THE ECONOMICS OF PIPELINE TRANSPORTATION OF MINERAL COMMODITIES

by

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Dedicated to my parents

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ABSTRACT

A technique is presented for the economic selection of a slurry pipeline with the aid of a computer. Mathematical models for the flow of slurries are utilized. Only the pipeline and its prime movers are considered.

Slurry flow properties are first obtained from rheology and/or pipeline data measurements. A mathematical model is selected for homogeneous suspensions from rheology data whereas a mathematical model is developed for heterogeneous suspensions from pipeline data. It must be emphasized that the accuracy of the method is affected by the accuracy of the slurry flow-property data. Rheological models for homogeneous slurries are utilized in this dissertation. The procedure for the analysis of heterogeneous slurries is similar.

Approximate cost parameters may be selected from data for plain and lined pipes, centrifugal and positive displacement pumps, motors and engines. Cost data for the purchase, operation, and maintenance of slurry pipelines are also included. A total cost equation for the ownership and operation of a slurry pipeline system is then established.

The complexity of the equation is a function of the mathematical model selected to describe the slurry. The equation is solved with the aid of a computer for several combinations of pipeline diameters and throughputs to yield minimum total annual cost for the system. A transportation cost in cents per ton-mile is obtained, incorporating straight-line depreciation and the time value of money concept.

A mean velocity is computed to give the required throughput. The velocity is constrained by an upper and lower bound. A high velocity is undesirable from an energy consumption viewpoint and if pipeline wear is possible. On the other hand, the velocity must exceed the deposition velocity for a heterogeneous suspension or the critical velocity for a homogeneous suspension. There is no guarantee that the velocity computed by this method will lie within the constraints applied, nor that the constraints are even known. This is particularly true for heterogeneous slurries.

An important feature of the method is the ease with which the variables can be adjusted to measure the sensitivity of the total cost to the variables.

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NOMENCLATURE

BHP = Brake horsepower of pump.

CE = Cost of electrical energy, \$/KW-hr.

CENTS = Transportation cost, ¢/ton-mile.

CF = Annual cash flow, \$/year.

CMOTOR = C Motor = Annual motor cost over whole pipe length, \$/year.

CPIPE = C Pipe = Annual fixed cost over whole pipe length, \$/year

CPM = Cost of prime movers (pumps + motors), \$/year.

CPUMP = C Pump = Annual pump cost over whole pipe length, \$/year.

CPMPNG = C Pumping = Annual operating cost over whole pipe length, \$/year.

CTOTAL = C Total = Annual total cost over whole pipe length, \$/year.

CV = Concentration by volume, decimal fraction

CW = Concentration by weight, decimal fraction

C1 = Intercept on a plot of weight per foot versus price per foot of pipe, \$

C2 = Intercept on a plot of BHP versus cost of the pump, \$

C3 = Intercept on a plot of hp versus cost of the motor or engine at hp less than 800, \$

C4 = Intercept on a plot of hp versus cost of the motor or engine at hp greater than 800, \$

DIA = Internal pipe diameter, inches

E = Pipe absolute roughness, feet

EFFCNC = Efficiency of pump and motor expressed as a fraction

EP = Efficiency of the pump expressed as a fraction

F = Fanning friction factor

FACTOR = Inflation factor for each future investment of prime movers (5 allowable), dimensionless

FPIL = Single payment counpound amount factor

FR1 = Ratio of the total cost for fittings and installation to total purchase cost of pipe, dimensionless

FR2 = Ratio of the total cost for fittings and installation to total purchase cost of pump, dimensionless

FR3 = Ratio of the total cost for fittings and installation to total purchase cost of motor, dimensionless

G = Gravitational acceleration, feet/sec^2.

GAMDOT = $\dot{\gamma}$= slurry shear rate, 1/sec.

GR = Annual gross revenue, $/year

H = Hours of pipeline operation per year, hours/year.

hp = Motor or engine horsepower

HP = Total dynamic head developed by pumps

INT = Annual cost of capital expressed as a fraction

K = Consistency index from rheology data, dynes-sec^n/cm^2.

LENGTH = L = Pipe length, feet

MASS = Mass flow rate, pound-mass/hour

MC = Annual maintenance cost, \$/year

M1 = Slope of a line on a plot of weight per foot versus price per foot of pipe, \$/foot

M2 = Slope of a line on a plot of BHP versus cost of the pump, \$/BHP

M3 = Slope of a line on a plot of hp versus cost of the motor or engine at hp less than 800, \$/hp.

M4 = Slope of a line on a plot of hp versus cost of the motor or engine at hp greater than 800, \$/hp

N = n = Flow behavior index, dimensionless

PAT = Annual profit after taxes, \$/year

PFIL = Single payment present worth factor

PIPEL = Operating life of the project, years

PSIMIL = Pressure drop per mile, PSI/mile

PUMPL = Operating life of the prime movers, years

P1 = Pressure at the entrance of the pipe, pound - force/foot^2

P2 = Pressure at the exit of the pipe, pound-force/foot^2

RE = Reynolds number of slurry flow, dimensionless

RHOP = Density of the pipe material, pound-mass/foot^3

S = Specific gravity of the solids, dimensionless

SCPM = Salvage value of prime movers, \$/year

SETL = Time required for the construction of the pipeline system, years

SL = Specific gravity of the liquid, dimensionless

SLD = Straight-line depreciation over project life, \$/year

SM = Specific gravity of the mixture, dimensionless

SMC = Factor for maintenance cost expressed as a fraction

SP = Salvage value factor for the pipe expressed as a fraction

SPIPE = Salvage value of pipe, \$/year

SPM = Salvage value factor for the prime movers expressed as a fraction

SUMLOS = Sum of the flow losses

T = Pipe-wall thickness, feet

TAU = τ = Slurry shear stress, dynes/cm^2

TAUY = τ_y = Slurry yield stress, dynes/cm^2

TEMP = Slurry temperature, degrees celsius

TI = Taxable income, \$/year

TONHR = Flow rate, dry short tons/hour

TR = Tax rate expressed as a fraction

V = Average slurry flow velocity, feet/sec.

VC = Critical velocity which delineates laminar flow from turbulent flow (RE=2100), feet/sec.

Z1 = Vertical distance above an arbitrary horizontal datum plane at the entrance of the pipe, feet

Z2 = Vertical distance above an arbitary horizontal datum plane at the exit of the pipe, feet

μ = Slurry dynamic viscosity, cp.

α_1 = Kinetic energy correction factor at point 1

α_2 = Kinetic energy correction factor at point 2

ρ = Density of the fluid, pound-mass/foot^3

INTRODUCTION

With the gradual depletion of the more accessible ore reserves and the increasing demand for minerals throughout the world, the vital role of economical and efficient transport systems has continued to receive greater recognition in the mineral industry. In the past, exploitation of reasonably rich deposits was abandoned due to excessive transportation cost involved in delivering mineral commodities to the market. Thus, the profitability of mineral ventures is significantly affected by well-designed transport systems as aids to operational effectiveness and costs.

The competitive role of alternate modes of transportation such as rail, truck, conveyor belt, barge, cableways, pipeline, and combinations of these is an important consideration in the planning and development of mineral resource projects. A technique is presented in this thesis for the economic selection of a slurry pipeline with the aid of a computer.

Likely candidates for large scale transportation of solids are coal, iron ore concentrates, potash, phosphate, sulfur, copper concentrates, limestone, and waste tailings from mineral processing plants. The carrier fluid will generally be water, although in some special cases, it may be convenient to use hydrocarbon fluids.

There are a few commercial slurry pipelines in existence throughout the world and many more are planned. As more precise knowledge of solid-liquid flow mechanisms and successful experience with constructed pipeline facilities is available, it is anticipated that pipeline transportation of minerals will assume a greater role than it has in the past.

STATEMENT OF THE PROBLEM

With the surge of growth that slurry pipelining is experiencing, more and more technical and economic evaluations are being conducted to determine the feasibility of pipeline transportation of mineral commodities. These evaluations are frequently based on data which are less precise than those associated with the more conventional materials-handling methods, and this uncertainty frequently leads to the rejection of the slurry pipeline concept.

Techniques similar to the one proposed in this study have been used for the design of oil and gas pipelines. Recognizing the complexity of slurry flow, it should still be possible to develop a similar tool for the flow of slurries in pipes. Cruz, Brison, and Engle (1) have developed a computer-based design system for slurry pipelines which provides information concerning piepline hydraulic characteristics, pipe selection, power requirements, and pump-station siting. The economics of pipeline transportation of slurries were not considered. Skelland (2) has presented an equation for Newtonian and non-Newtonian liquids which gives a total annual cost per foot of pipe length. The equation includes a pumping cost and the pipe cost, but excludes the cost of the pumps and motors. The method presented herein, equally valid for both Newtonian and non-Newtonian slurries, includes, in addition to Skelland's method, the cost of the prime movers in determining the optimum economic pipe diameter and then computes the necessary velocity from the continuity equation to deliver the required throughput.

Unfortunately, where slurries are concerned, the complex flow patterns may be difficult to analyze. This is why the accuracy of any evaluation technique is affected by the accuracy of the slurry data. Furthermore, the slurry pipeline equipment may be subjected to severe wear by the solids phase. Costs for operation and maintenance of existing slurry pipelines are sparsely documented, and the economic impact of slurry wear may only be estimated.

At the present time, past experience and rules of thumb play a major role in the design of slurry pipelines. A method by which an economic slurry pipeline can be selected with the aid of a computer is required to fill this gap in preliminary slurry pipeline design. To the author's knowledge, a computer technique capable of handling both the technical and economic considerations has not been developed to date. The computer program allows various transport aspects to be systematically investigated to determine their technical and economic merits. The technique developed herein considers only the transportation portion of the total cost. Only the pipeline and its prime movers (pumps and motors) are considered. Other unique investments in slurry pipeline facilities such as the slurry preparation plant, slurry separation plant, right-of-way, instrumentation and controls are not included in the system evaluation. According to Aude, Thompson, and Wasp (3), a typical breakdown of costs for a long distance slurry pipeline is as follows: Fixed-70%, Power-15%, and Labor & Supplies-15%. The general statistics indicate that slurry pipelines are capital-intensive.

The advantages of this method are several-fold. Although the initial output from the computer program is by no means a final design, it gives a good starting point for a detailed engineering study. With better input, the method can be used to give a final design. Indeed, the method could be altered to include some of the unique features such as right-of-way costs. A wide range of system costs is generated quickly with a minimum of input. An additional feature of the method is the ease with which the variables can be adjusted to measure the sensitivity of the total cost to changes in the variables. The purpose of the sensitivity analysis is to identify those critical variables that, if changed, can considerably affect the total cost. Mathematically, individual variables are changed and the effect of such a change on the annual total cost is computed. But from a designer's point of view, individual components in the system are changed to study their effect on the annual total cost. A change in one component of the system may involve a change in one or more variables. For example, the replacement of a steel pipe by a smooth-lined pipe will change the pipewall roughness and wall thickness as well as purchase, operating, and maintenance costs.

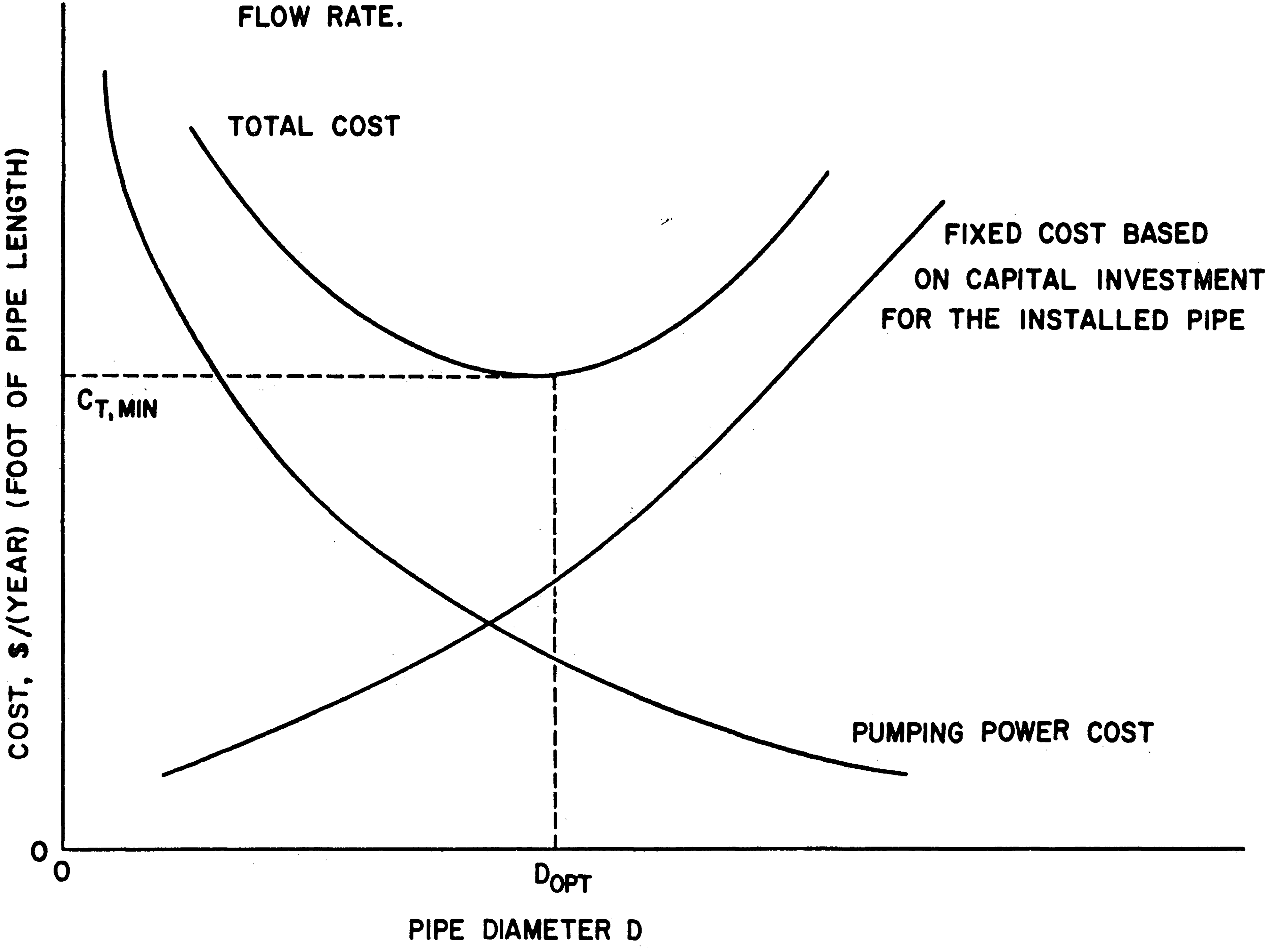
THEORETICAL AND ECONOMIC CONSIDERATIONS

For any given set of flow conditions, the use of an increased pipe diameter will cause an increase in the fixed costs (capital costs) for the piping system and a decrease in the pumping costs (operating costs). Therefore, an optimum economic pipe diameter must exist. The value of this optimum diameter can be determined by combining the principles of fluid dynamics with cost considerations. The optimum economic pipe diameter is found at the point where the sum of pumping costs and fixed costs based on the cost of the piping system is a minimum.

Fig. 1 illustrates a typical situation. As the pipe diameter, D, increases, the friction losses and the related pumping costs decrease. However, the larger pipe diameter and associated equipment results in a greater fixed cost because of the larger investment. The sum of the fixed and operating cost curves results in a total cost curve whose minimum is the optimum pipe diameter for the system to be considered.

In accordance with the exceptions noted earlier, the total cost expression will comprise standard equipment only.

FIGURE I. OPTIMUM PIPE DIAMETER FOR MINIMUM TOTAL COST AT A FIXED MASS FLOW RATE.



Unique features that vary from one situation to another are not considered here. Thus, the annual total cost expression (C Total) for pipeline transportation of mineral commodities can be expressed as follows:

$$\text{C Total}=\text{C Pumping}+\text{C Pipe}+\text{C Pump}+\text{C Motor} \qquad (1)$$

The first term on the right-hand side of Eq. (1) represents the operating cost and the last three terms represent the capital and maintenance costs of the pipe, pumps and motors, respectively.

The starting point in the development of the total cost expression is the total energy balance between the source and terminal of the pipeline. The total energy balance for this system between point 1 near the entrance and exit point 2 may be written as follows:

$$\frac{1}{2G}\left(\frac{V2^2}{\alpha_2}-\frac{V1^2}{\alpha_1}\right)+\frac{P2-P1}{\rho}+(Z2-Z1)+HP+SUMLOS=0 \qquad (2)$$

The variables are defined in the Nomenclature section. The total energy balance, thus, consists of five terms, namely the velocity head, the differential pressure head, the elevation gradient, pump input, and a term that includes all the losses in the system. The losses are due to entrance effects, pipe fittings, and the frictional loss in the pipe. Since the pipe is of constant diameter, $V_2=V_1=V$; also the energy coefficients α_1 and α_2 are assumed to be identical.

Substituting the Fanning equation for head loss and using the continuity equation, we can arrive at an expression for the pumping cost. The Fanning equation can be written as

$$SUMLOS = \frac{2FV^2L}{GD} \tag{3}$$

and the continuity equation can be written as

$$V = \frac{MASS}{900\pi D^2\rho} \tag{4}$$

The pipe cost is essentially a function of the weight of pipe material. Depreciation, maintenance, and the cost of fittings are incorporated into the expression for the pipe cost.

The pump cost and the motor cost expressions are a function of the pumping cost, in addition to the functional relationship of the type of pump and motor themselves. Here again, depreciation, maintenance, and the cost of accessories are incorporated in the final expression for the pump and motor.

Ratios of the total cost for fittings and installation to total purchase cost of the pipe, pumps, and motors are also incorporated in the annual total cost expression.

The complexity of the total cost expression is a function of the flow regime and the mathematical model selected to describe the slurry. According to Govier and Aziz (4), many non-Newtonian homogeneous slurries can be defined by the general mathematical model $\tau - \tau_y = K\dot{\gamma}^n$. The generalized model reduces to simpler expression for other rheological models as follows:

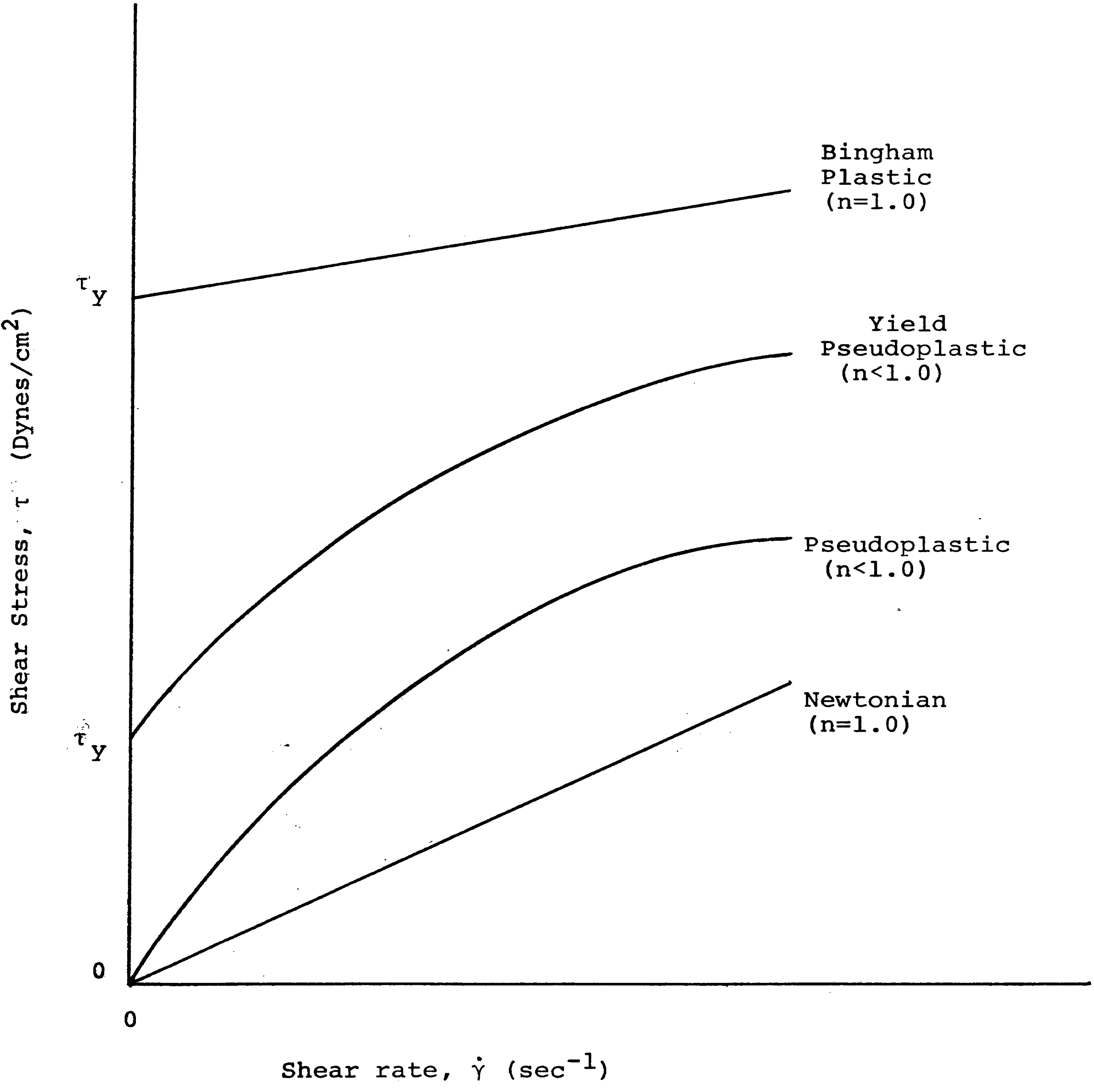
1. Newtonian fluids $\tau = \mu\dot{\gamma}$; $(n = 1.0, K = \mu)$
2. Bingham plastic slurries $\tau - \tau_y = K\dot{\gamma}$; $(n = 1.0)$
3. Pseudoplastic slurries $\tau = K\dot{\gamma}^n$

The generalized model remains unchanged for a yield-pseudoplastic. Fig. 2 shows the general shape of the curves on a rheogram for different rheological models.

In order to utilize the models shown above, laboratory measurements must be obtained from the slurry being examined. These measurements will provide data which will yield values for τ_y, τ, $\dot{\gamma}$, K, and n. From these data, the slurry Reynolds number may be determined, and then, by means of a Moody diagram, the friction factor. The friction factor is then used to compute the friction head losses by means of the Fanning equation.

The computer program used here is comprised of two parts. The first reduces the rheological data and computes all of the data necessary to design the pipeline. The second portion of the program computes the annual cost of the piping system. The emphasis in this study is on the second portion of the program.

Figure 2. Flow Curves for Various Types of Time-Independent Fluids.



The designer must be aware of the fact that few homogeneous slurries are, in fact, truly homogeneous. Inevitably some coarse solids are present which can deposit on the invert of the pipe at low velocities. Therefore, such slurries are approximated by the models mentioned above and it is the duty of the designer to establish the accuracy of the mathematical model selected from rheological data.

The procedure for the analysis of heterogeneous slurry flow in pipes is similar to that for homogeneous flow. A computer program developed at the Colorado School of Mines is capable of handling heterogeneous slurries. Viscometers, whether rotational or capillary, cannot provide precise rheological measurements for slurries containing particles coarser than about 65 mesh (0.20 mm). For this reason, pipeline loop studies are necessary to develop mathematical models for heterogeneous slurries.

The mathematical models are used to compute a friction factor for the slurries which, in turn, is used to determine the pumping costs. Capital cost data for plain and lined pipes, centrifugal and positive displacement pumps, motors and engines were collected from several domestic and foreign companies. The detailed data are presented in appendices II and III. Plain and lined pipe data showed a straight-line relationship for weight versus cost on rectangular coordinates.

Centrifugal pumps were correlated by a straight line fit of brake horsepower versus cost on logarithmic plots and the positive displacement pumps showed straight-line relationship for the same two variables on rectangular coordinates. The mathematical model for logarithmic plots is $Y=CX^M$, whereas the mathematical model for rectangular plots is $Y=MX+C$. In these equations Y is the dependent cost variable, X is the appropriate independent variable, M is the slope and C is the intercept. The motors and engines showed good correlation of horsepower versus cost on rectangular coordinates. All the curves for pipes, pumps, motors and engines on rectangular coordinates were forced through the origin. The coefficient of correlation for each of the plots was greater than 0.95.

Since the pump cost and the motor cost expressions in Eq. (1) are similar, they can be combined into one term. As a safety precaution, the horsepower of the motor or the engine is always selected higher than that required by the pump. A service factor of 1.15 was recommended by manufacturers of the prime movers and is incorporated in the computer program.

Depreciation is a tax deduction allowed for obsolecence, wear and tear of the equipment or the property during its normal use in a business operation. Some of the most common methods of depreciation allowed by the Internal Revenue Service and implemented in the mineral industry are the straight-line method, the declining balance method, and the sum of the years-digits method.

The straight-line method is the simplest for computing depreciation. Under this method, the cost of the equipment or the property less its salvage value is generally deducted in equal annual amounts over the period of its depreciable life.

The declining balance method applies a depreciation rate of up to twice the straight-line rate. This double declining balance method provides the most accelerated depreciation method allowed by the Internal Revenue Service. Salvage value is neglected with declining balance method, although the total accumulated depreciation cannot exceed the purchase cost less the salvage value.

The sum of the years-digits method applies a different depreciation rate each year to the cost of the asset less its estimated salvage value. Therefore, a varying rate each year is applied to a constant amount.

For simplicity, straight-line depreciation is assumed over the life of the slurry pipeline project in the case study analyzed. Also, since the throughput in a slurry pipeline is essentially constant over the life of the project, it is only logical to deduct straight-line depreciation for tax purposes.

According to Rudawsky (5, 6),

> ...a very basic concept in economics is that money has a time value--a given sum of money now is normally worth more than an equal sum at some future date. An investor is ready to give up some rights to present income only if he can get more future income. Likewise, firms and individuals borrow money at present, to be repaid at a somewhat higher amount in the future.

The time lag between outlays of investment funds for a slurry pipeline and the inflow of revenue once this pipeline becomes operative necessarily implies that different values of money are under consideration because of the effect of time. The difference between the value of earlier availability rather than later availability of money is called the interest rate or the cost of capital. The interest rate is almost invariably positive and is usually expressed as a percent per unit time.

Cash flow measures the actual flow of funds into or out of a specific project. Net cash flow is the excess of inflows over outlays for operating costs and capital expenditures. Time value of money and cash flow are the basic concepts incorporated in many of the investment appraisal techniques.

The net present value (N.P.V.) method is the most common evaluation technique in use. A predetermined interest rate which represents the firm's cost of capital is required for the analysis. Expected net cash flows throughout the life of the project, either negative or positive, are compounded or discounted to a given time period (usually the present) and summed up. A positive net present value indicates a favorable venture.

The discounted cash flow rate-of-return (D.C.F.) method determines that interest rate which makes the present value of the aggregate cash inflows equal to the present value of the combined investment outlays. The interest rate is determined by trial and error.

Stermole (7) has presented several techniques for computing the net present value and the discounted cash flow rate-of-return analyses.

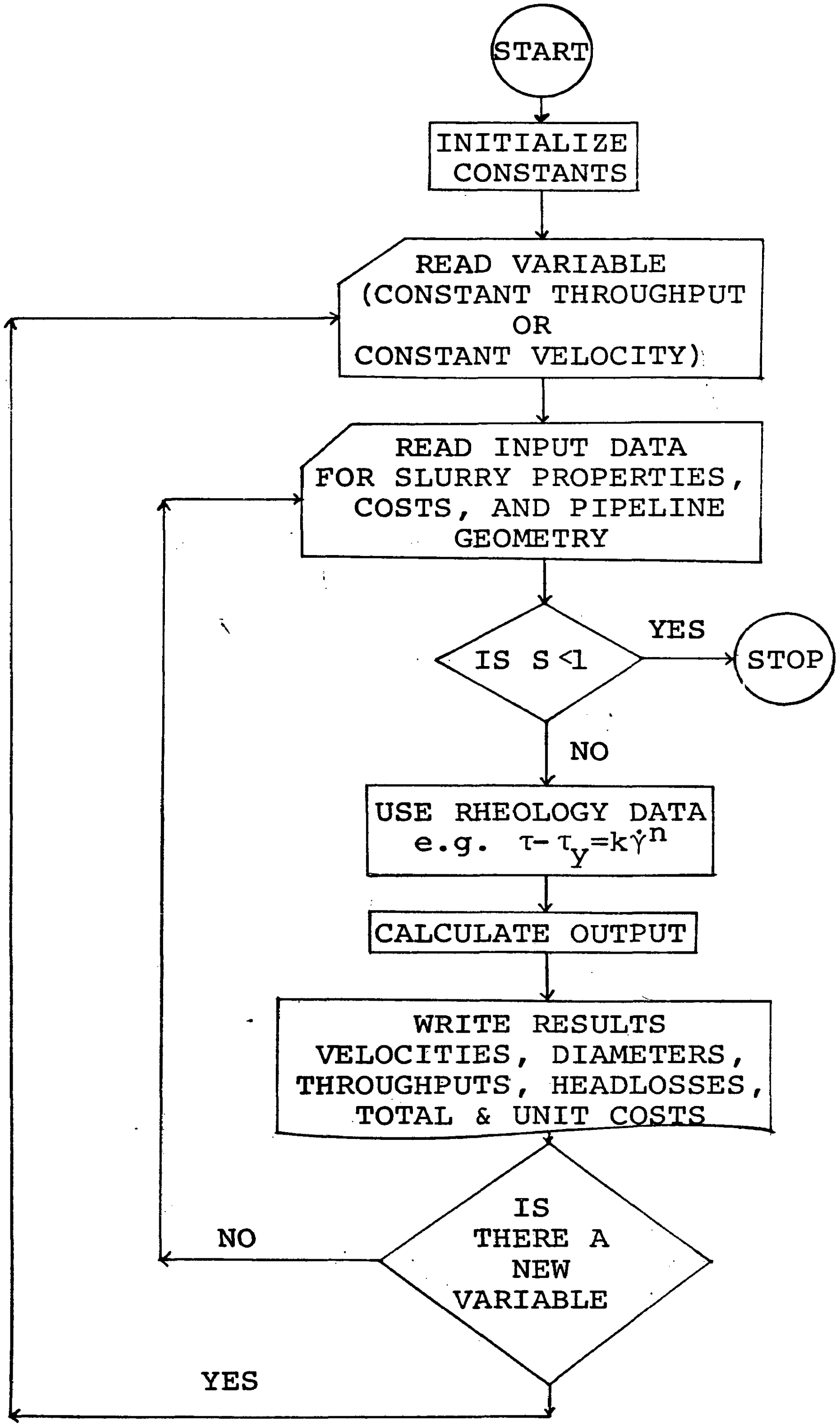
PROCEDURE

Fig. 3 shows a flow chart of the computer program to determine optimum pipe diameter and approximate pipeline cost for homogeneous slurries.

The computer program for homogeneous slurries (as presented in appendix I) is capable of handling constant throughput or constant velocity. Either a range of throughputs and pipe diameters or a range of velocities and pipe diameters may be specified. The continuity equation can be solved for the remaining unknown. Since it was desired to compare costs in different diameter pipes, a range of throughputs and pipe diameters was specified for the case study analyzed.

Input data including rheological parameters are read into the computer program for homogeneous slurries. The analysis for the heterogeneous slurries is similar where pipeline data are read into the computer program for heterogeneous suspensions. Many non-Newtonian homogeneous slurries may be defined, for example, by the general mathematical model $\tau-\tau_y=K\dot{\gamma}^n$ for yield pseudoplastic slurries.

Figure 3. Flow Chart for the Computer Program



The computer program determines the flow regime by checking the Reynolds number of flow. Conventional equations for laminar flow, turbulent flow in smooth pipes, rough-wall turbulence, and fully rough-wall turbulent flow are included in the program. An annual total cost comprising the pumping cost (operating cost) and the capital cost of the pipe and the prime movers is then computed. Finally, a unit transportation cost in cents per ton-mile, incorporating straight-line depreciation and the time value of money concepts, is obtained, using the net present value analysis. Comment cards are inserted in the economics section of the computer program to aid in the understanding of the step-by-step calculations for the net present value analysis in determining the unit transportation cost for a slurry pipeline.

It must be pointed out that the net present value analysis approach utilized in the computer program is an unconventional method of solving problems in the mineral industry. In most mineral projects, the market price of the commodity is essentially fixed. Knowing the quantity sold, annual revenue can be calculated and the annual cash flow computed. But in the case study analyzed, the annual cash flow is calculated and the problem worked backwards to determine the unit transportation cost, incorporating the time value of money concept.

CASE STUDY AND RESULTS

In order to evaluate the computer approach to pipeline selection, a case study was made. In this case study, data obtained from a Research Institute project were evaluated by the computer program to determine optimum pipe sizes and approximate pipeline costs. The results of the computer analysis were then compared with the results of a study based upon the same data as analyzed by an independent engineering firm.

The material-handling problem stated that fine limestone was to be transported at a rate of 200 dry short tons per hour, in the form of a slurry, by a pipeline over a distance of 11.74 miles. The quarry is located on a hill and the limestone slurry is pumped down to a cement plant. The pipeline drops from the quarry which is located at an elevation of 2,660 feet down to 720 feet. The pipeline then rises over a ridge to an elevation of 1360 feet and finally drops to its terminus at 270 feet above sea level at the cement plant.

The computer program presented herein does not take into account the specific topography. Considered only are elevations at the entrance and the exit of the pipeline. For further detailed analysis, the computer program can be modified to include various topographic considerations.

The limestone is crushed at the quarry to a mean particle size of 200 mesh and is mixed with water in a mixing tank. A centrifugal pump at the bottom of the mixing tank feeds a positive displacement pump, which--in turn--feeds the pipeline. At the terminus, the slurry is discharged into a storage tank.

As mentioned earlier, only the pipeline and its prime movers are considered in the evaluation of the transportation cost. Other unique investments in slurry pipeline facilities, such as the slurry preparation plant, slurry separation plant, right-of-way, coating and wrapping of the pipe, instrumentation and controls are not included in the system evaluation. Indeed, for a detailed analysis, the computer program could be expanded to include some or all of these unique features.

Since the limestone pipeline in the case study analyzed has a favorable gradient, some of the results given by the sensitivity analyses may be distorted. In order to show a range of costs, all the computer runs were repeated for an adverse gradient by switching the numerical values of the elevation gradient at the entrance of the pipe (Z1=2,600) and the elevation gradient at the exit of the pipe (Z2=270). The results for a favorable gradient and an adverse one are both summarized on the same tables. Numbers without parentheses represent results for a favorable gradient, whereas numbers in parentheses are for an adverse gradient. The results for a horizontal pipeline transporting limestone will be somewhere in between the results for a favorable gradient and an adverse gradient.

A series of rheology studies were conducted in the Rheology Laboratory at the Colorado School of Mines on a 200-mesh limestone. The rheological measurements were made with a Brookfield rotational viscometer for a slurry concentration of 66.4 percent by weight. The slurry was first mixed in a blender. The viscometer spindle was then lowered into the blender jar to obtain the readings. The slurry was agitated briefly prior to the recording of each value, but the measurements were made in a quiescent slurry under controlled temperatures. In addition to the rheology measurements, solids' specific gravity was determined. A value of 2.712 was obtained for the limestone. From the rheological studies, the slurry was found to be homogeneous and the mathematical model assumed for the slurry was yield-pseudoplastic. The results of these tests at the Rheology Laboratory were incorporated in the computer runs for the specific case study.

The net present value method is utilized in the computer program to determine the unit transportation cost for a slurry pipeline. Dimensionless ratios for the total cost of fittings and installation to total purchase cost of the pipe, pumps and motors are also incorporated in the program. The numerical values for these ratios are obtained by dividing the variable costs by the fixed costs. The advantage of using these ratios is that a sensitivity analysis can be easily performed to determine their impact on total or unit transportation cost. The time required for the construction of the pipeline is taken into account. Federal, state, and local taxes are incorporated in the form of an overall tax rate. Other factors for pump and motor efficiency, slurry pressure at entrance and exit of the pipe, cost data from appendices II and III, elevation gradient, etc., are also included.

Slurry pressure at the entrance of the pipe is measured at the point where the centrifugal pump at the bottom of a mixing tank feeds the positive displacement pump. At the end of the pipeline, the slurry is discharged into a storage tank where the exit pressure is recorded.

Data for a study case of a limestone slurry pipeline are presented in Table 1.

TABLE 1

Data For a Limestone Slurry Pipeline

CE = Cost of electrical energy, \$/KW-hr =0.02

CW = Concentration by weight, decimal fraction =0.664

C1 = Intercept on a plot of weight per foot versus price per foot of pipe, \$ =0.00

C2 = Intercept on a plot of BHP versus cost of the pump, \$ =0.00

C3 = Intercept on a plot of hp versus cost of the motor or engine at hp less than 800, \$ =0.00

C4 = Intercept on a plot of hp versus cost of the motor or engine at hp greater than 800, \$ =4300.00

E = Pipe absolute roughness, feet =0.00015

EFFCNC = Efficiency of pump and motor expressed as a fraction =0.675

EP = Efficiency of the pump expressed as a fraction =0.75

FACTOR = Inflation factor for each future investment of prime movers (5 allowable), dimensionless =1.0, 0.0, 0.0, 0.0, 0.0

FR1 = Ratio of the total cost for fittings and installation to total purchase cost of pipe, dimensionless =1.32

FR2 = Ratio of the total cost for fittings and installation to total purchase cost of pump, dimensionless =0.14

FR3 = Ratio of the total cost for fittings and installation to total purchase cost of motor, dimensionless =0.36

G = Gravitational acceleration, feet/sec^2 =32.1573

H = Hours of pipeline operation per year, hours/year =7884.

INT = Annual cost of capital expressed as a fraction =0.10

K = Consistency index from rheology data dynes-sec^n/cm^2 =57.2

LENGTH = L = Pipe length, feet =62,000.

M1 = Slope of a line on a plot of weight per foot versus price per foot of pipe, $/foot =0.1557

M2 = Slope of a line on a plot of BHP versus cost of the pump, $/BHP =96.25

M3 = Slope of a line on a plot of hp versus cost of the motor or engine at hp less than 800, $/hp =17.19

M4 = Slope of a line on a plot of hp versus cost of the motor or engine at hp greater than 800, $/hp =11.43

N = n = Flow behavior index, dimensionless =0.209

PIPEL = Operating life of the project, years =20.0

PUMPL = Operating life of the prime movers, years =20.0

P1 = Pressure at the entrance of the pipe, pound - force/foot^2 =7,200.

P2 = Pressure at the exit of the pipe, pound - force/foot^2 =2,880.

RHOP = Density of the pipe material, pound - mass/foot^3 =491.

S = Specific gravity of the solids, dimensionless =2.712

SETL = Time required for the construction of the pipeline system, years =1.0

SL = Specific gravity of the liquid, dimensionless =1.0

SMC = Factor for maintenance cost expressed as a fraction =0.1

SP = Salvage value factor for the pipe expressed as a fraction =0.0

SPM = Salvage value factor for the prime movers expressed as a fraction =0.2

T = Pipe-wall thickness, feet =0.0208

TAUY = τ_y = Slurry yield stress, dynes/cm^2 =17.91

TEMP = Slurry temperature, degrees celsius =20.6

TR = Tax rate expressed as a fraction =0.50

Z1 = Vertical distance above an arbitrary horizontal datum plane at the entrance of the pipe, feet =2,600

Z2 = Vertical distance above an arbitrary horizontal datum plane at the exit of the pipe, feet =270.

Cost data for plain and lined pipes, centrifugal and positive displacement pumps, motors and engines were adjusted to June 1974 values, using Marshall and Swift's "all industries" equipment cost index (8). The indices are tabulated in Table 2.

TABLE 2

Marshall and Swift Equipment Cost Index

(Base: 1926=100)

Year	Quarter Ending	All Industries	Factor
1972	March	326.8	100.00
1972	June	330.6	101.16
1972	September	334.1	102.23
1972	December	336.7	103.04
1973	March	338.8	103.67
1973	June	342.9	104.93
1973	September	345.2	105.63
1973	December	349.5	106.95
1974	March	362.2	110.83
1974	June	386.1	118.15

Primary Analyses

A wide range of pipe diameters (4-, 6-, 8-, 10-, and 12-inch) was specified for the first set of computer runs. The purpose of these runs was to narrow the range of pipe diameters for the final study. The pertinent results from the computer output are presented in Table 3.

From Table 3, it will be seen that a minimum transportation cost in cents per ton-mile occurs with an 8-inch diameter pipe. It also appears that a transport velocity of

TABLE 3

Primary Analysis for 200 Dry Short Tons Per Hour of Limestone

Pipe I.D. (in.)	4	6	8	10	12
Critical Velocity (ft/sec)	5.5 (5.5)*	5.2 (5.2)	5.0 (5.0)	4.9 (4.9)	4.8 (4.8)
Operating Velocity (ft/sec)	17.9 (17.9)	7.9 (7.9)	4.5 (4.5)	2.9 (2.9)	2.0 (2.0)
PSI/mile	1575.03 (1575.03)	289.85 (289.85)	78.88 (78.88)	55.84 (55.84)	42.19 (42.19)
Annual Total Cost ($)	1,953,024 (2,342,807)	303,622 (702,363)	152,351 (358,969)	189,286 (386,946)	226,221 (423,881)
Cost (¢/ton-mile)	10.548 (12.653)	1.640 (3.793)	0.823 (1.939)	1.022 (2.090)	1.222 (2.289)
Prime Movers	Yes (Yes)	Yes (Yes)	No (Yes)	No (Yes)	No (Yes)

*Values in parentheses represent results for an adverse gradient.

4.5 feet per second will be required to transport 200 tons per hour of dry solids, and that the favorable elevation gradient is great enough to overcome friction losses so that a pump is not needed. Note, however, that the operating velocity of 4.5 feet per second is less than the critical velocity of 5.0 feet per second and hence the design is unfeasible. Also note that the critical velocities, the operating velocities, and the pressure drops to overcome wall friction are unaffected by the elevation gradient.

The two constraints usually applied in the economic selection of a slurry pipeline to transport a given throughput are that the operating velocity exceed the critical velocity which delineates laminar flow from turbulent flow and that the Reynolds number exceed 4,000. Laminar flow prevails for a Reynolds number less than approximately 2,100, whereas the transition flow exists between a Reynolds number of 2,100 and 4,000. Due to erratic behavior in the laminar flow regime and the instability of pressure and velocity in the transition flow regime, it is customary to operate in the turbulent flow regime. Operating in the turbulent zone will also prevent coarse particles from settling in the pipe.

Since the limestone in the case study considered is quite fine, only the constraint that operating velocity exceed the critical velocity was applied for subsequent runs.

Secondary Analyses

A closer range of pipe diameters (5-, 6-, 7-, 8-, and 9-inch) was specified for subsequent computer runs, whose results are summarized in Table 4. From these runs, it will be seen that, for a favorable gradient, a minimum cost of 0.790 cents per ton-mile is obtained with a 7-inch pipe, and that a pump is required. The operating velocity of 5.8 feet per second does exceed the ciritical velocity of 5.1 feet per second.

For an adverse gradient, a minimum cost of 1.939 cents per ton-mile is obtained with a 8-inch pipe. However, the operating velocity of 4.5 feet per second does not exceed the critical velocity of 5.0 feet per second and hence the design is unfeasible. A 7-inch diameter pipe with a unit transportation cost of 2.944 cents per ton-mile would offer a feasible solution. The unit transportation cost for an adverse gradient is approximately 3.5 times that for a favorable gradient, despite the fact that an identical 7-inch diameter pipeline is recommended for each case.

In the case of a favorable gradient, for pipe diameters greater than 7 inches, the annual total cost for a given pipe diameter remains constant over the throughput range of 150 to 250 dry short tons per hour because the gravitational force due to the elevation gradient is sufficient to permit slurry flow without the aid of prime movers. Thus, pumping cost, the pump cost, and the motor cost from Eq. (1) drop out and the total cost comprises pipe cost only. On the basis of these runs, a 7-inch pipe with a pump would offer the minimum cost for the transport problem outlined earlier.

The mine is located on a hill and water needed for the limestone slurry has to be pumped up to the mine site. A positive displacement type of pump is used to transport water. Multi-stage centrifugal pumps in several pump stations would offer a better design but for simplicity, a positive displacement type of pump was specified. The minimum annual cost for transporting 400 U.S. gallons of water per minute occurs when a 6-inch diameter pipe is used. The results are presented in Table 5.

TABLE 4

Secondary Analysis for 200 Dry Short Tons Per Hour of Limestone

Pipe I.D. (in.)	5	6	7	8	9
Critical Velocity (ft/sec)	5.3 (5.3)*	5.2 (5.2)	5.1 (5.1)	5.0 (5.0)	5.0 (5.0)
Operating Velocity (ft/sec)	11.4 (11.4)	7.9 (7.9)	5.8 (5.8)	4.5 (4.5)	3.5 (3.5)
PSI/mile	613.31 (613.31)	289.85 (289.85)	155.86 (155.86)	78.88 (78.88)	65.70 (65.70)
Annual Total Cost ($)	709,580 (1,108,321)	303,622 (702,363)	146,278 (545,018)	152,351 (358,969)	170,818 (377,436)
Cost (¢/ton-mile)	3.832 (5.986)	1.640 (3.793)	0.790 (2.944)	0.823 (1.939)	0.923 (2.038)
Prime Movers	Yes (Yes)	Yes (Yes)	Yes (Yes)	No (Yes)	No (Yes)

* Values in parentheses represent results for an adverse gradient.

TABLE 5

Secondary Analysis for 400 U.S. Gallons Per Minute of Water

Pipe I.D. (in.)	4	5	6	7	8
Critical Velocity (ft/sec)	0.07	0.05	0.05	0.04	0.03
Operating Velocity (ft/sec)	10.2	6.5	4.5	3.3	2.6
PSI/mile	198.92	64.41	25.84	12.01	6.21
Annual Total Cost ($)	271,121	201,439	194,631	204,031	218,697
Cost (¢/ton-mile)	2.929	2.176	2.102	2.204	2.362
Prime Movers	Yes	Yes	Yes	Yes	Yes

SENSITIVITY ANALYSES

The purpose of subsequent runs was to illustrate the value of the sensitivity analysis. It is conceivable that some of the variables in the study case for the limestone pipeline considered earlier may have large tolerances. This section attempts to identify those critical variables that, if changed, can considerably affect the slurry transportation cost. It must be pointed out that the results of the analyses cannot be generalized for every case study under consideration. The favorable gradient encountered here for the limestone pipeline has a very important impact on the energy consumption, frictional losses, and number of pump stations. The same pipeline system transporting the limestone slurry uphill would show different results in the sensitivity analyses.

The following procedure may be a typical one that an engineer might follow in exploring the sensitivity of the variables.

If a slurry under consideration happens to be abrasive and/or corrosive, it would be necessary to increase the pipe wall thickness or line the pipe. In one run, the pipe wall thickness was doubled from 0.25 inches to 0.50 inches and the effect of this change for a favorable gradient was to double approximately the pipe cost. The total costs are not exactly doubled, because the maintenance cost and the fixed cost of fittings were not adjusted accordingly due to insufficient data. Also, the cost of the prime movers remained unchanged. For an adverse gradient, the increase in cost is not very pronounced because the major contribution to the total cost comes from the operating costs and not from the capital cost. The results of these runs are presented in Table 6.

The manufacturers claim that the effect of lining a pipe with polyethylene is to double approximately the pipe cost and quadruple its expected life, due to reduced oxygen corrosion. The cost of a rubber-lined pipe is 3 to 4 times that of an unlined steel pipe and it gives up to 6 times the service life of an unlined carbon steel pipe. A new polyurethane-lined steel pipe costs 3 to 4 times that of an unlined steel pipe and gives up to 20 times the service life of an unlined carbon steel pipe on abrasive slurry duties (9). For pipe diameters less than 8 inches, the cost of rubber-lined and polyurethane-lined pipes is 4 times that of an unlined steel pipe, whereas for pipe diameters greater than 8 inches, the cost of rubber-lined and polyurethane-lined pipes is 3 times that of an unlined steel pipe. Of course, the type of pipe and the thickness of the lining play an important role in cost determination. The long-life expectancy of the polyurethane-lined steel pipe has obviously spurred interest in the mineral industry despite its rather recent entry into the field of slurry pipelining.

In another run, the steel pipe with 0.25 inches wall thickness was lined with polyethylene to obtain a smooth wall. The effect of lining the pipe was to double approximately the capital cost of the pipe. One of the variables in the computer program is the density of the pipe material (RHOP). Due to insufficient data, the density of the polyethylene-lined pipe was assumed to be the same as the API pipe. Also, it was assumed that the inside diameter of the pipe was not affected by the lining. The results of this run are summarized in Table 7.

Note that for a favorable gradient, the optimum pipe diameters for the lined pipe and the steel pipe are 5 inches and 7 inches, respectively. However, for an adverse gradient, the optimum pipe diameter for both the lined pipe and the steel pipe is 7 inches. It is evident from Tables 6 and 7 that lining the pipe with polyethylene is an economical alternative to doubling the pipe wall thickness.

TABLE 6

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone (Pipe-Wall Thickness Doubled)

Pipe I.D. (in.)	5	6	7	8	9
Critical Velocity (ft/sec)	5.3 (5.3)*	5.2 (5.2)	5.1 (5.1)	5.0 (5.0)	5.0 (5.0)
Operating Velocity (ft/sec)	11.4 (11.4)	7.9 (7.9)	5.8 (5.8)	4.5 (4.5)	3.5 (3.5)
PSI/mile	613.31 (613.31)	289.85 (289.85)	155.86 (155.86)	78.88 (78.88)	65.70 (65.70)
Annual Total Cost ($)	815,747 (1,214,487)	428,256 (826,997)	289,380 (688,121)	313,921 (520,538)	350,856 (557,474)
Cost (¢/ton-mile)	4.406 (6.559)	2.313 (4.467)	1.563 (3.716)	1.695 (2.811)	1.895 (3.011)
Prime Movers	Yes (Yes)	Yes (Yes)	Yes (Yes)	No (Yes)	No (Yes)

* Values in parentheses represent results for an adverse gradient.

TABLE 7

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone (Rough versus Smooth Pipe)

Pipe Type	Optimum Pipe I.D. (in.)	Critical Velocity (ft/sec)	Operating Velocity (ft/sec)	PSI/mile	Annual Total Cost ($)	Cost (¢/ton-mile)	Prime Movers
API 5L* (rough)	7 (7)**	5.1 (5.1)	5.8 (5.8)	155.86 (155.86)	146,278 (545,018)	0.790 (2.944)	Yes (Yes)
Polyethylene -lined pipe (smooth)	5 (7)	5.3 (5.1)	11.4 (5.8)	175.17 (49.02)	226,140 (556,852)	1.221 (3.007)	Yes (Yes)

*Design pipe

**Values in parentheses represent results for an adverse gradient.

Another set of runs tested the sensitivity of the annual total costs as the rheological parameters K and n were both varied ± 25% and ± 50% from the design values. The results are summarized in Tables 8 and 9. The constraint applied in each case for the desired throughput was that the operating velocity exceeds the critical velocity which delineates laminar flow from turbulent flow.

Tables 8 and 9 show that a decrease in K and n does not affect cost as much as an increase in these parameters. For a favorable gradient, this is attributed to the fact that no prime movers are required when K and n are decreased; the prime movers are required when K and n are increased. Also, in order to satisfy the constraints mentioned earlier, the pipe diameter is reduced to maintain a sufficiently high velocity when K and n are increased. Thus, for this particular case study, the accuracy of the rheological parameters K and n is not extremely critical when the data are varied -25% and -50% from the design value. On the other hand, the accuracy of the rheological parameters K and n is extremely critical when the data are varied +25% and +50% from the design value. Likewise, for an adverse gradient, the accuracy of the rheological parameters K and n is not as critical when the data are varied -25% and -50% from the design value as when the data are varied +25% and +50% from the design value.

TABLE 8

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone
(Change K ±25% and ±50%)

K dynes-sec^n cm2	Pipe I.D. (in.)	Critical Velocity (ft/sec)	Operating Velocity (ft/sec)	PSI/mile	Annual Total Cost ($)	Cost (¢/ton-mile)	Prime Movers	% Change in Cost
28.6	7 (9)**	3.5 (3.4)	5.8 (3.5)	127.64 (46.46)	133,883 (438,399)	0.723 (2.368)	No (Yes)	-8.47 (-19.56)
42.9	7 (8)	4.4 (4.3)	5.8 (4.5)	143.13 (83.97)	133,883 (469,156)	0.723 (2.534)	No (Yes)	-8.47 (-13.92)
57.2*	7 (7)	5.1 (5.1)	5.8 (5.8)	155.86 (155.86)	146,278 (545,018)	0.790 (2.944)	Yes (Yes)	0.00 (0.00)
71.5	6 (6)	5.9 (5.9)	7.9 (7.9)	308.87 (308.87)	328,575 (727,315)	1.775 (3.928)	Yes (Yes)	+124.62 (+33.45)
85.8	6 (6)	6.5 (6.5)	7.9 (7.9)	325.82 (325.82)	350,822 (749,563)	1.895 (4.048)	Yes (Yes)	+139.83 (+37.53)

* Design Value

**Values in parentheses represent results for an adverse gradient.

TABLE 9

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone (change n ±25% and ±50%)

n	Pipe I.D. (in.)	Critical Velocity (ft/sec)	Operating Velocity (ft/sec)	PSI/mile	Annual Total Cost($)	Cost (¢/ton-mile)	Prime Movers	% Change in Cost
0.105	7	4.0	5.8	136.38	133,883	0.723	No	-8.47
	(8)**	(4.0)	(4.5)	(80.78)	(464,959)	(2.511)	(Yes)	(-14.70)
0.157	7	4.5	5.8	145.64	133,883	0.723	No	-8.47
	(7)	(4.5)	(5.8)	(145.64)	(531,606)	(2.871)	(Yes)	(-2.46)
0.209*	7	5.1	5.8	155.86	146,278	0.790	Yes	0.00
	(7)	(5.1)	(5.8)	(155.86)	(545,018)	(2.944)	(Yes)	(0.00)
0.261	6	6.0	7.9	311.46	311,973	1.793	Yes	+126.95
	(6)	(6.0)	(7.9)	(311.46)	(730,713)	(3.947)	(Yes)	(+34.07)
0.313	6	6.8	7.9	335.56	363,590	1.964	Yes	+148.56
	(6)	(6.8)	(7.9)	(335.56)	(762,331)	(4.117)	(Yes)	(+39.87)

*Design value

**Values in parentheses represent results for an adverse gradient.

A similar analysis was performed on the sensitivity of the annual total costs as the rheological parameter τ_y was varied ±25% and ±50% from its design value. Since τ_y does not appear in the equations for turbulent flow regime, these results remained unchanged from the design values.

In a slurry pipeline operation, the maintenance cost may comprise of routine checks along the pipeline route, pipeline repairs, lubrication of the prime movers, and regular maintenance of the pumping stations. Maintenance costs for existing slurry pipelines are sparsely documented and the purpose of the next run was to determine the impact of a ±50% change in the maintenance cost on the annual total cost. The results are presented in Table 10.

The maintenance cost was assumed to be constant over the life of the project. But in reality, the maintenance cost changes over the years due to more wear and tear as the equipment ages. Also, the maintenance cost is a function of the type of slurry (homogeneous versus heterogeneous), type of pump (positive displacement versus centrifugal), climatic conditions and, above all, preventive maintenance schedules.

It can be seen from Table 10 that, for both a favorable and an adverse gradient, the annual total cost is relatively insensitive to the maintenance cost.

Table 11 shows the sensitivity of the annual total cost as the cost of capital is varied ±25% and ±50% from the

TABLE 10

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change Maintenance Cost Factor ±50%)

SMC (%)	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
5	145,936 (532,011)**	0.788 (2.873)	-0.23 (-2.39)
10*	146,278 (545,018)	0.790 (2.944)	0.00 (0.00)
15	146,619 (558,026)	0.792 (3.014)	+0.23 (+2.39)

TABLE 11

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change Cost of Capital ±25% and ±50%)

INT (%)	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
5.0	106,050 (475,261)**	0.573 (2.567)	-27.50 (-12.80)
7.5	125,020 (508,220)	0.675 (2.745)	-14.53 (-6.75)
10.0*	146,278 (545,018)	0.790 (2.944)	0.00 (0.00)
12.5	169,668 (585,247)	0.916 (3.161)	+15.99 (+7.38)
15.0	195,025 (628,494)	1.053 (3.394)	+33.33 (+15.32)

*Design values

**Values in parentheses represent results for an adverse gradient.

design value. For a favorable gradient, a 25% reduction in the cost of capital decreases the cost by 14.53%, whereas an identical increase in the cost of capital increases the cost by 15.99%. For an adverse gradient, a 25% reduction in the cost of capital decreases the cost by 6.75%, whereas an identical increase in the cost of capital increases the cost by 7.38%. This difference is attributed to the fact that straight line depreciation is applied for each case and the cost of capital is compounded annually. Discrete interest factors are compounded or discounted annually because taxes and depreciation are charged on an annual basis. Also, all the expenses and revenues are assumed to occur at the end of the year.

Table 12 shows the sensitivity of the annual total cost as the cost of electrical energy is varied ±50% from the design value. For a favorable gradient, the power required for operating the pipeline is not significant and hence the annual total cost is not very sensitive to changes in the cost of electrical energy. The converse is true for a pipeline with an adverse gradient.

Salvage value is the estimate, at the time of acquisition of an asset, of the amount of money that will be realized on its sale upon completion of use. Since the pipeline in the case study analyzed would normally be buried, its salvage

TABLE 12

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change Cost of Electrical Energy ±50%)

CE ($/KW-hr)	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
0.01	142,523 (401,936)**	0.770 (2.171)	-2.57 (-26.25)
0.02*	146,278 (545,018)	0.790 (2.944)	0.00 (0.00)
0.03	150,032 (688,100)	0.810 (3.716)	+2.57 (+26.25)

TABLE 13

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change Salvage Value Factor of Prime Movers ±50%)

SPM (%)	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in cost
10	146,304 (545,687) **	0.7903 (2.947)	+0.02 (+0.12)
20*	146,278 (545,018)	0.7902 (2.944)	0.00 (0.00)
30	146,251 (544,350)	0.7901 (2.940)	-0.02 (-0.12)

* Design values

**Values in parentheses represent results for an adverse gradient.

value was assumed to be zero because at the end of the project it would be uneconomical to dig up the pipe. An in-plant pipeline could definitely have a salvage value since it might be dismantled readily at the end of the project and sold as scrap.

As can be seen from Table 13, the effect of a change in salvage value factor of the prime movers by ± 50% from the design value is insignificant.

Numerical values for the ratio of the total cost for fittings and installation to total purchase cost of the pipe, FR1, were obtained from the Oil and Gas Journal (10). The data on existing crude oil and products pipelines indicate that FR1 lies between 1.22 and 1.42. The average of the two numbers was used as a design value for the limestone pipeline. The numerical values for FR2 and FR3 were obtained from an engineering firm.

FR1, FR2, and FR3 are the ratios of the variable costs to the fixed costs of the pipe, pumps, and motors, respectively. The numerator in each of the ratios comprises the cost of the fittings and the installation cost, whereas the denominator comprises the capital cost. The numerator may vary considerably, depending on whether it is an in-plant pipeline or a long-distance pipeline. The unit capital cost in the denominator will remain unchanged once the specific pipe, pumps, and motors are selected. In general, the numerical values of FR1, FR2, and FR3 may be lower for an in-plant pipeline as compared to a long-distance pipeline. The cost of the fittings for an in-plant pipeline may be higher than that for a long distance pipeline. On the other hand, the installation cost for an in-plant pipeline may be substantially lower than that for a long-distance pipeline. Since the denominator remains unchanged, it is logical to assume that the ratios FR1, FR2, and FR3 may be lower for an in-plant pipeline as compared to a long-distance pipeline.

FR1 may have a large range depending on the type of pipe used for slurry transportation. If a slurry under consideration happens to be abrasive and/or corrosive, it would be necessary to increase the pipe wall thickness or line the pipe. The increased wall thickness or lining of the pipe will substantially increase the total purchase cost of the pipe. The cost of the fittings may also increase slightly, but the installation cost should remain unchanged. Thus, the effect of increasing the pipe wall thickness or lining a pipe will be to lower the numerical value of FR1.

FR2 and FR3 may also have a large range depending on the types of pump and motor or engine. Also, the numerous options on the prime movers for which the cost data are collected will play a significant role in determining the numerical values for the ratios FR2 and FR3.

Tables 14, 15, and 16 show that the annual total cost is relatively insensitive to changes in FR1, FR2, and FR3.

Another run tested the sensitivity of the annual total cost as the pipe absolute roughness, E, was varied ±25% and ±50% from the design value. It is evident from Table 17 that changes in E are not critical because the pressure drops do not change significantly and hence the effect on cost is insignificant.

Table 18 shows the sensitivity of the annual total cost to the installation of new prime movers in year 10 with an inflation factor of 2. For a favorable gradient, the pumping power required is negligible and hence the sensitivity of the annual total cost to the life expectancy of the prime movers is not critical. The converse is true for a limestone pipeline with an adverse gradient.

If the throughput is anticipated to change during the life of the project, it is desirable to measure the sensitivity of the cost in cents per ton-mile as a function of throughput before the final design is made. The results for this run are summarized in Table 19. The constraint applied here was that the operating velocity exceeds the critical velocity for the desired throughput. For a favorable gradient, when the throughput is decreased by 25 percent from the design value, the capital cost of the pipe decreases

TABLE 14

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change FR1)

FR1	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
1.22	140,507 (539,248)**	0.759 (2.912)	-3.95 (-1.06)
1.32*	146,278 (545,018)	0.790 (2.944)	0.00 (0.00)
1.42	152,048 (550,789)	0.821 (2.975)	+3.95 (+1.06)

TABLE 15

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change FR2 ±50%)

FR2	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
0.07	146,107 (538,507)**	0.789 (2.908)	-0.12 (-1.20)
0.14*	146,278 (545,018)	0.790 (2.944)	0.00 (0.00)
0.21	146,449 (551,530)	0.791 (2.979)	+0.12 (+1.20)

*Design values

**Values in parentheses represent results for an adverse gradient.

TABLE 16

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change FR3 ±50%)

FR3	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
0.18	146,170 (542,514)**	0.789 (2.930)	-0.07 (-0.46)
0.36*	146,278 (545,018)	0.790 (2.944)	0.00 (0.00)
0.54	146,386 (547,523)	0.791 (2.957)	+0.07 (+0.46)

*Design value

**Values in parentheses represent results for an adverse gradient.

because of the smaller pipe diameter, but the operating cost increases, resulting in a 44.18 percent increase in cost per ton-mile. When the throughput is increased by 25 percent from the design value, the capital cost of the pipe increases because of the larger pipe diameter, but the operating cost goes to zero, resulting in a 16.71 percent decrease in the transportation cost. The results for an adverse gradient are also summarized. Table 19 shows the economy of scale--the more the material to be transported, the cheaper it is in cents per ton-mile. Thus, a big mineral deposit and a large market are essential ingredients for the economic feasibility of the slurry pipeline concept.

TABLE 17

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Change E ± 25% and ± 50%)

E (ft.)	Pipe I.D. (in.)	Critical Velocity (ft/sec)	Operating Velocity (ft/sec)	PSI/mile	Annual Total Cost ($)	Cost (¢/ton-mile)	Prime Movers	% Change in Cost
0.000075	7 (7)**	5.1 (5.1)	5.8 (5.8)	155.45 (155.45)	145,732 (544,473)	0.787 (2.941)	Yes (Yes)	-0.37 (-0.10)
0.0001125	7 (7)	5.1 (5.1)	5.8 (5.8)	155.66 (155.66)	146,005 (544,746)	0.789 (2.942)	Yes (Yes)	-0.19 (-0.05)
0.00015*	7 (7)	5.1 (5.1)	5.8 (5.8)	155.86 (155.86)	146,278 (545,018)	0.790 (2.944)	Yes (Yes)	0.00 (0.00)
0.0001875	7 (7)	5.1 (5.1)	5.8 (5.8)	156.07 (156.07)	146,550 (545,291)	0.792 (2.945)	Yes (Yes)	+0.19 (+0.05)
0.000225	7 (7)	5.1 (5.1)	5.8 (5.8)	156.28 (156.28)	146,822 (545,563)	0.793 (2.947)	Yes (Yes)	+0.37 (+0.10)

*Design values

**Values in parentheses represent results for an adverse gradient.

TABLE 18

Sensitivity Analysis for 200 Dry Short Tons Per Hour of Limestone

(Install New Prime Movers After 10 Years)

Life Expectancy of Prime Movers (years)	Annual Total Cost ($)	Cost (¢/ton-mile)	% Change in Cost
20*	146,278 (545,018)**	0.790 (2.944)	0.00 (0.00)
10	150,930 (664,049)	0.815 (3.586)	+3.18 (+21.84)

* Design value

** Values in parentheses represent results for an adverse gradient.

TABLE 19

Sensitivity Analysis for Different Throughputs of Limestone
(Change Throughput ±25%)

Throughput dry short-tons hour	Pipe I.D. (in.)	Critical Velocity (ft/sec)	Operating Velocity (ft/sec)	PSI/mile	Annual Total Cost ($)	Cost (¢/ton-mile)	Prime Movers	% Change In Cost
150	6 (6)**	5.2 (5.2)	6.0 (6.0)	189.40 (189.40)	158,123 (457,178)	1.139 (3.292)	Yes (Yes)	+44.18 (+11.82)
200*	7 (7)	5.1 (5.1)	5.8 (5.8)	155.86 (155.86)	146,278 (545,018)	0.790 (2.944)	Yes (Yes)	0.00 (0.00)
250	8 (8)	5.0 (5.0)	5.6 (5.6)	126.77 (126.77)	152,351 (618,138)	0.658 (2.671)	No (Yes)	-16.71 (-9.27)

* Design value

**Values in parentheses represent results for an adverse gradient.

DISCUSSION OF RESULTS

The computer selection technique upon which the dissertation is based selected a 7-inch diameter pipe for the limestone slurry transport problem postulated. On the basis of the hydraulic and system data, a positive displacement pump was recommended. The author has presented similar analyses for limestone slurries in previous publications (11, 12).

The analysis performed by the engineering company was a portion of a larger study designed to provide total plant costs. The engineering firm recommended a nominal 5-inch diameter pipe for the transport system and a positive displacement type of pump.

Although the engineering study was based in part on the same data as the computer study, the engineering firm included considerations not evaluated by the computer program. One of these was the topography. The pipeline will drop 2,390 feet from its beginning, and will then rise over a ridge before reaching its terminus. The engineering contractor was faced with the alternative of very high pipe pressure in the low portion of the line or a pump station.

The contractor also felt that a total gravity system was undesirable because of the lack of control in such a system. He, therefore, recommended a single pump station at the start of the line and heavy pipe wall thickness to stand the hydraulic pressures.

The sensitivity analyses revealed the importance of those critical variables that, if changed, could considerably affect the total cost. The results of the sensitivity analyses for a favorable and an adverse gradient are summarized in Tables 20 and 21, in their decreasing order of importance. Note that the ranking for a favorable and an adverse gradient is different. The annual total cost is sensitive to changes in the rheological parameters and the pipe-wall thickness for both a favorable and an adverse gradient. The unit transportation cost is insensitive to changes in the salvage value of prime movers, pipe absolute roughness, FR2, and FR3 for both a favorable and an adverse gradient. The cost of electrical energy is an important factor for an adverse gradient, but it is unimportant for a favorable gradient. The annual total cost is sensitive to the cost of lining the pipe with polyethylene for a favorable gradient, but it is insensitive for an adverse gradient.

The major limitation of the computer technique presented herein is that only part of the transportation cost is evaluated

TABLE 20

Results of the Sensitivity Analyses (Favorable Gradient)

Variable	Value	Pipe I.D. (in.)	Cost (¢/ton-mile)	% Change in Cost	Prime Movers
	0.105	7	0.723	-8.47	No
	0.157	7	0.723	-8.47	No
n	0.209*	7	0.790	0.00	Yes
	0.261	6	1.793	+126.95	Yes
	0.313	6	1.964	+148.56	Yes
	28.6	7	0.723	-8.47	No
	42.9	7	0.723	-8.47	No
K	57.2*	7	0.790	0.00	Yes
	71.5	6	1.775	+124.62	Yes
	85.8	6	1.895	+139.83	Yes
T	0.25*	7	0.790	0.00	Yes
	0.50	7	1.563	+97.85	Yes
API 5L	(rough)*	7	0.790	0.00	Yes
Polyethylene-lined	(smooth)	5	1.221	+54.55	Yes
	150	6	1.139	+44.18	Yes
Throughput	200*	7	0.790	0.00	Yes
	250	8	0.658	-16.71	No
	5.0	7	0.573	-27.50	Yes
	7.5	7	0.675	-14.53	Yes
INT	10.0*	7	0.790	0.00	Yes
	12.5	7	0.916	+15.99	Yes
	15.0	7	1.053	+33.33	Yes
	1.22	7	0.759	-3.95	Yes
FR1	1.32*	7	0.790	0.00	Yes
	1.42	7	0.821	+3.95	Yes
Life expectancy of prime movers	20*	7	0.790	0.00	Yes
	10	7	0.815	+3.18	Yes

Table 20 continued

Variable	Value	Pipe I.D. (in.)	Cost (¢/ton-mile)	% Change in Cost	Prime Movers
	0.01	7	0.770	-2.57	Yes
CE	0.02*	7	0.790	0.00	Yes
	0.03	7	0.810	+2.57	Yes
	0.000075	7	0.787	-0.37	Yes
	0.0001125	7	0.789	-0.19	Yes
E	0.00015*	7	0.790	0.00	Yes
	0.0001875	7	0.792	+0.19	Yes
	0.000225	7	0.793	+0.37	Yes
	5	7	0.788	-0.23	Yes
SMC	10*	7	0.790	0.00	Yes
	15	7	0.792	+0.23	Yes
	0.07	7	0.789	-0.12	Yes
FR2	0.14*	7	0.790	0.00	Yes
	0.21	7	0.791	+0.12	Yes
	0.18	7	0.789	-0.07	Yes
FR3	0.36*	7	0.790	0.00	Yes
	0.54	7	0.791	+0.07	Yes
	10	7	0.7903	+0.02	Yes
SPM	20*	7	0.7902	0.00	Yes
	30	7	0.7901	-0.02	Yes

*Design values

TABLE 21

Results of the Sensitivity Analyses (Adverse Gradient)

Variable	Value	Pipe I.D. (in.)	Cost (¢/ton-mile)	% Change in Cost	Prime Movers
	0.105	8	2.511	-14.70	Yes
	0.157	7	2.871	-2.46	Yes
n	0.209*	7	2.944	0.00	Yes
	0.261	6	3.947	+34.07	Yes
	0.313	6	4.117	+39.87	Yes
	28.6	9	2.368	-19.56	Yes
	42.9	8	2.534	-13.92	Yes
K	57.2*	7	2.944	0.00	Yes
	71.5	6	3.928	+33.45	Yes
	85.8	6	4.048	+37.53	Yes
	0.01	7	2.171	-26.25	Yes
CE	0.02*	7	2.944	0.00	Yes
	0.03	7	3.716	+26.25	Yes
T	0.25*	7	2.944	0.00	Yes
	0.50	7	3.716	+26.22	Yes
Life Expectancy of prime movers	20*	7	2.944	0.00	Yes
	10	7	3.586	+21.84	Yes
	150	6	3.292	+11.82	Yes
Throughput	200*	7	2.944	0.00	Yes
	250	8	2.671	-9.27	Yes
	5.0	7	2.567	-12.80	Yes
	7.5	7	2.745	-6.75	Yes
INT	10.0	7	2.944	0.00	Yes
	12.5	7	3.161	+7.38	Yes
	15.0	7	3.394	+15.32	Yes
	5	7	2.873	-2.39	Yes
SMC	10*	7	2.944	0.00	Yes
	15	7	3.014	+2.39	Yes

Table 21 continued

Variable	Value	Pipe I.D. (in.)	Cost (¢/ton-mile)	% Change in Cost	Prime Movers
API 5L	(rough)*	7	2.944	0.00	Yes
Polyethylene-lined	(smooth)	7	3.007	+2.14	Yes
	0.07	7	2.908	-1.20	Yes
FR2	0.14*	7	2.944	0.00	Yes
	0.21	7	2.979	+1.20	Yes
	1.22	7	2.912	-1.06	Yes
FR1	1.32*	7	2.944	0.00	Yes
	1.42	7	2.975	+1.06	Yes
	0.18	7	2.930	-0.46	Yes
FR3	0.36*	7	2.944	0.00	Yes
	0.54	7	2.957	+0.46	Yes
	10	7	2.947	+0.12	Yes
SPM	20*	7	2.944	0.00	Yes
	30	7	2.940	-0.12	Yes
	0.000075	7	2.941	-0.10	Yes
	0.0001125	7	2.942	-0.05	Yes
E	0.00015*	7	2.944	0.00	Yes
	0.0001875	7	2.945	+0.05	Yes
	0.000225	7	2.947	+0.10	Yes

*Design values

by the program. Only the pipeline and its prime movers are considered. Unique investments in slurry pipeline facilities, such as the slurry preparation plant, slurry separation plant, right-of-way, instrumentation, and controls are not included in the system evaluation.

A total plant cost, including all the factors mentioned above, must be evaluated before the unit transportation cost for a slurry pipeline operation can be compared with the unit transportation costs for alternate modes of transportation such as trucks, barges, or unit-trains.

There are some other unique factors that need to be considered in determining the total unit transportation cost for any mode of transportation. If, for example, the material being transported in a pipeline has to be crushed for further processing at the terminus, the crushing charges should be attributed to the process and not to the pipeline, although crushing during slurry preparation will reduce pipeline transportation cost. On the other hand, if it is required to dry the material at the terminus, drying cost should be attributed to the pipeline. In the case study analyzed, water needed for the limestone slurry had to be pumped up the hill to the mine site. The transportation cost for water should be attributed to the slurry pipeline. Similarly, if a highway or a railroad track has to be built specifically for the transportation of any commodity, the cost of building a highway or a railroad track must be included in computing the appropriate total unit cost of transportation.

The market requirements also play a significant role in determining the transport mode selected. Certain markets, such as coking coal for steel mills, require a somewhat coarser product than the coal-fired thermal electric generating stations. If the pipeline transportation of coal for steel mills results in substantial particle degradation, the slurry pipeline concept may have to be rejected despite its economic feasibility over other modes of transportation.

CONCLUSIONS

This investigative study revealed the following general conclusions:

1. For a required throughput, the optimum pipe diameter and estimated minimum annual total cost can be computed for a slurry system comprising a pipeline and prime movers only.

2. A wide range of system costs is generated quickly with a minimum of input.

3. An important feature of the method is the ease with which the variables can be adjusted to measure the sensitivity of the annual total cost to changes in the variables.

4. The technique presented herein is an excellent tool for the preliminary design of pipelines, transporting homogeneous or heterogeneous slurries.

5. The slurry data upon which the evaluation is based will govern the reliability of the technical analysis, and similarly the cost data will govern the reliability of the economic analysis.

The computer approach to the selection of the limestone slurry pipeline revealed the following specific conclusions:

1. The engineering firm recommended a 5-inch diameter pipe, whereas the computer technique selected a 7-inch diameter pipe. The discrepency may be explained by the fact that the computer program takes into account the

average elevation gradient and not the actual topography. Also, the engineering firm had taken into consideration the properties of three different types of limestones from the quarry being pumped to the cement plant for the manufacture of different types of cement.

2. Both the engineering firm and the computer technique recommended a positive displacement pump for the limestone slurry transport problem postulated, despite the presence of a favorable elevation gradient.

3. The unit transportation cost of limestone slurry pipeline for a favorable gradient is 0.790 cents per ton-mile whereas the unit transportation cost for an adverse gradient is 2.944 cents per ton-mile based on a 10 percent rate of return after taxes.

RECOMMENDATIONS

Because of the strong potential of using such a computer technique as a design tool for slurry pipelines, this preliminary study should be extended in several areas:

1. Accurate rheology data for homogeneous slurries and pipeline data for heterogeneous slurries should be obtained for several mineral slurries.
2. The accuracy of the computer program should be verified for existing slurry pipelines if the raw data can be obtained from private companies.
3. Several analyses should be performed to provide total plant costs. In addition to the costs considered in the computer program, costs for slurry preparation, slurry separation, right-of-way, instrumentation, and controls should be included in the system evaluation.
4. If several alternate modes of transportation are to be compared, a discounted cash flow rate-of-return or a net present value analysis should be preformed to determine the economic feasibility of pipeline transportation of mineral commodities. The same net present value technique utilized in the computer program for the economic selection of a slurry pipeline can be applied to any other mode of transportation, provided the appropriate capital and operating costs are made available.

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APPENDIX I

COMPUTER PROGRAM

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C  THE FOLLOWING PROGRAM IS CODED IN FORTRAN IV LANGUAGE.
C
C                              PLYBRK - ECONO
C
C  PROGRAM PLYBRK (POWER LAW YIELD BROOKFIELD) PREDICTS PIPELINE ENERGY
C  REQUIREMENTS FOR YIELD PSEUDOPLASTIC SLURRIES USING
C  YIELD-POWER LAW EQUATION, TAU - TAUY = K * GAMDOT ** N
C  PROGRAM ECONO EVALUATES TOTAL ANNUAL AND UNIT PIPELINE TRANSPORTATION
C  COSTS.
C  NOTE:  PROGRAM COMPUTES IN SI UNITS.  SOME OUTPUT DATA ARE IN ENGLISH
C  UNITS.
C  SLURRY TEMPERATURE SAME FOR RHEOLOGY AND PREDICTED PIPELINE DATA
C  PIPE ROUGHNESS = (EPSILON) = E IN FEET
      DIMENSION        M(479),R(40),TID1(6),TID2(6),TID3(4),DIA(20)
      DIMENSION READAT(16),FACTOR(5),LIFE(5),CPM(5),SLDCPM(5),SLDTOT(5)
      DATA END,G,PI,X/5HEND  ,32.1573,3.1415926,.1/
C  DENSITY TABLE FROM "CHEMICAL ENGINEERS' HANDBOOK" BY JOHN H. PERRY,
C  PAGE 3-70 (NOT REPRODUCED HERE).
      INTEGER COUNT,PIPEL,PUMPL,SETL
      REAL K,K1,KWHTM,LENGTH,LHS,LOW,LOWX,M1,M2,M3,M4,MASS,N,INT,INVEST,
     1MC
1000  READ(1,1001)VARBLE,ISTART,IFINSH,INMENT
1001  FORMAT(A5,3I)
1     READ(1,2)TID1,TID2,TID3,CW,TEMP,S,SL,TAUY,K,N,E,
     1C1,C2,C3,C4,CE,EFFCNC,EP,FR1,FR2,FR3,H,
     2LENGTH,M1,M2,M3,M4,P1,P2,T,Z1,Z2,RHOP,
     3FLAG,FLAG2,PIPEL,PUMPL,SETL,SP,SPM,SMC,TR,INT,FACTOR
2     FORMAT(16A5,/,8F,2(/,11F),(/,2F,3I,6F),(/,4F))
      NAYANA='1'
      IF(S.LT.1.)GOTO999
      READ(1,2001)DIA
2001  FORMAT(20F)
      DO 2002 NUMDIA=1,20
      IF(DIA(NUMDIA).EQ.0.)GOTO2003
2002  CONTINUE
2003  NUMDIA=NUMDIA-1
      CV=SL*CW/(S-CW*(S-SL))
      K1=K*((3.*N+1.)/(4.*N))**N
      GAMMA=K1*8.**(N-1.)
      SM=S*CV/CW
      L=TEMP*10.
      A=M(L)
      SW=.99*A/1.E+07
      GAMSM=62.42796*SW*SM
      DO 22 I=1,NUMDIA
      DSI=DIA(I)*2.54
      RELRUF=E*12./DIA(I)
COMPUTE CRITICAL VELOCITY
      VCSI=(2100.*GAMMA/DSI**N/SM)**(1./(2.-N))
      VC=VCSI/30.48
      WRITE(6,4)NAYANA,DIA(I),TID3,E,RELRUF,VC
```

```
4      FORMAT(/,/,A1,' DIA =',F7.3,' INCHES  PIPE TYPE - ',4A5,'  E =',F9
      1.6,' FEET  E/D =',F9.6,'  VC =',F5.2,' FPS',/)
       WRITE(3,40 )DIA(I),TID3,E,RELRUF,VC
40     FORMAT(/,' DIA =',F7.3,' INCHES  PIPE TYPE = ',4A5,/,' E =',F9.6,'
      1 FEET  E/D =',F9.6,'  VC =',F5.2,' FPS',/)
       NAYANA=' '
       WRITE(6,41)
41     FORMAT(' VELCTY    GEN      FANN      TAUWAL      SHRATE  FRICTION-PO
      1WER-REQUIRED  THROUGHPUT   COUNT  KOUNT  REG   REK   ANNUAL TOTAL
      4   CENTS/',
      2/,' FT/SEC     RE       F      DYNES/CM/CM   1/SEC  PSI/MILE    KWH/T
      3ON/MILE  DRY-TONS/HR',28X,'COST ($)',6X,'TON-MILE'/)
       WRITE(3,42)
42     FORMAT(' VELCTY    GEN     FRICTION-POWER-REQUIRED  THROUGHPUT',/,'
      1 FT/SEC     RE     PSI/MILE    KWH/TON/MILE  DRY-TONS/HR',/)
       DO 22 IV=ISTART,IFINSH,INMENT
       IF(VARBLE.EQ.'CSTT ')GO TO 44
       V=IV
       GO TO 45
44     TONHR=IV
       MASS=2000.*TONHR/CW
       VEL=TONHR*576./(1.8*PI*DIA(I)**2.*CW*GAMSM)
       V=VEL*30.48
45     RE=V**(2.-N)*DSI**N*SM/GAMMA
       REK=0.
       IF(RE.GT.2100.)GO TO 10
C   FOLLOWING EQUATIONS ARE FOR LAMINAR FLOW
       COUNT=1
       F=0.
       LHS=2.*V/DSI
       REG=3HLAM
C   SHEAR STRESS AT PIPE WALL (TAUW) INITIALIZED
       TAUW=4.*K*LHS
5      X=TAUY/TAUW
       RHSB=TAUW*(1.-4.*X/3.+X**4/3.)/(4.*K)
       ERROR=ABS(RHSB-LHS)
       IF(ERROR.LE..01)GO TO 6
       COUNT=COUNT+1
       TAUW=TAUW*LHS/RHSB
       GO TO 5
6      TAUW=.25*TAUW
       D1=(1.+    N)/N
       D2=(1.+2.*N)/N
       D3=(1.+3.*N)/N
       HIGH=10000.
       KOUNT=1
       LOW=.001
7      DT=TAUW-TAUY
       IF(DT.GT.0.)GO TO 9
       WRITE(6,8)DT
       WRITE(3,8)DT
```

```
8      FORMAT(' TAUW - TAUY =',1PE10.3)
       GO TO 22
9      RHSPLY=DT**D1/K**(1./N)*(DT*DT/D3+2.*TAUY*DT/D2+TAUY**2/D1)/TAUW**
     13
       ERROR=ABS(LHS-RHSPLY)
       IF(ERROR.LE..01)GO TO 20
       IF(LHS.LT.RHSPLY)HIGH=TAUW
       IF(LHS.GT.RHSPLY)LOW =TAUW
       KOUNT=KOUNT+1
       TAUW=(HIGH+LOW)/2.
       GO TO 7
10     REPLC=RE*((1.+3.*N)/(4.*N))**N
       IF(E.GT.0.)GO TO 14
C
C
C   FOLLOWING EQUATIONS ARE FOR TURBULENT FLOW IN SMOOTH PIPES
       B=4.53/N
       COUNT=0
       ERROR2=1.
       FSW=.004
       KOUNT=0
100    HIGH=.02
       LOW=.002
11     FSWNEW=(2.69/N-2.95+B*ALOG10(1.-X)+B*ALOG10(REPLC*SQRT((FSW)**(2.-
     1N)))+.68/N*(5.*N-8.))*SQRT(FSW**3)
       COUNT=COUNT+1
       ERROR1=ABS(FSW-FSWNEW)
       IF(ERROR1.LE..00001)GO TO 12
       IF(FSW.LT.FSWNEW)HIGH=FSW
       IF(FSW.GT.FSWNEW)LOW=FSW
       IF((HIGH-LOW).LE..00001)GO TO 12
       FSW=(HIGH+LOW)/2.
       GO TO 11
12     IF(ERROR2.LE..01)GO TO 13
       DO 120 J=1,10
       KOUNT=KOUNT+1
       A=J
       X=(A-1.)/10.
       FSWNEW=(2.69/N-2.95+B*ALOG10(1.-X)+B*ALOG10(REPLC*SQRT((FSW)**(2.-
     1N)))+.68/N*(5.*N-8.))*SQRT(FSW**3)
       TAUW =FSWNEW*SM*V*V/2.
       X1=TAUY/TAUW
       R(J)=ABS(X-X1)
       IF(J.EQ.1)GO TO 120
       IF(R(J).GE.R(J-1))GO TO 121
120    CONTINUE
121    IF(X.EQ..1)X=.2
       Y=X-.2
       DO 122 J=1,40
       KOUNT=KOUNT+1
       A=J
```

```
      X=Y+(A-1.)/200.
      FSWNEW=(2.69/N-2.95+B*ALOG10(1.-X)+B*ALOG10(REPLC*SQRT((FSW)**(2.-
     1N)))+.68/N*(5.*N-8.))*SQRT(FSW**3)
      TAUW =FSWNEW*SM*V*V/2.
      X1=TAUY/TAUW
      R(J)=ABS(X-X1)
      IF(J.EQ.1)GO TO 122
      IF(R(J).GE.R(J-1))GO TO 123
122   CONTINUE
123   ERROR1=ABS(FSW-FSWNEW)
      X=X-.005
      ERROR2=ABS(X  -X1     )
      IF(ERROR1.GT..00001.OR.ERROR2.GT..01)GO TO 100
13    F=FSWNEW
      RE=REPLC
      REG=3HSWT
      GO TO 20
C
C
C  FOLLOWING EQUATIONS ARE FOR ROUGH WALL TURBULENCE
14    COUNT=0
      KOUNT=0
      FCBI=.025
16    FCB=(-1./(2.*ALOG10(E*30.48/DSI/3.7+2.51/(REPLC*SQRT(FCBI)))))**2
      TEST=ABS(FCBI-FCB)
      IF(TEST.LE..0001)GO TO 17
      FCBI=(FCBI+FCB)/2.
      GO TO 16
17    FRW=FCB/4.
      REK=E*30.48/DSI*REPLC*SQRT(FRW /2.)
      IF(REK.GT.70.)GO TO 19
      F=FRW
      RE=REPLC
      REG=3HRWT
      TAUW=FRW*SM*V*V/2.
      GO TO 20
C
C
C  FOLLOWING EQUATIONS ARE FOR FULLY ROUGH WALL TURBULENT FLOW.
19    RHS=4.07*ALOG10(DSI/60.96/E)+6.-2.65/N
      FFRW=1./RHS**2
      F=FFRW
      REG=3HFRT
      TAUW=FFRW*SM*V*V/2.
20    SHRATE=8.*V/DSI*(1.+3.*N)/(4.*N)
      V=V/30.48
      PDROP=4.*TAUW/DSI
      PSIMIL=PDROP*2.335784
      KWHTM=PSIMIL*.108465/(CW*GAMSM)
      SUMLOS=24.*F*LENGTH*V*V/(G*DIA(I))
      HP=(P2-P1)/GAMSM+(Z2-Z1)+SUMLOS
```

```
      IF(VARBLE.EQ.'CSTT ')GO TO 20001
      TONHR=1.8*V*PI*DIA(I)*DIA(I)*CW*GAMSM/576.
      MASS=2000.*TONHR/CW
C  ECONOMICS SECTION.
20001 CPMPNG=3.766E-7*CE*MASS*H*HP/EFFCNC
      IF(HP.LT.0.)CPMPNG=0.
      CPIPE=(FR1+1.)*LENGTH*(M1*PI*RHOP*(DIA(I)/12.*T+T*T)+C1)
      SPIPE=SP*CPIPE
      SLD=(CPIPE-SPIPE)/PIPEL
      BHP=MASS*SM*HP/(1.98E6*EP)
      SCPMTT=0.
      IMAX=PIPEL/PUMPL
C  COMPUTE CAPITAL COSTS OF PRIME MOVERS
      DO 222 II=1,IMAX
C  IF FLAG = 0, EQUATION FOR COST VS. BHP IS       LINEAR
C  IF FLAG = 1, EQUATION FOR COST VS. BHP IS CURVILINEAR
      IF(FLAG.GT..5)GO TO 200
      CPUMP=FACTOR(II)*(FR2+1.)*(M2*BHP+C2)
      GO TO 201
200   CPUMP=FACTOR(II)*(FR2+1.)*(C2*BHP**M2)
201   IF(BHP.LE.800.)GO TO 20002
C  ASSUME PLOT OF HP VS. MOTOR COST IS FOR DELIVERABLE POWER.
      C3=C4
      M3=M4
20002 CMOTOR=FACTOR(II)*(FR3+1.)*(1.15*M3*BHP+C3)
      IF(HP.LT.0.)CPUMP=0.
      IF(HP.LT.0.)CMOTOR=0.
      LIFE(II)=(II-1.)*PUMPL
      CPM(II)=CPUMP+CMOTOR
C  COMPUTE SALVAGE VALUES OF PRIME MOVERS.
      SCPM=SPM*CPM(II)
C  ALL SALVAGE VALUES OF PRIME MOVERS DISCOUNTED TO OPERATION START-UP.
      SCPMTO=SCPM*(1./(1.+INT)**(II*PUMPL))
      SCPMTT=SCPMTO+SCPMTT
222   SLDCPM(II)=(CPM(II)-SCPM)/PUMPL
C  ALL SALVAGE VALUES OF PRIME MOVERS DISTRIBUTED EVENLY OVER
C  OPERATING LIFE OF PROJECT.
      SCPTTT=SCPMTT*(INT*((1.+INT)**PIPEL))/(((1.+INT)**PIPEL)-1.)
C  COMPUTE FUTURE COST OF PRESENT VALUE OF PIPE.
      FPIL2=(1.+INT)**SETL
      FCPIPE=CPIPE*FPIL2
C  COST OF PIPE SPREAD EVENLY OVER OPERATING LIFE OF THE PROGECT.
      TFCPIP=FCPIPE*(INT*(1.+INT)**PIPEL)/(((1.+INT)**PIPEL)-1.)
      INVEST=0.
C  COMPUTE PRESENT WORTH OF FUTURE COSTS (PRIME MOVERS)
      DO 111 II=1,IMAX
      PFIL=(1./((1.+INT)**LIFE(II)))*CPM(II)
111   INVEST=PFIL+INVEST
C  ALL CAPITAL COSTS OF PRIME MOVERS SPREAD EVENLY OVER OPERATING LIFE
C  OF PROJECT.
      SINV=(INT*(1.+INT)**PIPEL)/(((1.+INT)**PIPEL)-1.)*INVEST
```

```
      ANNUAL=SINV+TFCPIP
C  COMPUTE DEPRECIATION OF EQUIPMENT.
      DO 333 II=1,IMAX
333   SLDTOT(II)=SLD+SLDCPM(II)
      DEPTOT=0.
      DO 444 II=1,IMAX
      DO 444 JJ=1,PUMPL
      K2=(II-1.)*PUMPL+JJ
C  COMPUTE DEPRECIATION DISCOUNTED TO OPERATION START-UP
      PFIL1=1./((1.+INT)**K2)
      DEPSET=SLDTOT(II)*PFIL1
444   DEPTOT=DEPSET+DEPTOT
C  ALL DEPRECIATION SPREAD EVENLY OVER OPERATING LIFE OF PROJECT.
      DEP=DEPTOT*(INT*(1.+INT)**PIPEL)/(((1.+INT)**PIPEL)-1.)
C  COMPUTE PRESENT WORTH OF FUTURE SALVAGE VALUE OF PIPE AND SPREAD
C  EVENLY OVER OPERATING LIFE OF THE PROJECT.
      PFIL3=(1./((1.+INT)**PIPEL))*SPIPE
      SSPIPE=(INT*(1.+INT)**PIPEL)/(((1.+INT)**PIPEL)-1.)*PFIL3
      SAL=SCPTTT+SSPIPE
      CF=ANNUAL+DEP+SAL
      PAT=CF-DEP
      TI=PAT/(1.-TR)
      GR=TI+DEP
      MC=SMC*CPMPNG
      CTOTAL=GR+CPMPNG+MC
      NOPUMP=' '
      IF(HP.LT.0.)NOPUMP='*'
      CENTS=CTOTAL*100./(TONHR*LENGTH/5280.*H)
      WRITE(6,21)V,RE,F,TAUW,SHRATE,PSIMIL,KWHTM,TONHR,COUNT,KOUNT,REG,R
     1EK,CTOTAL,NOPUMP,CENTS
21    FORMAT(F6.1,F10.0,F8.4,F10.2,F11.2,F10.2,F11.3,F14.1,I8,I7,4X,A3,F
     17.1,F14.0,1X,A1,F7.3)
      WRITE(3,210)V,RE,PSIMIL,KWHTM,TONHR
210   FORMAT(F6.1,F10.0,F10.2,F12.3,F12.1)
22    CONTINUE
      WRITE(6,23)
23    FORMAT(1H1)
      IF(FLAG2.EQ.9.)GO TO 1000
      GO TO 1
999   STOP
      END
CSTT 50,400,50
LIMESTONE (BASIC DESIGN)                                            STEEL
.664 20.6 2.712 1. 17.91 57.2 .209 .00015
0. 0. 0. 4300. .02 .675 .75 1.32 .14 .36 7884.
62000. .1557 96.25 17.19 11.43 7200. 14400. .0208 2660. 270. 491.
0. 0. 20 20 1 0. .2 .1 .5 .1 1.
0. 0. 0. 0.
5. 6. 7. 8. 9.
END
0.
```

APPENDIX II

PIPES

Data for plain and lined pipes were collected from several manufacturers. The data showed a straight-line relationship for weight versus cost on rectangular coordinates. Thus, the pipe cost is essentially a function of the weight of pipe material. The data are presented in Figs. 4, 5, 6, 7 and 8.

All the cost data are adjusted to June 1974 in Table 22, using price indices from Table 2.

TABLE 22

Cost Data for Pipes

Figure No.	Prices ($/lb) As Of		Prices ($/lb) Adjusted to 6/30/74
4	1/1/73	0.1379	0.1581
5	1/1/73	0.1358	0.1557
6	1/1/73	0.1400	0.1605
7	11/1/72	1.1110	1.2740
8	1/1/73	0.6220	0.7133

Table 22 shows that the cost of a polyurethane-lined pipe is approximately 4 times that of an API pipe, whereas the cost of the ultra-high molecular weight high-density polyethylene pipe is approximately 8 times that of an API pipe.

Figure 4. Weight Per Foot Versus Price Per Foot of Seamless Steel Pipe

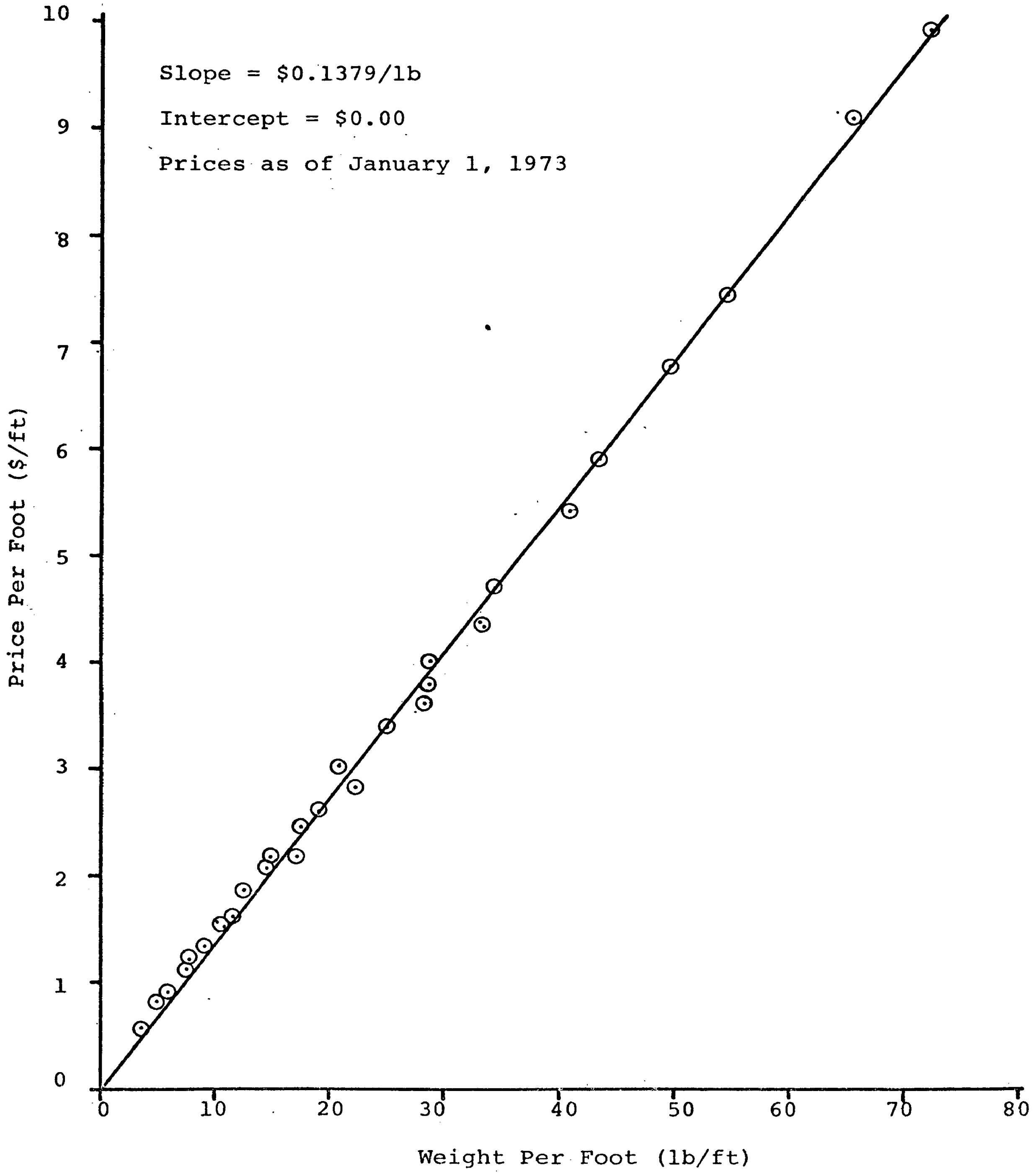


Figure 5. Weight Per Foot Versus Price Per Foot of of API 5L Pipe

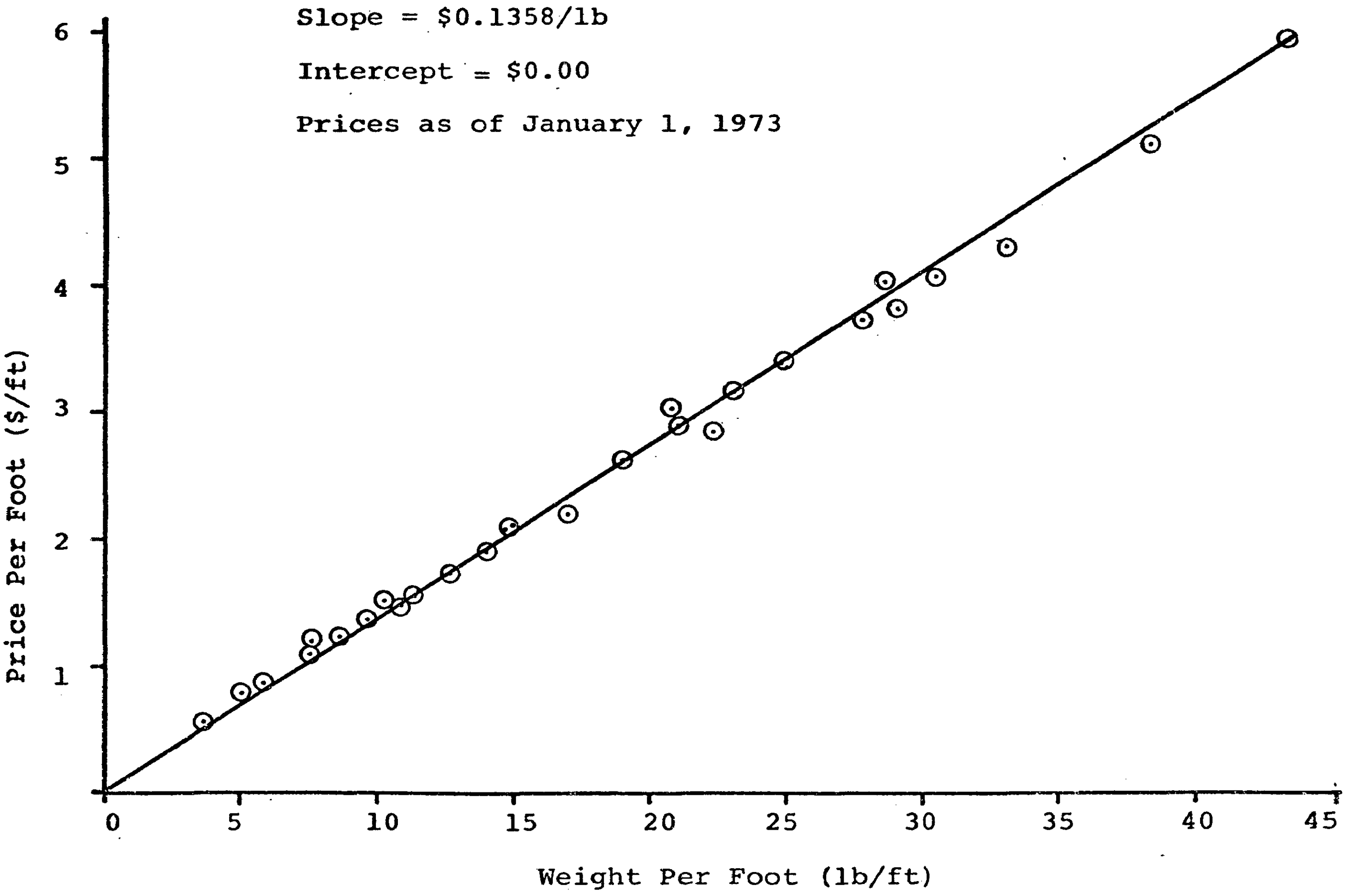


Figure 6. Weight Per Foot Versus Price Per Foot of API 5LX Pipe

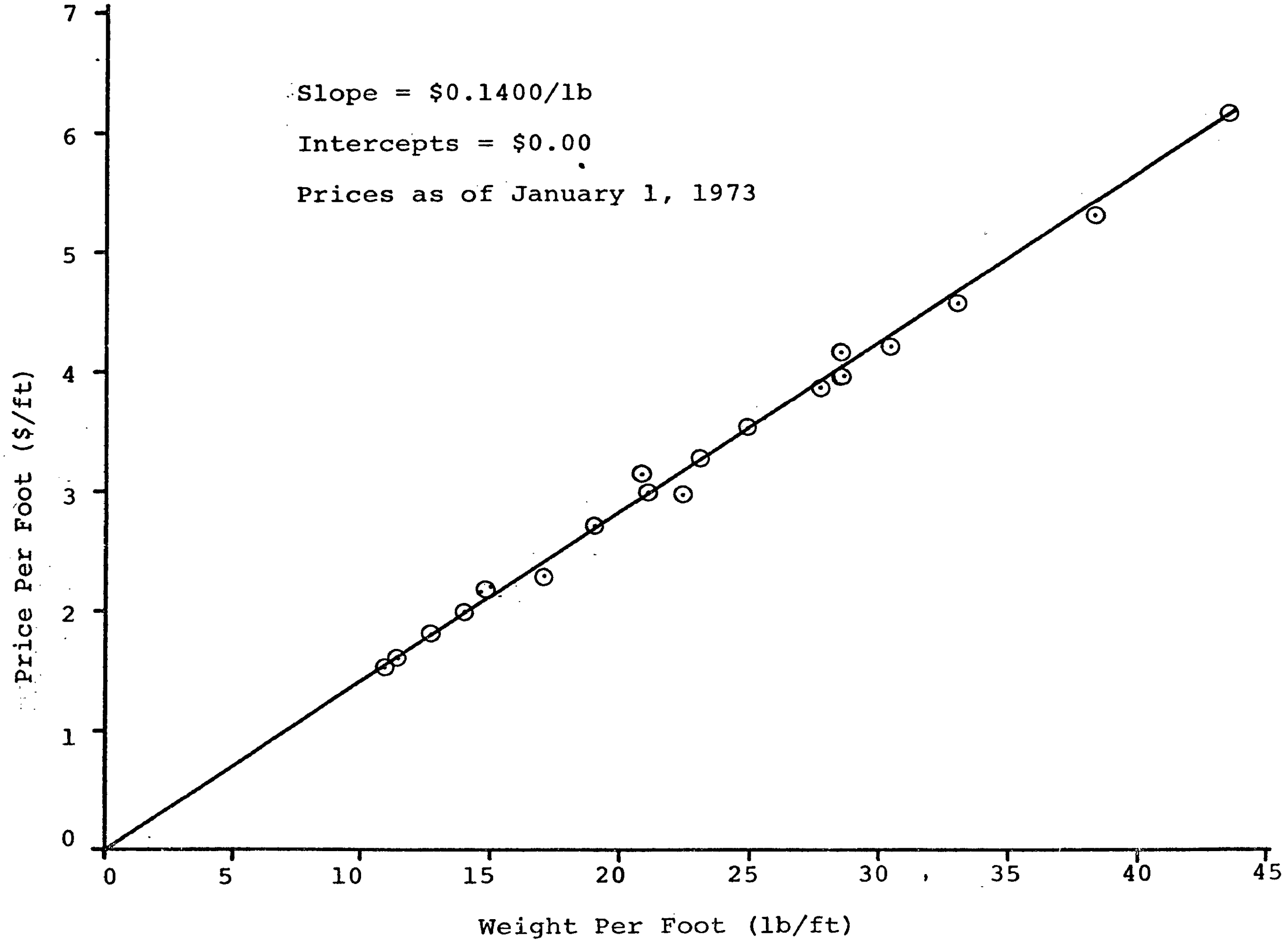
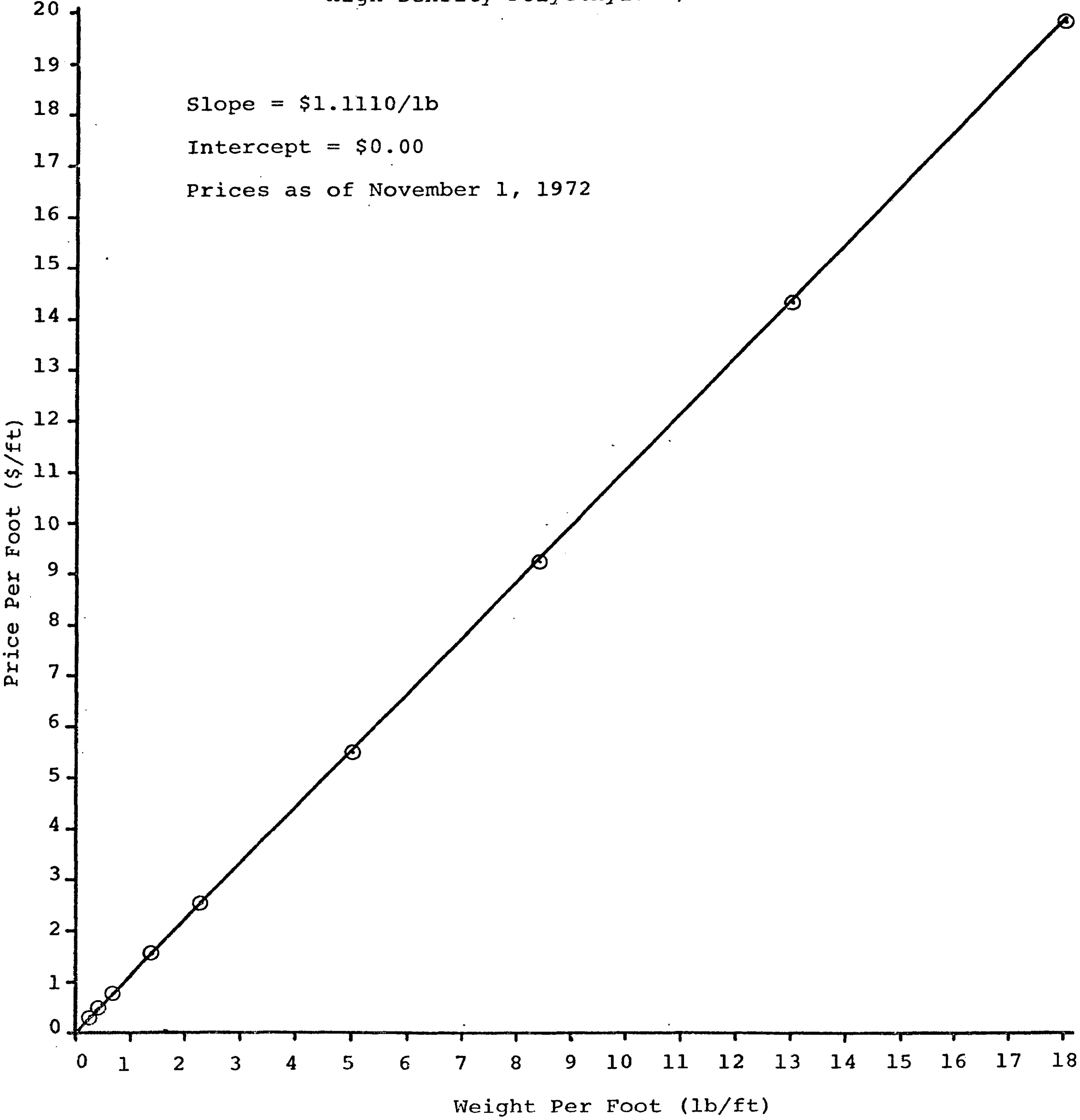


Figure 7. Weight Per Foot Versus Price Per Foot of 150 PSI Pressure Pipe (Ultra-High Molecular Weight High Density Polyethylene).



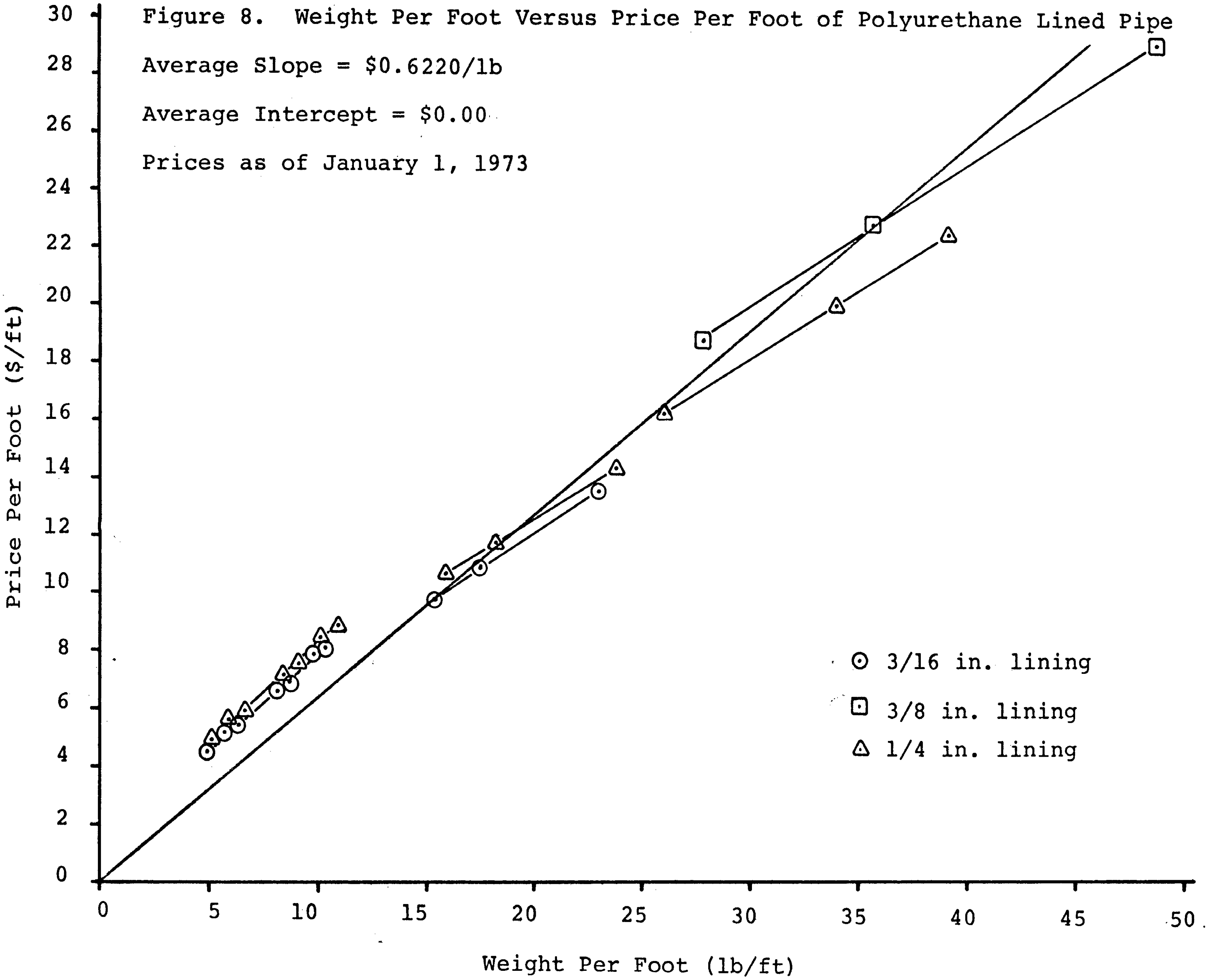


Figure 8. Weight Per Foot Versus Price Per Foot of Polyurethane Lined Pipe

Average Slope = $0.6220/lb

Average Intercept = $0.00

Prices as of January 1, 1973

APPENDIX III

PRIME MOVERS

Pumps

Capital cost data for centrifugal and positive displacement pumps were collected from four manufacturers. Centrifugal pumps were correlated by a straight-line fit of brake horsepower versus cost on logarithmic plots and the positive displacement pumps showed straight-line relationship for the same two variables on rectangular coordinates. The data are presented in Figs. 9, 10, 11, 12 and 13.

The pump cost data were adjusted to June 1974 in Table 23, using price indices from Table 2.

TABLE 23

Cost Data for Pumps

Figure No.	Prices ($/BHP) As Of		Prices ($/BHP) Adjusted to 6/30/74
9	5/10/73	85.48	96.25
10	10/1/73	29.21	32.27
11	10/1/73	29.17	32.23
12	3/30/73	36.20	41.25
13	6/1/73	24.21	27.26

Figure 9. Pump BHP Versus Cost for Triplex Mud Pumps

Slope = $85.48/BHP

Intercept = $0.00

Prices as of May 10, 1973

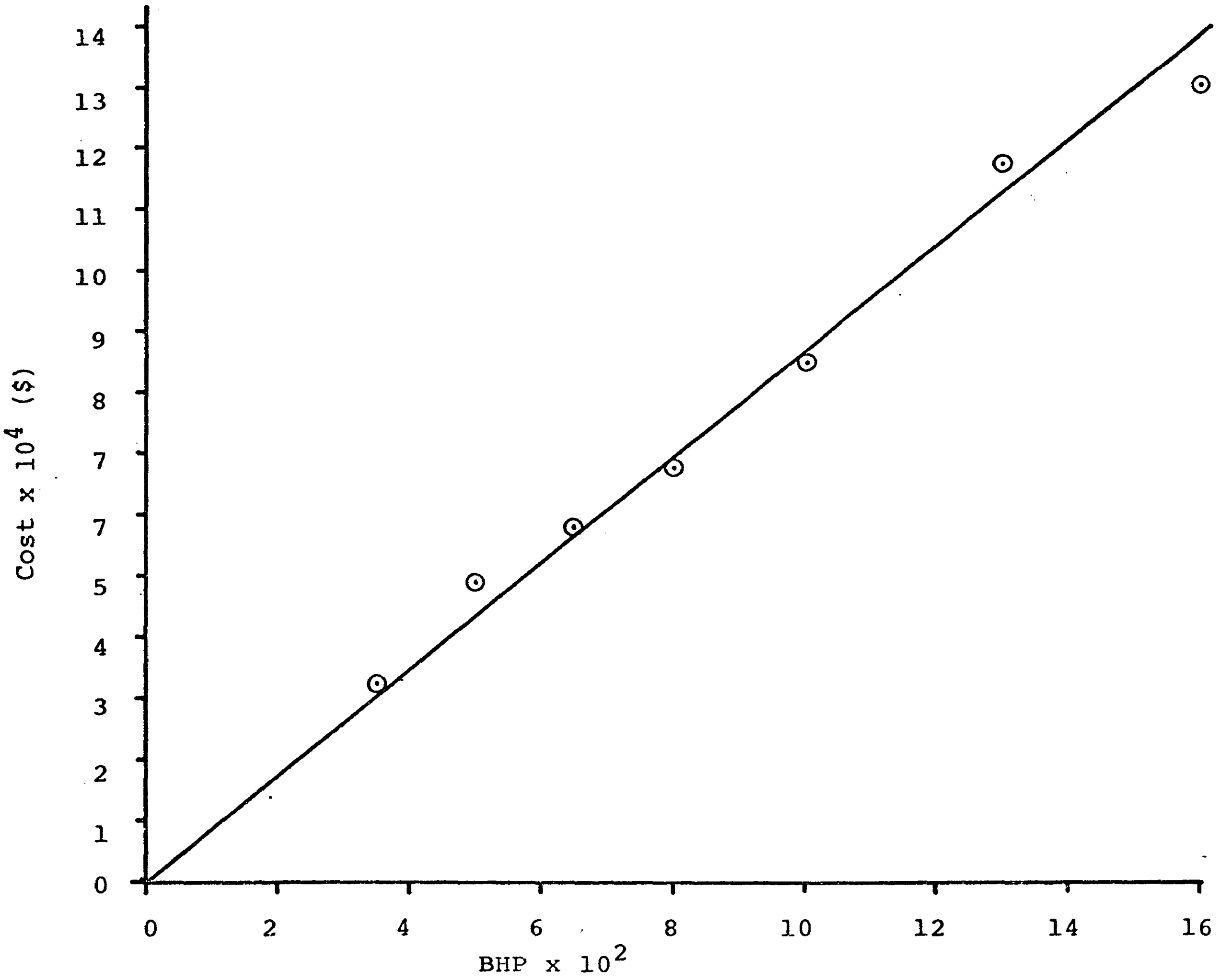


Figure 10. Pump BHP Versus Cost for Rubber-Lined Plunger-Type Slurry Pumps.

Slope = \$29.21/BHP

Intercept = \$0.00

Prices as of October 1, 1973

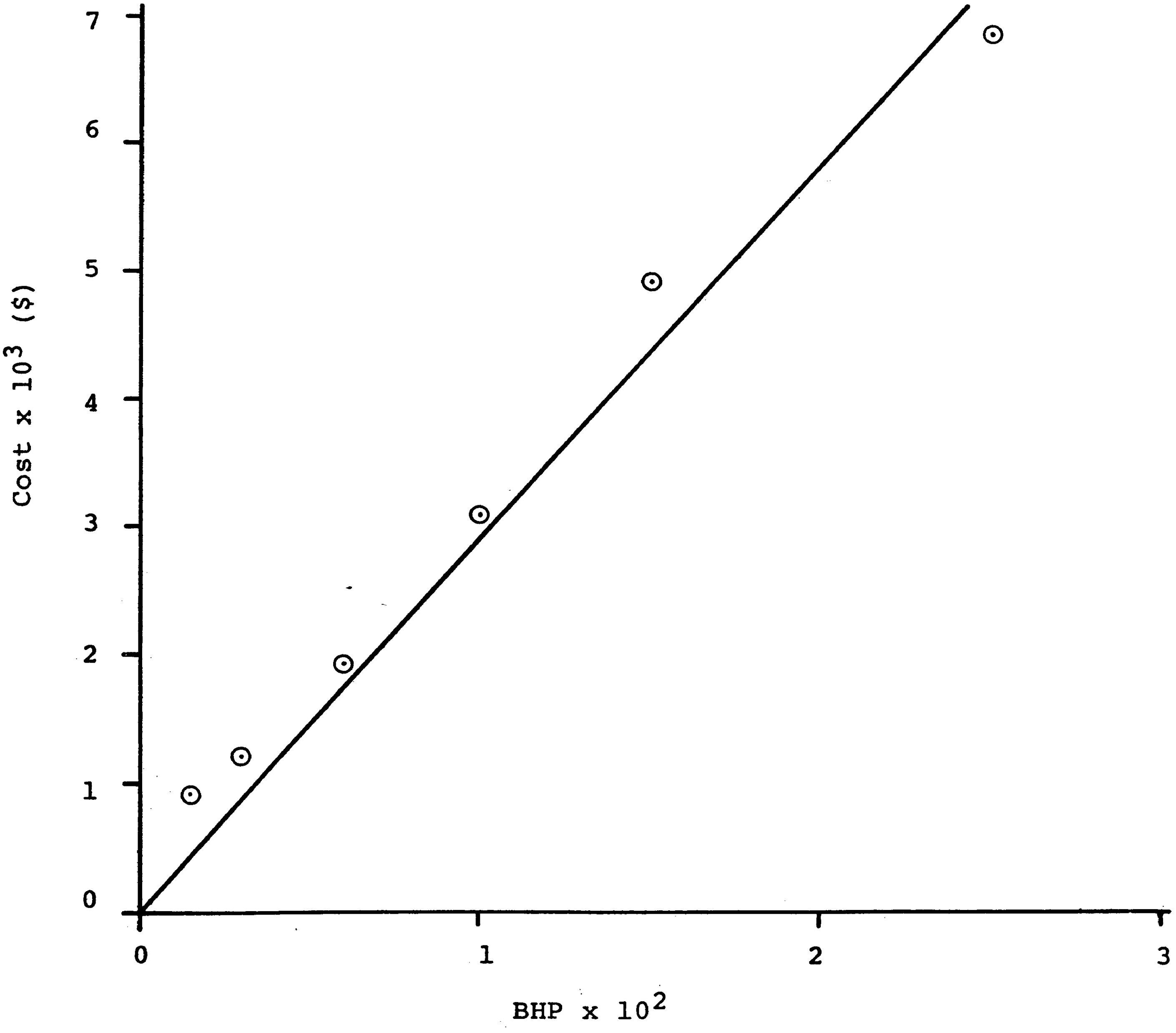


Figure 11. Pump BHP Versus Cost for Ni-Hard Plunger-Type Slurry Pumps.

Slope = \$29.17/BHP

Intercept = \$0.00

Prices as of October 1, 1973

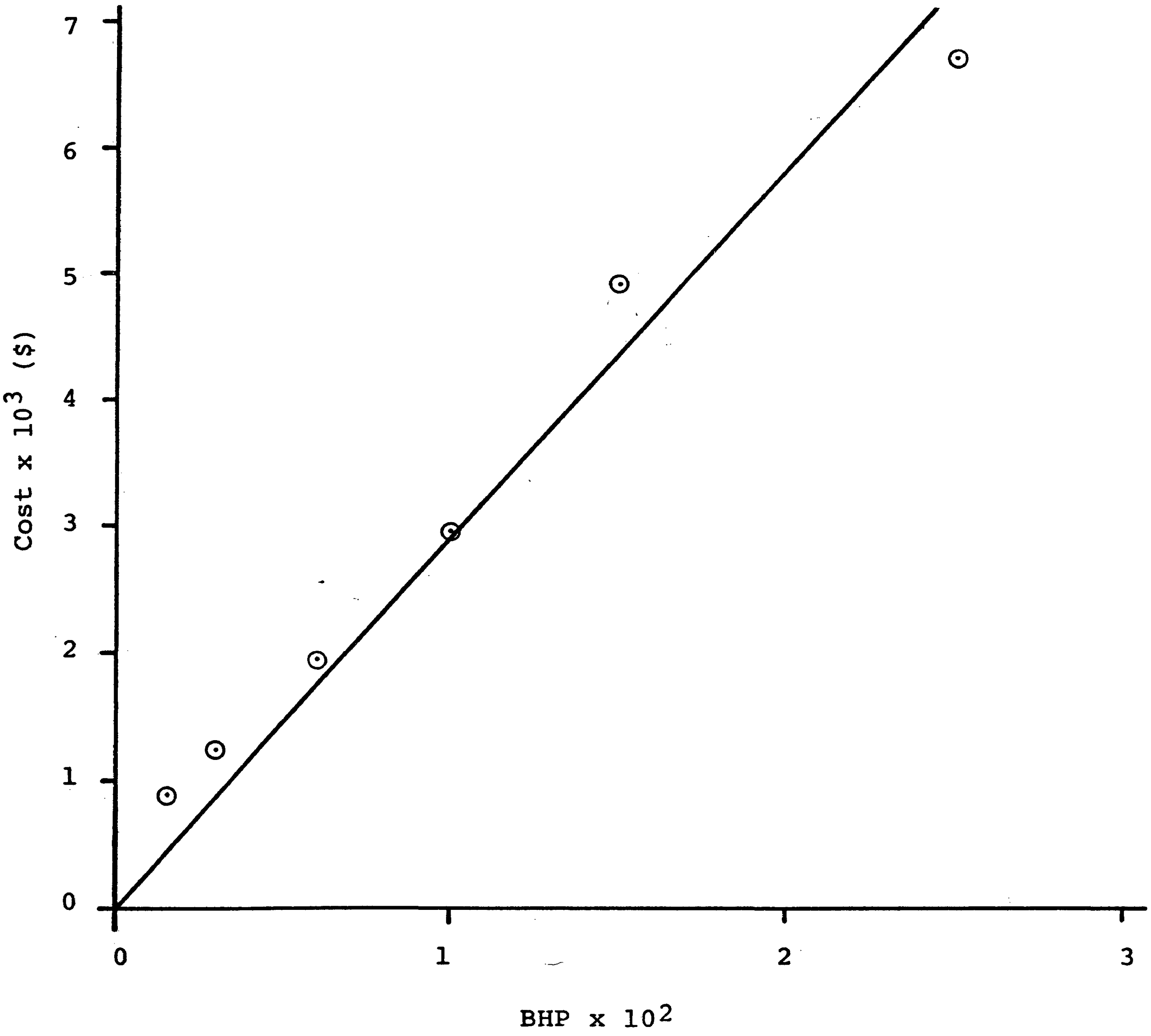


Figure 12. Pump BHP Versus Cost for Soft Rubber-Lined--Closed Impeller Centrifugal Pumps

Slope = $36.20/BHP

Intercept = $340.00

Prices as of March 30, 1973

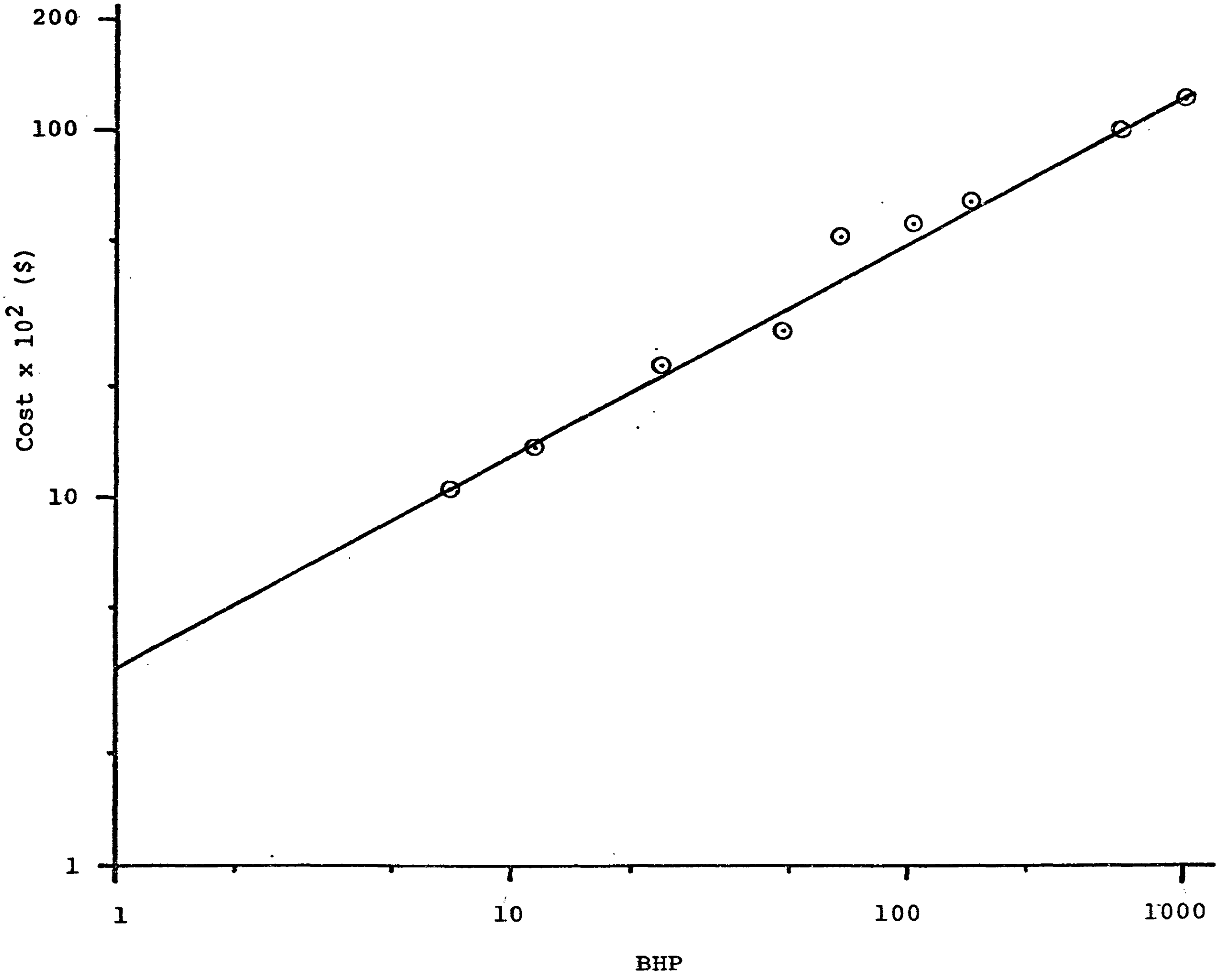
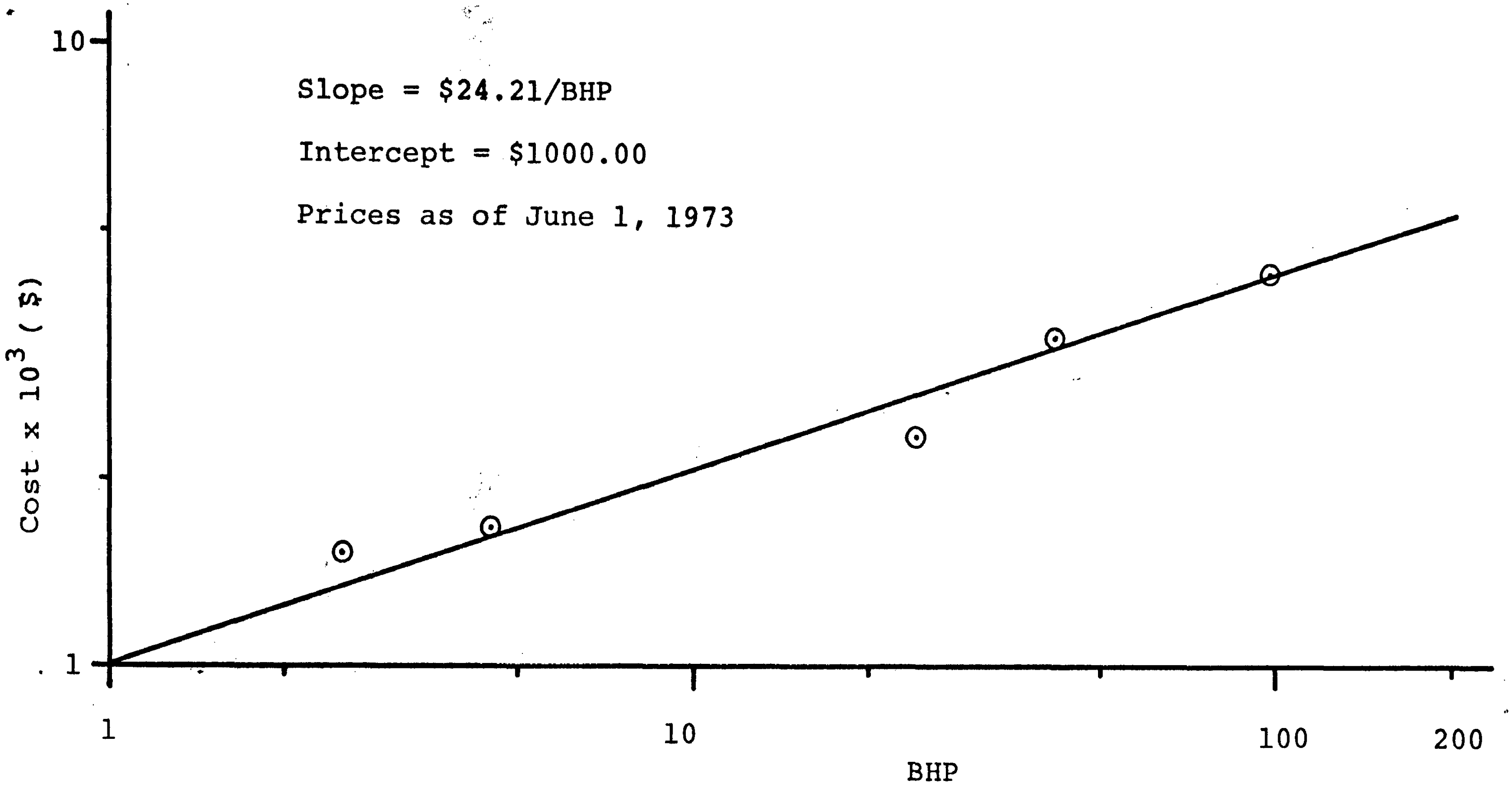


Figure 13. Pump BHP Versus Cost for Cast-Iron Centrifugal Pumps.



Slope = \$24.21/BHP

Intercept = \$1000.00

Prices as of June 1, 1973

Motors and Engines

Cost data for motors and engines were collected from two manufacturers. They showed good correlation of horsepower versus cost on rectangular coordinates. The cost data are adjusted to June 1974 in Table 24, using price indices from Table 2.

TABLE 24

Cost Data for Motors and Engines

Figure No.	Prices ($/hp) As Of		Prices ($/hp) Adjusted to 6/30/74
14	5/10/73	20.91	23.54
15	12/31/73	15.56	17.19
		10.35	11.43
16	5/30/73	75.00	84.45
17	5/30/73	68.75	77.41

Note that the motors are considerably cheaper than the engines.

Figure 14. Motor hp Versus Cost for 1200 RPM Motors (Three Phase, 60 Hertz, Totally Enclosed, Fan Cooled).

Slope = $20.91/hp

Intercept = $60.00

Prices as of May 10, 1973

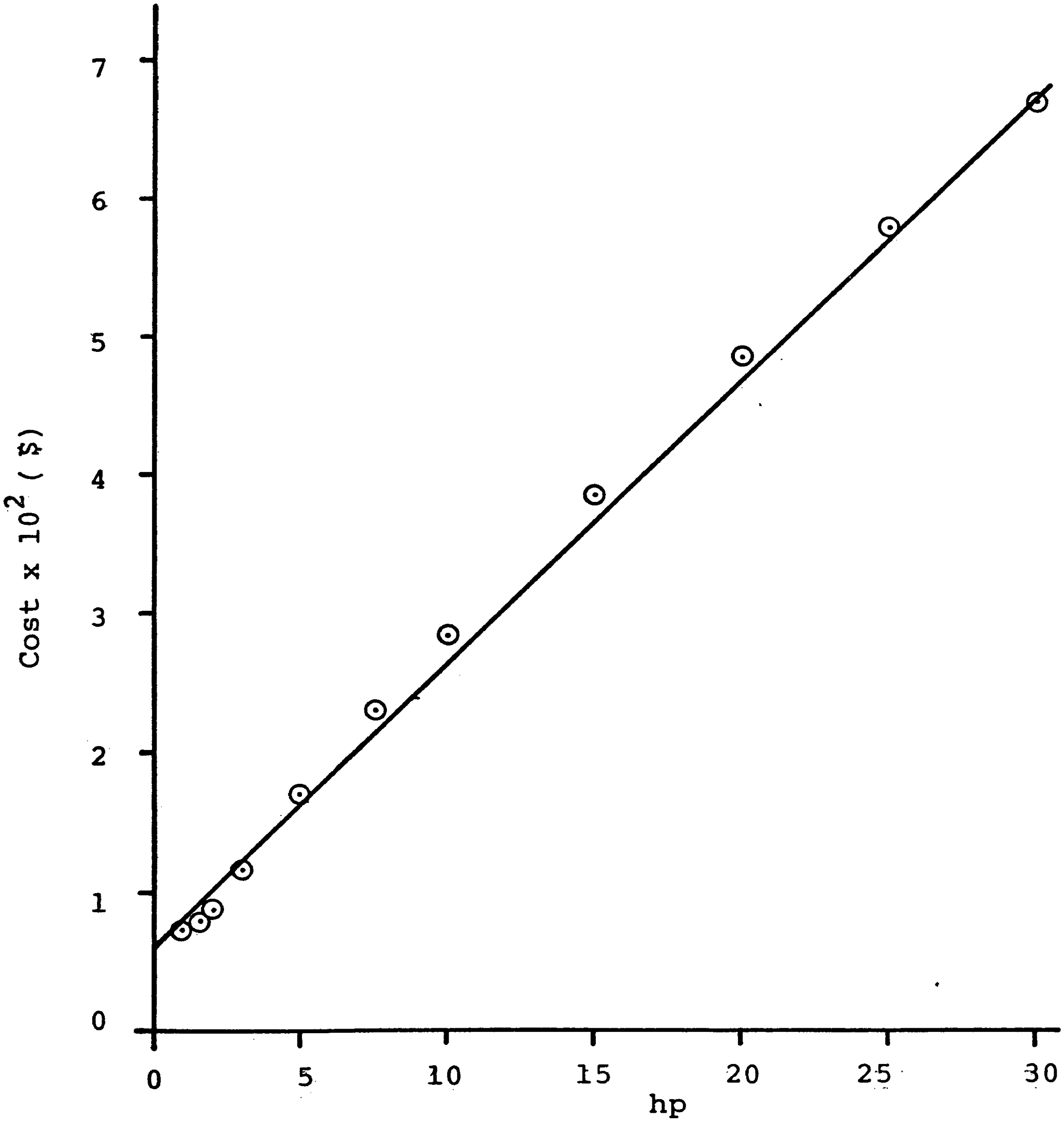
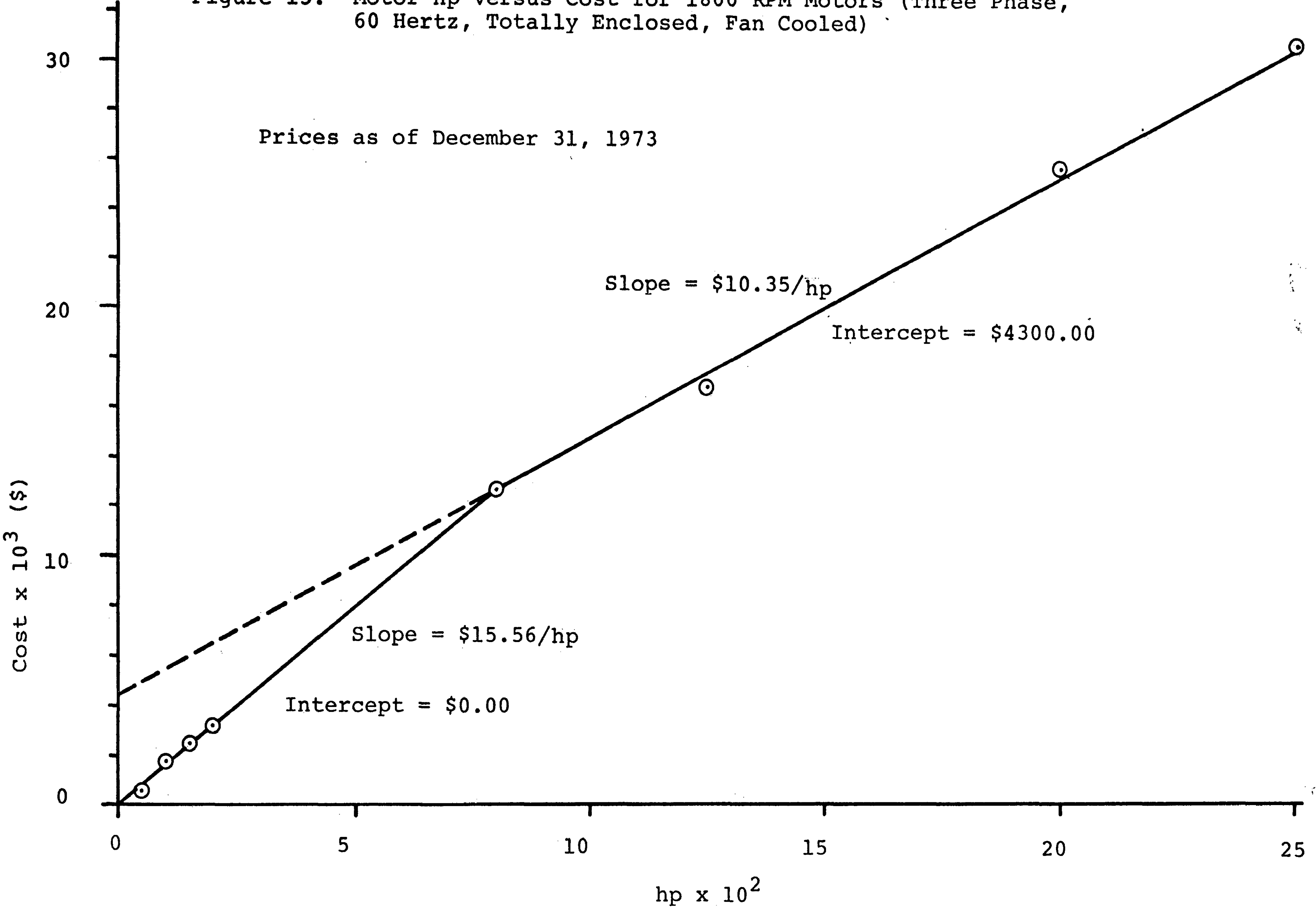
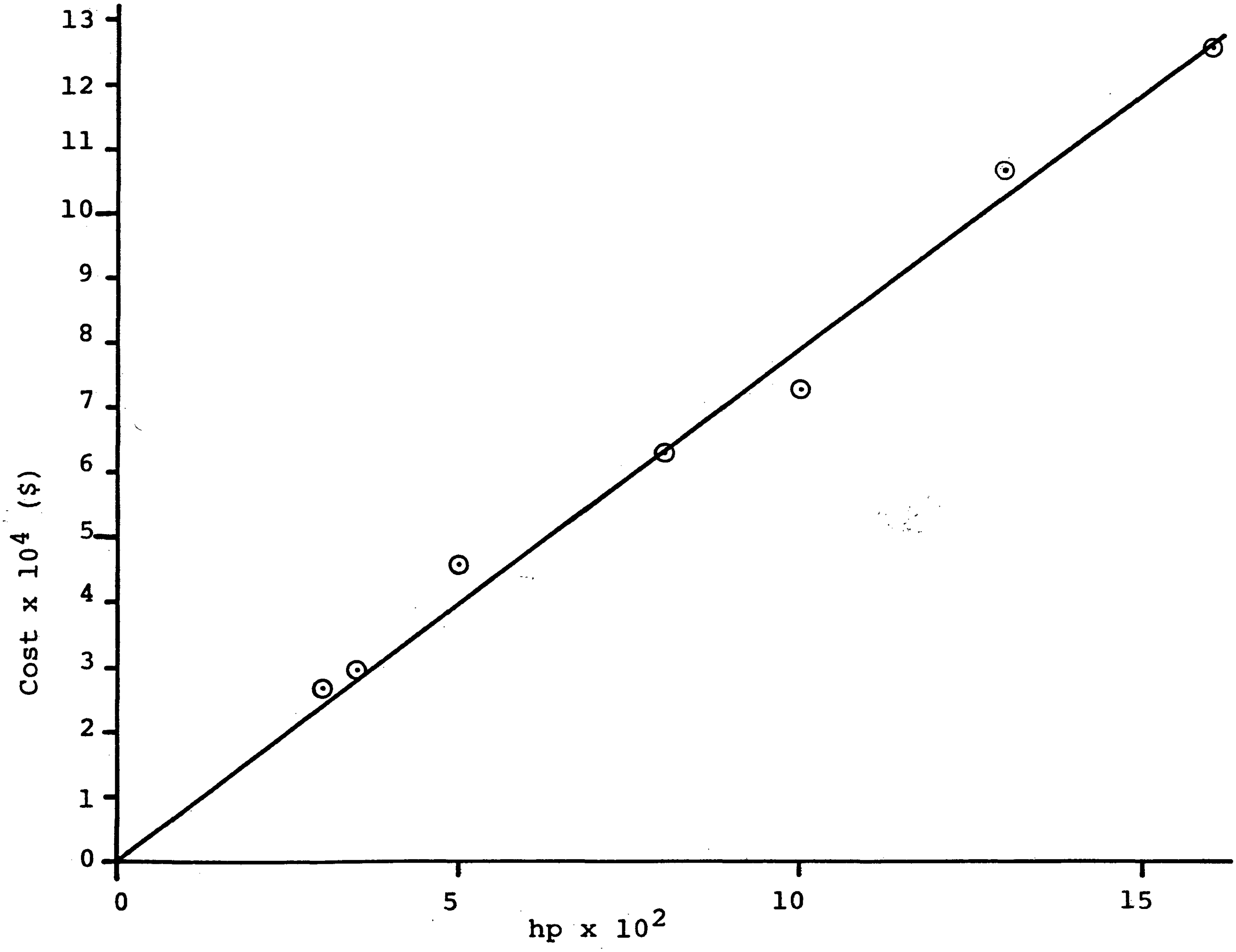


Figure 15. Motor hp Versus Cost for 1800 RPM Motors (Three Phase, 60 Hertz, Totally Enclosed, Fan Cooled)



Prices as of December 31, 1973

Figure 16. Engine hp Versus Cost for Gas Engines



Slope = \$75.00/hp

Intercept = \$0.00

Prices as of May 30, 1973

Figure 17. Engine hp Versus Cost for Diesel Engines