limited to materials which will have significant immediate application for slurry pipelines. Those materials are coal, iron concentrates, copper concentrates and limestone for Portland cement manufacture. A future candidate for the list is phosphate minerals. This list is limited by two factors:

The existence of point-to-point transportation requirements of volumes large enough to justify a slurry pipeline. Following are annual world-wide production figures for 1970 (millions of tons):

Coal	2,983
Iron Concentrate	104
Copper Concentrates	20
Limestone	545

When a small pipeline system carries half a million tons per year, the instances are limited where tonnages of that magnitude of other pipelineable solids will be going point to point. One special case was the Gilsonite Pipeline in Utah and Colorado. The chances of a second application of slurry pipeline transportation of Gilsonite are quite remote.

The second factor limiting this list is the amenability of the material to transportation in a liquid medium, generally water. For a cross-country solids pipeline to be practical, the slurry is designed to be extremely stable hydraulically. This means, basically, that the particle top size is limited so that the flow rate in the system can be kept to a modest level and so that there will not be any abrasive wear of the mainline pipe.

In this paper we will review the technical experience in transporting these materials, the physical dimensions of the systems that transport them and that will be transporting them in the future, the environmental impact and energy usage of this mode of transportation and, finally, the economics of pipeline transportation systems. One important feature which will be discussed is the impact of escalation on the transportation costs in slurry pipelines as a function of power, labor and materials cost escalation.

2. TECHNICAL FEASIBILITY

The technology of long distance pipeline transportation of solids is now approaching the realm of a mature art. The list of commercially operating systems, Exhibit 1, is becoming quite

SLURRY PIPELINE SYSTEMS

System	Length Miles	Diameter Inches	Capacity M Tons/yr.	Operation
Goal				
Ohio	108	10	1.3	1957
Black Mesa	273	18	4.8	1970
Planned — USA	1000	38	25	1978
Iron Concentrate				
Savage River	53	9	2.5	1967
Pena Colorado — Mexico	30	8	1.8	1974
Sierra Grande — Argentina	20	8	2.1	1974
Las Truchas — Mexico	17	8	1.5	1975
Planned — Africa	350	18	6.6	1977
Planned — Brazil	240	20	12.0	1976
Copper Concentrate				
Bougainville	17	6	1.0	1972
West Irian	69	4	0.3	1972
Pinto Valley — USA	11	4	0.4	1974
Limestone				
Trinidad	6	8	0.6	1959
Rugby — England	57	10	1.7	1964
Calaveras — USA	17	7	1.5	1971
Australia	44	8	0.9	1975

EXHIBIT I

Economics of Slurry Pipeline Systems

by T. C. Aude; T. L. Thompson**; E. J. Wasp****

lengthy. Systems now operating account for more than 1.7 billion ton-miles of transportation annually. Those systems have an aggregate history of almost half a century. The systems in Exhibit 1 which are not in operation are either under construction or will be committed in the next year. The ton-mile capacity of these new systems will increase the total slurry pipeline system operating capacity by well over an order-of-magnitude.

Much of the expansion in slurry pipeline volume will be due to large coal pipeline systems. Coal stands out by itself since it is a source of energy rather than a raw material. It must be transported to the vicinity of use in one form or another—either in its natural state, as electricity, or as a refined product such as a gas or a liquid. Currently, the economics of coal utilization, particularly as an energy source for electric power generation, favor moving it (as close to the load center as possible) and using it in its natural state. The overall volume of coal movement and the volume of usage at single sites particularly enhance the use of slurry pipelines. For instance, the Mohave power plant uses five million tons per year of coal. Power plant sites which will use ten to twelve million tons per year of coal are being developed in the Mid-West. This coal will come from the coal reserves of Wyoming and Montana; therefore, the potential for long, large capacity coal slurry pipelines is great.

As the world demand for iron increases, more and more remote reserves are becoming economically attractive. Grass-roots development of remote ore bodies is a natural application of slurry pipeline transportation. This has been the case for all the iron concentrate pipeline applications shown in Exhibit 1. The planned Brazilian and African iron concentrate pipelines indicate a significant step both in line size and length.

Like iron concentrate, copper concentrates are being sought in more and more remote places which are prime applications for slurry pipelines. However, the diameter of copper concentrate pipelines is not expected to increase significantly. Note that the Bougainville project is among the largest existing copper producers, yet requires only a six-inch diameter pipeline to transport all the concentrate produced.

Cement, due to economics, is traditionally produced locally for local consumption from local raw materials. This will limit the length and diameter of pipelines designed for limestone.

2.1 Commercial Slurries

The physical properties of these four commercially transported minerals are as follows:

	Solids Specific Gravity	Maximum Particle Size	Average Slurry Concentration % Solids by Wt.
Coal	1.4	8 mesh	50
Limestone	2.7	48 mesh	70
Copper Concentrate	4.3	65 mesh	55
Iron Concentrate	4.9	100 mesh	60

The solids specific gravity is a basic component, of course, in both the selection of the top size and the slurry concentration. Here we span a broad range from 1.4 for coal to almost 5.0 for iron concentrate. At their operating velocity, all these slurries are as nearly homogeneous as is likely to be found in commercial applications. This, of course, is not at all by chance since the restriction of the top size and selection of the solids concentration was specifically aimed at a slurry with nearly homogeneous characteristics. In each case, moderate pumping velocities only slightly above five feet per second are used. The slurries are non-abrasive at design velocities and non-corrosive; therefore, carbon steel line pipe, with no interior treatment, is used. Another significant property of these slurries is that they are restartable; that is, when (and it's always going to happen sometime) the pipeline shuts down and the slurry settles, it settles in such a way that the system can be restarted.

2.2 Equipment

As mentioned above, the homogeneous nature of these slurries, by choice,

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is such that a buried carbon steel line pipe, with welded joints, is used for their commercial transportation. This allows the well-developed system of cross-country pipeline construction to be used with the inherent economies of this production line technique of pipeline installation.

All the commercial slurry pipelines shown in Exhibit 1 use positive displacement type pumps, except one: The Pena Colorado System in Mexico is a gravity flow system. Positive displacement pumps are selected because of their higher pressure capabilities and higher operating efficiency as compared to centrifugal pumps. Commercially available pumps for slurry pipeline service range up to about 1750 horsepower with annual capacities per pump of two to three million tons. Designs are now underway which would more than double the horsepower capacity of positive displacement pumps to about 4,000 horsepower. The main difficulty with positive displacement pumps is to achieve volumes consistent with large slurry pipelines. Achieving the pressure with positive displacement pumps has never been a problem.

The third major component of slurry pipeline systems is storage tanks. An order-of-magnitude jump in the capacity of agitated slurry storage tanks was taken in the Black Mesa System when tanks of 6 million gallons operating capacity were installed at the Mohave Generating Station. These tanks had 500 horsepower agitators. Agitator manufacturers have installed units for other services with 3500 horsepower. It does not appear there will be any serious limitation of system flexibility due to the availability of large agitated storage tanks.

3. THE SYSTEM

Existing commercial systems were described in the previous section. In this section, some simple tools will be provided for estimating line size, pumping power, and water requirements for slurry systems. The configuration and boundaries of typical systems will also be described.

One important factor in sizing a pipeline system is the annual operating factor. Basically, pipelines are designed to operate 24 hours a day, 365 days a year. Since spare pumps are provided in pumping station, the instances of unplanned system outage are limited primarily to the instances of power failures. A system availability of 95 percent per annum is commonly used for design and that figure has been assumed in the following discussion. However, commercial experience has been much better than that. For example, the Black Mesa Pipeline, in 1972, had an availability of over 99%, and in 1973 the periods of unavailability of the Black Mesa System were counted in terms of hours. (Ref. 4)

Exhibit 2 gives a quick means of estimating the pipe diameter, given the annual throughput requirement in tons

SLURRY PIPELINE DIAMETER

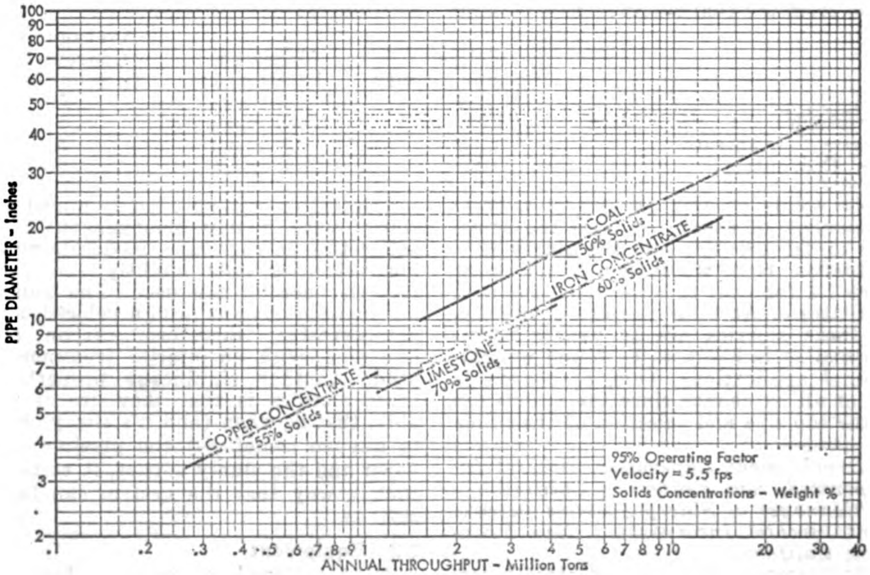


EXHIBIT 2

SLURRY PIPELINE ENERGY CONSUMPTION DURING TRANSPORTATION

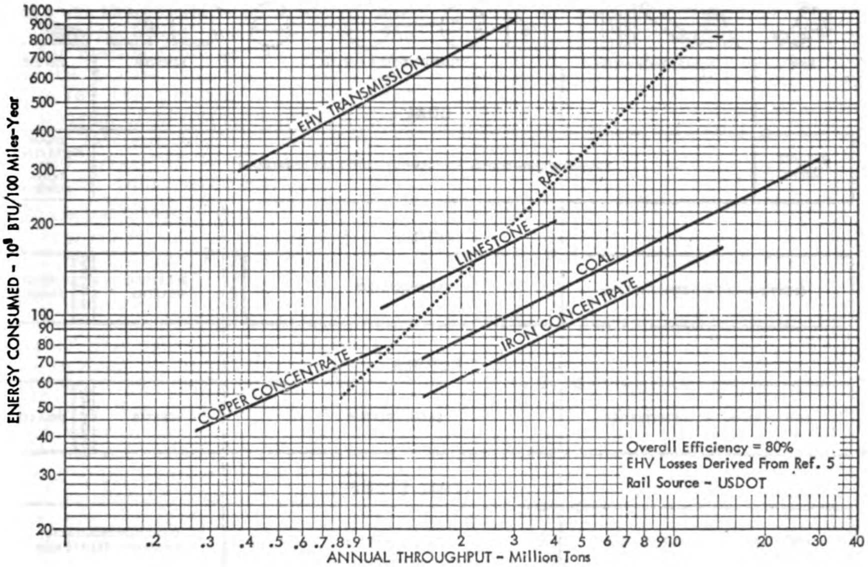


EXHIBIT 3

per year. Here, a design velocity of 5.5 feet per square second is used, which is consistent with the commercial experience for these materials. A 95 percent availability factor is also assumed.

Pumping energy requirements for flat terrain can be estimated using Exhibit 3. These curves assume an overall efficiency of 80 percent which includes a 95 percent volumetric efficiency for the pump and allowances for mechanical losses in the pump power end and drive train, and losses in the electric driver. The spacing of pump stations depends on terrain, line size and the economic balance between multiple pump stations and high design pressures. Generally, stations are spaced at 60 to 80 mile intervals. As the pipeline diameter gets smaller, say below 10 inch, the station spacing will tend to be shorter, due to the high friction losses in small diameter pipes.

To date, water has been the vehicle for transporting commercial solids in slurries. There have been some special cases studied using other vehicles such as oil, but it is going to be a rare instance when the appropriate quantities of oil and solids are going from the same source area to the same use area especially over a 20 to 30 year period. And given that situation, the liquid must not contaminate the solid or vice-versa, nor can there be a wide disparity in value between the two materials, since loss of 8 to 10 percent of the liquid onto the surface of the solid will result. Exhibit 4 gives a means of estimating the water required annually to transport a given annual tonnage of solids.

Exhibit 5 is a diagram of the four slurry systems under discussion. Prior to application of slurry transportation to

SLURRY PIPELINE WATER REQUIREMENTS

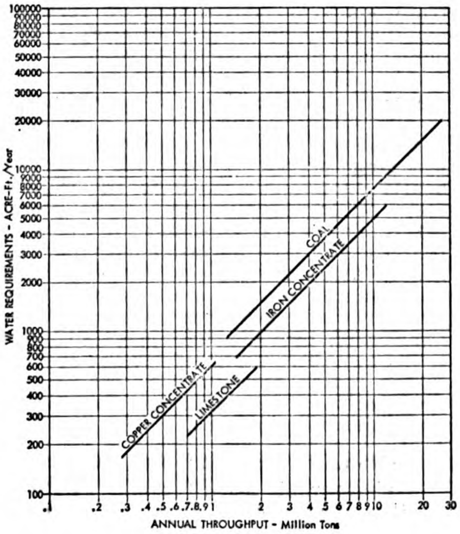
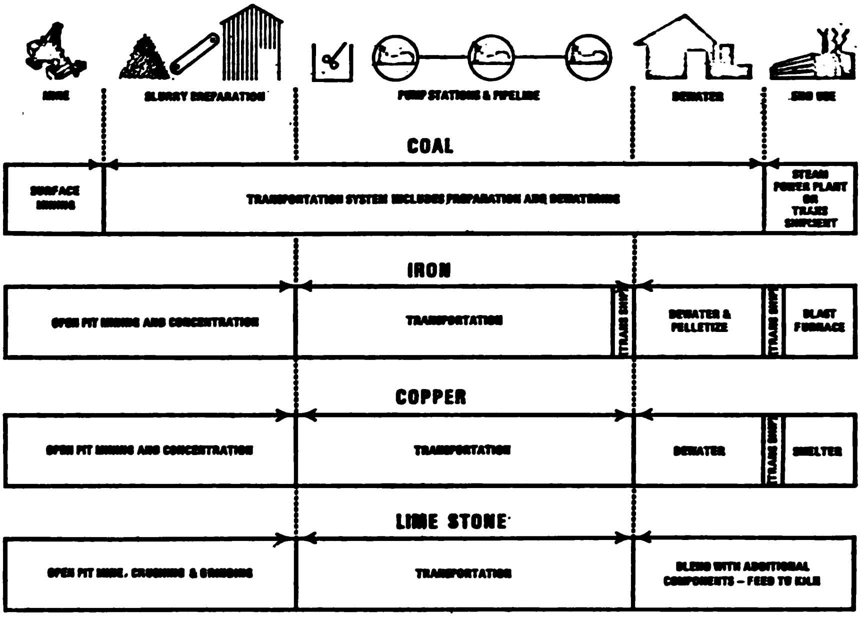


EXHIBIT 4



SLURRY PIPELINE TYPICAL SYSTEMS

EXHIBIT 5

iron, copper and limestone industries, processing the material involved preparing a slurry and dewatering for utilization or utilizing the material as a slurry. Therefore, application of slurry pipeline transportation simply involves adding a pipeline as a "wide spot" in the process chain. The mine is seldom near the point of use, particularly in the case of iron and copper. Often, the concentratrate has to be moved through very remote country before any existing transportation mode is encountered.

Coal slurry, on the other hand, is a different situation. Here the preparation of the slurry is specially done to meet the transportation requirement; the dewatering process brings the coal, as nearly as possible, back to its original state of dryness for use in the power plant. The work expended in grinding the coal for transportation is a savings for the firing process since the coal must be ground to pass 48 mesh before entering pulverized coal fired boiler. The coal application provides an opportunity for the slurry to be designed for the system, taking into consideration the slurry preparation, transportation, dewatering and utilization process.

4. ENVIRONMENTAL IMPACT

A photograph titled "Along the Route of the Black Mesa Pipeline" visually summarizes the environmental impact of slurry pipelines. The impression given is one of little or no effect of the pipeline system on the environment and this is, generally speaking, a fair assessment of the situation.

Cross-country pipelines, including slurry pipelines, are buried 2½ to 3 feet underground. They are out of sight and silent. Pump stations are usually electric motor-driven, hence have no effluent gas. The water used for transportation is clarified and returned to the environment or used as a part of the terminal process or power plant make-up. The risk of spills from slurry pipelines is slight. Minerals (coal, iron, etc.) are in a sense 'rocks' and thus non-toxic to plant and animal life.

Due to the continuous nature of slurry pipeline operations and the high efficiencies of the equipment involved, pipeline transportation is an efficient mode of transportation from the energy conservation standpoint. Exhibit 3 illustrates the BTU requirement per 100 miles for transportation by slurry pipelines. Energy consumed in transport by rail, diesel fuel, and extra high voltage transmission of power are also shown. These figures are presented as a function of annual throughput. It can be seen that pipeline systems have improved efficiency of transportation as the capacity of the system increases.

5. ECONOMIC FEASIBILITY

In this section, the cost of transportation of solids by slurry pipeline will be presented and compared to alternate modes of transportation. For steam coal in the U.S. the viable alternative is unit train transportation over existing rail lines; for metals from remote ore bodies, it may be a new rail system built specifically for the project. One important characteristic of slurry pipelines is their relatively low exposure to escalation of costs due primarily to the high capital intensity of these systems.

5.1 Transportation Costs

The transportation costs presented include direct operating costs plus an annual allowance of 15 percent of capital to cover service of debt, taxes, depreciation and payment of profit to the equity owners of the system. The capital cost of the system includes the direct cost of materials and installation, plus indirect costs for engineering, management of construction, contingency, start-up and owners' costs.

Coal pipeline systems include the capital and operating costs of slurry preparation and dewatering. The pipeline systems contemplated are complete operating entities with maintenance, communications and storage facilities as required for the operation of the system. It is assumed that downstream pump stations will be remotely operated with one day maintenance man assigned. Provision is made for management and administrative staff for the systems in addition to the direct operating and maintenance labor.

Transportation costs for coal are shown on Exhibit 7 as a function of annual throughput and system length. Rail figures are shown for comparison, as are lower Mississippi River barge figures. Note that pipeline transportation cost for large diameter systems approach those for barge transportation. These figures do not take into account the greater mileage that will invariably be required for a rail or barge haul as compared to pipeline, which is basically a direct line. In recent evaluations of a 1000-mile pipeline, the rail distance was 350 miles longer. Exhibit 8 presents transportation costs for iron concentrate, copper concentrate and limestone as a function of annual throughput. Note that these figures do not include the cost of crushing and grinding or dewatering since those are part of the process whether pipeline transportation is used or not. They are not greatly affected by length of system once it is longer than some minimum length on the order of 30 to 50 miles. Transportation costs for a new 50-mile rail system are also shown above the pipeline curve. Since there is now a large capital component directly chargeable to the rail transportation, it shows a larger benefit from increased annual throughput, i.e., economy of scale.

SLURRY PIPELINE TRANSPORTATION COST COAL

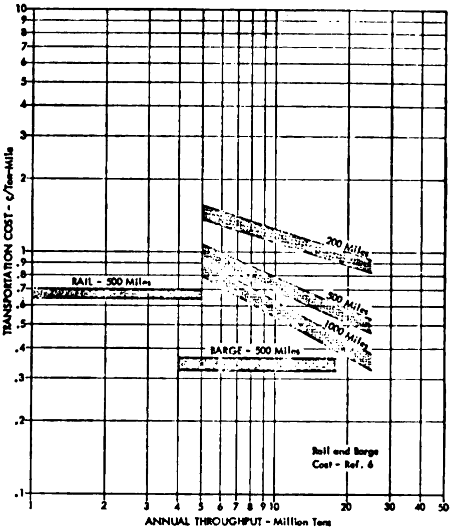


EXHIBIT 7

5.2 Escalation

The effects of escalation on transportation costs over the 20, 30 or even 40 year design life of a pipeline system can be very dramatic: Dramatic in that taking pipeline tariffs as equal, for instance, to rail tariffs at the beginning of a project, values of one-half, one-third or even one-quarter of the projected rail tariff can be expected after a number of years of escalation. Before the days of electronic pocket calculators, engineers used a rule-of-thumb for the time in years for a quantity to double at a compounded percentage rate. The rule-of-thumb went like this: If you divide 72 by the percentage rate, the quotient is approximately the time in years for the quantity to double at that rate of compounding. For instance, at a compound percentage rate of five percent per year, a tariff will double in a little over 14 years. If that rate is only two percent a year, the tariff will double in approximately 35 years. Exhibit 9 is a plot of relative cost versus years at several rates of escalation. This figure will be used to illustrate the effects of combining the different rates of escalation for the components of a transportation tariff.

Pipeline tariffs escalate at modest rates for a simple reason: About 70

SLURRY PIPELINE TRANSPORTATION COST OF IRON OR COPPER CONCENTRATE—LIMESTONE

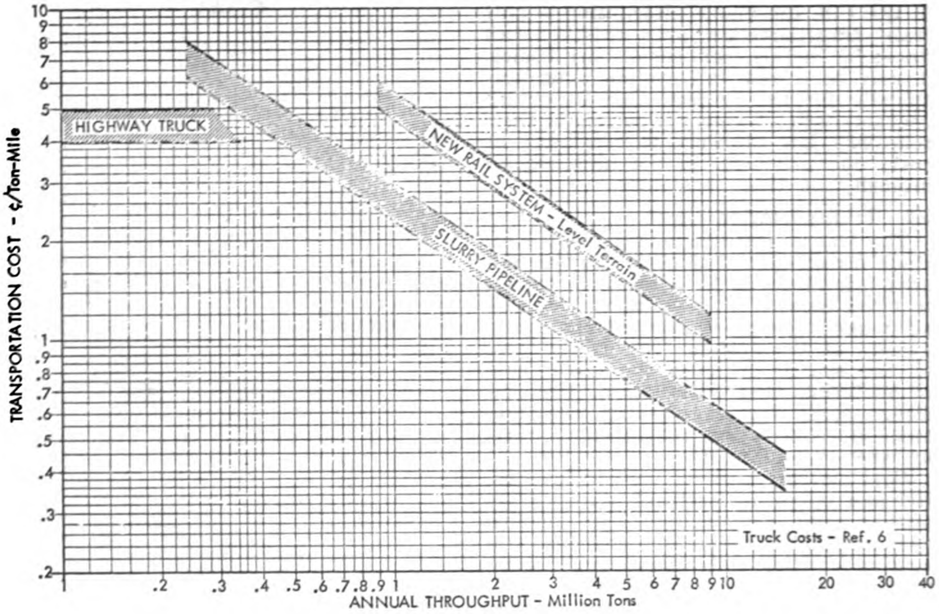


EXHIBIT 8

SLURRY PIPELINE TRANSPORTATION COST ESCALATION

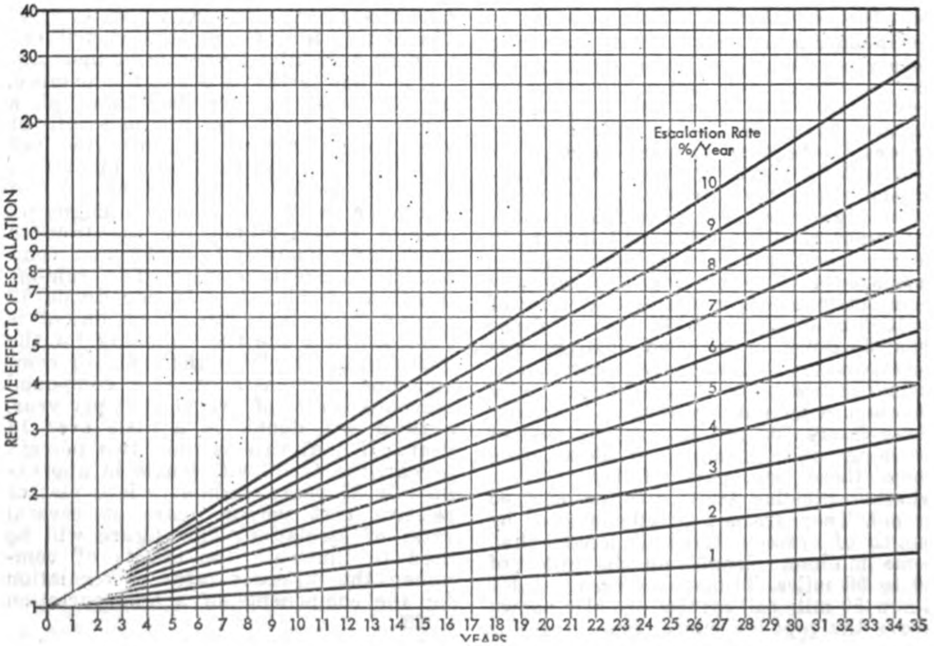


EXHIBIT 9

percent of the pipeline tariff is capital-related charges. Once the capital investment is made, these charges are fixed. Of the remaining 30 percent of the tariff, about half is pumping power. Until the last few years, power costs were very stable due to the capital-intensive nature of electric power generation and the stability of energy prices. This situation, of course, is now changing rapidly since energy prices are increasing and will continue to do so (except at western coal-fired power plants). Over the last five years, the index of electric power cost has increased at the rate of five percent per year, so let us use that number in an example. The remaining 15 percent of pipeline tariff is made up of labor, maintenance materials and services. These items, of course, may experience the most striking escalation. A range of escalation rates for labor and supplies of five to ten percent per year should cover the possibilties. Sample calculations of overall pipeline tariff escalation rates are shown on Exhibit 10. If power costs escalate at 5 percent and labor and supplies at 5 percent, the pipeline tariff escalates at 2.1 percent per year. If escalation of labor and supplies doubles to 10 percent, the overall escalation goes to 3.8 percent per year.

How do these escalation figures compare with those for the alternate form of transportation—rail? Over the last 10 years the average rate of escalation of railroad operating costs has been 6.5 percent per year according to the U.S. Railroad Association. For each of the last three years this figure has been above 8 percent. Railroad tariffs for existing systems are made up of about 80 percent operating cost and 20 percent capital-related cost. Using 8 percent per year escalation for railroad variable costs, an overall escalation rate for railroad tariffs of 7 percent per year can be calculated (see Exhibit 10).

Over the 20 year period projected, railroad tariffs increased 300 percent while slurry pipeline tariffs increased only 50 percent.

6. CONCLUDING DISCUSSION

The technology of pipeline transportation of coal, limestone, copper concentrate and iron concentrate has reached a maturity based on 1.7 billion annual ton-miles of commercial experience.

Slurry pipelines have a small environmental impact relative to alternate modes of bulk transportation.

Energy requirements for pipeline transportation of solids are comparable to those for alternate transportation modes. Pipelines enjoy economy of scale in energy usage; therefore, larger systems require less energy than rail or barge.

Transportation costs for coal, including slurry preparation and dewatering, are, on a current cost basis, below those for existing rail lines. Pipelines benefit from direct routing; generally, considerably shorter than routes following existing rail lines or water ways. Although slurry pipelines for minerals are of a smaller scale, transportation costs are lower than for new rail lines or truck transport over existing roadways.

Pipelines are relatively insensitive to

ESCALATION EXAMPLE
20-Year Period

		Costs		
	Fixed	Power	Labor & Supplies	Total
PIPELINE				
Proportion	70%	15%	15%	100%
Example 1				
Escalation Rate, %/yr	0%	5%	5%	
20-Yr. Factor	1.0	2.7	2.7	
Overall Factor				
Overall Escalation Rate				2.1%/yr.
Example 2				
Escalation Rate, %/yr.	0%	5%	10%	
20-Yr. Factor	1.0	2.7	6.7	
Overall Escalation Rate				3.8%/yr.

RAILROAD	Fixed	Variable	
Proportion	20%	80%	100%
Escalation Rate, %/yr.	0%	8%	
20-Yr. Factor	1.0	4.7	
Overall Escalation Rate			7%/yr.

EXHIBIT 10

escalation due to their capital-intensive nature. It was demonstrated that doubling the rate of escalation of labor and supplies from 5 percent per year to 10 percent per year increased the projected tariff escalation from 2.1 percent per year to 3.8 percent per year. Unit train rail rates have been escalating at 5 to 8 percent per year.

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