A method for optimizing a network of pipelines for transporting woodchips
by Irving Campos Hoffman

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Civil Engineering
Montana State University


Abstract:
A method is presented in this study for optimizing an economic model of a pipeline network transporting woodchips hydraulically by determining the concentration of woodchips and pipe diameter for each line of the system which minimize the cost.

A cost function for a single pipeline is investigated by defining a response surface whose characteristics provide a method for reducing to two the number of pipe diameters which could minimize the cost. The optimum concentration and cost for each size is determined, the costs for the two are compared, and the pipe giving the lowest cost is selected.

Optimization of three- and five-line networks utilizes the cost function of single lines and, in addition, requires that the continuity of flow of the two-phase fluid be satisfied at the junctions.

The optimization technique is applied to an existing area.

Costs of pipeline transportation of woodchips from chipping areas to a processing plant are compared with costs of moving the chips by rail and truck. The comparison shows rail costs are lowest in all cases.

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Approved:

Head, Major Department

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MONTANA STATE UNIVERSITY
Bozeman, Montana

December, 1967

## ACKNOWLEDGEMENTS

The optimizing techniques presented in this study are developed as part of the project investigating the transportation of woodchips in pipelines sponsored by the Forest Engineering Research Branch of the Intermountain Forest and Range Experiment Station, U.S. Forest Service, Department of Agriculture, as a cooperative aid project in the Department of Civil Engineering and Engineering Mechanics of Montana State University.

The cooperation of the Montana Power Company, Butte, Montana, Continental Pipe Line Company, Billings, Montana, and Utility Builders, Inc., Great Falls, Montana, is greatly appreciated.

The author wishes to extend personal thanks to Dr. William A. Hunt for his encouragement and guidance, to the faculty of the Department of Civil Engineering and Engineering Mechanics, and to the research engineers of the U.S. Forest Service associated with the project.

Gratitude is expressed to Elizabeth A. Hoffman, the author's wife, for her help in completing this thesis.

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# ABSTRACT

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CHAPTER I

INTRODUCTION

Transportation of solids in pipelines is not a recent innovation. Successful applications have been made for over one hundred years in fields ranging from placer mining to grain handling. High costs of labor and maintenance in other transportation systems have intensified interest in pipelines in recent years. Presently, many successful pipeline installations exist, most of which occur in the mineral and mining industry (1), (2)*. A 72-mile pipeline is transporting 800 tons per day of gilsonite from a mine in northeastern Utah to a refinery in western Colorado. Copper concentrate is pumped 14 miles in Chile. The mines in South Africa have several pipelines, some up to 16 miles long, successfully transporting uranium-bearing gold tailings.

Since 1957, the Pulp and Paper Research Institute of Canada (3) has been investigating the possibility of using pipelines to transport woodchips to processing plants. In 1961, the U.S. Forest Service began a program to examine pipelines as a means of conveying woodchips. The Forest Service is seeking more economical methods of transporting wood to stimulate greater utilization of woodlands in this country. Reduction in transportation costs will allow low-value wood (cull and dead trees, slash, and residue from sawmills) now being discarded to be moved to the processing plant. Private processors are continuously searching

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*Numbers in parentheses refer to numbered references in the Literature Cited.

for methods to lower handling and transportation costs of chips to increase production and profit. Pipelines may offer a means of reducing these costs.

The economic advantages of pipeline transportation are quite attractive:

<u>Automation</u>. Gas and oil pipelines have been automated for approximately twenty years. Once the fluid has been injected into the pipeline it is left unattended until the next input or discharge point. Pumping stations are controlled automatically from a central master station.

<u>Dependability</u>. Dependability of pipelines has been proven. The gilsonite pipeline in Utah has been operating for seven years (1). The Consolidated Coal Company operated a 108-mile pipeline in Ohio without a shutdown for three years (4).

<u>Operating Costs</u>. Operating costs are low; other costs are mostly fixed and remain nearly constant over the life of the installation. Other transportation systems have higher operating costs and are more easily affected by the rising costs of labor and personnel.

<u>Maintenance Costs</u>. Maintenance costs are low since pumping stations have few moving parts and the pipeline is buried and subject to little wear.

These advantages have been confirmed in the transport of single-phase fluids such as gas and oil. The advantages may potentially be applied to the transportation of solids by defining the hydraulics of two-phase flow.

The hydraulics of coal and gilsonite presently being transported long distances in pipelines are defined well enough to permit the design of pipeline systems. Although the mechanisms of flow for solids are not fully understood it is known that the small, uniform size of crushed coal and gilsonite produces a homogenous two-phase fluid at high velocities giving well defined friction loss relationships and allowing power requirements to be calculated and operating costs to be predicted. The hydraulic properties of woodchip mixtures are less well defined. Woodchips are relatively large and nonuniform in shape and size. The specific gravity of woodchips is lower than that of coal or gilsonite. Accurate relationships among head loss, which is shown to be the greatest economic factor, and other flow parameters, such as pipe size, velocity, and woodchip concentration, are required to predict the power requirements and, accordingly, the economics of woodchip pipeline transportation. Research is being conducted to investigate the mechanisms of motion of woodchips and to describe more accurately the head loss relationships involved.

A large research program sponsored by a group of ten interested companies was conducted in Marathon, Ontario (5). Friction loss tests for woodchip-water mixtures were conducted on 2,000 feet of 6-, 8-, and 10-inch steel pipe. Woodchip pipeline research projects at Montana State University (MSU) have been conducted to investigate the moisture absorptive properties of woodchips under pressure (6), the energy losses of woodchip-water mixtures passing through expansions and valves (7), the effect of woodchips on the performances of centrifugal pumps (8), and the economic feasibility of woodchip pipelines (9). Tests are currently being conducted at MSU to define the energy losses due to friction by various woodchip mixtures. Queen's University in Kingston, Ontario (10), the Pulp and Paper Research Institute of Canada (3), and the Shell Pipeline Corporation have conducted head loss studies on transporting woodchips in pipelines.

Several equations exist for head loss in two-phase flow. Durand (11) proposed an equation giving head loss for sand and gravel. Elliott and de Montnorency (3) modified Durand's equation to express head loss for woodchip-water mixtures in pipelines. Faddick (12) developed an equation for woodchips quite similar to Durand's from tests conducted at Queen's University on 4-inch pipeline.

A mathematical model developed by Hunt (9) to investigate the feasibility and economics of woodchip pipelining uses the head loss equation proposed by Faddick (12) for determing energy requirements, number and size of the pumping units, and costs of the variable salaries and wages. The analysis gives the best operating concentration and pipe size along with costs for a given throughput and length of pipeline. Investigation of this economic model showed that pump efficiency, frictional loss coefficient, capital recovery factor, and the chip concentration are the variables having the greatest effect on pipeline economics. The results of the model for a single pipeline with the chip source at one end and the processing plant at the other show pipeline transportation costs to be competitive with rail and truck. The analysis was applied to an area in Alaska which had no existing transportation facilities;

a savings of 58 percent was anticipated over road construction and haul.

The disadvantage of Hunt's model is that it cannot be applied to a network of pipelines which many of its applications will require. A network model is more complicated than a single-line model since the total costs are influenced by the operating characteristics of each line. A model analysis which gives the pipe size and concentration of woodchips for each line of a pipeline network producing the lowest cost for the system is needed.

This thesis develops a technique for determining these optimum conditions and predicting the lowest cost for pipeline networks. The method of analysis uses the response surface (13) generated by the mathematical expression developed by Hunt (9) describing the economics of the pipeline system. This expression, called the objective function, contains all the information required for a rational decision and when minimized gives the optimum operating conditions for a pipeline network.

# CHAPTER II

## SINGLE-LINE OPTIMIZATION

A technique of analyzing a response surface to determine the optimum operating conditions for a single-line pipeline system is described in this chapter. The response surface is produced from the objective function for the mathematical model developed by Hunt to describe the economics of a woodchip pipeline. This objective function contains three decision variables: (1) investment costs, (2) operating expenses, and (3) overhead costs. The three decision variables, in turn, are expressed by seven cost groups: (1) energy cost, $x_1$, (2) installed cost of the pipeline, $x_2$, (3) installed cost of the pump stations, $x_3$, (4) installed cost of injection and separation equipment, $x_4$, (5) cost of fixed salaries and wages, $x_5$, (6) cost of variable salaries and wages, $x_6$, and (7) cost of water treatment, $x_7$. The units for each of these groups are dollars per ton-mile which is the total expense of moving one ton of woodchips (oven-dry basis) one mile in a given transportation system. This unit was selected because it provides a basis for easily comparing rates of other transportation systems, such as rail and truck. The objective function for the single-line system is the summation of the seven cost groups and is expressed as

$$X_t = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7$$

The equations developed by Hunt (9) and used in this thesis for these seven cost groups are summarized in this chapter on page 8 and are functions of the variables listed below:

$C$ = Concentration of chips in the mixture by volume

crf = Capital recovery factor

$D$ = Pipe diameter, feet

$e$ = Combined efficiency of motor-pump drivers

$f$ = Friction factor for Weisbach equation

$H_t$ = Head due to friction and difference in elevation, feet/mile

$L$ = Length of pipeline, miles

$R_1$ = Cost of electrical energy, \$/kwh

$R_2$ = Installed cost of pipeline, including right-of-way, \$/(in-mile)

$R_3$ = Cost of pump station and controls, \$/(installed horsepower)

$R_4$ = Cost of chip injection system \$/(ton per day of oven-dry chips)

$R_5$ = Cost of separation system \$/(ton per day of oven-dry chips)

$R_6$ = Annual cost of fixed wages, salaries, operation maintenance; exclusive of pipeline maintenance and pump station operations, \$/year

$R_7$ = Annual wages, salaries, etc. for pump station, \$/(pump station)

$R_8$ = Annual maintenance cost of pipeline, \$/mile

$R_9$ = Cost of water and treatment, \$/million gallons

$S_m$ = Specific gravity of water-chip mixture

$S_{odc}$ = Specific gravity of oven-dry chips

$W$ = Throughput, tons per day of oven-dry chips (TPD)

The variables $S_m$ and $H_t$, which are developed in Appendix B, are functions of the following additional variables listed in Appendix A:

$g$ = Gravitational constant, ft/sec$^2$

$M$ = Moisture content of chips, decimal fraction of oven-dry chips

$Z_t$ = Difference in elevation between the ends of pipe, feet

The seven cost groups, expressed in units of dollars per ton-mile, are developed in Appendix B as functions of the above-listed variables and summarized by the following equations:

1. Energy cost,

$$x_1 = 0.000753 \left(\frac{R_1}{e\, S_{odc}}\right) \left(\frac{S_m H_t}{C}\right) \tag{1}$$

2. Installed cost of pipeline,

$$x_2 = \left(\frac{R_2\, D}{365\, W}\right) \text{crf} \tag{2}$$

3. Installed cost of pump stations,

$$x_3 = 0.000000115 \left(\frac{R_3}{e\, S_{odc}}\right) \left(\frac{S_m H_t}{C}\right) \text{crf} \tag{3}$$

4. Installed cost of injection and separation systems,

$$x_4 = \left(\frac{R_4 + R_5}{365\, L}\right) \text{crf} \tag{4}$$

5. Cost of fixed salaries and wages,

$$x_5 = \frac{R_6}{365\, W\, L} \tag{5}$$

6. Cost of variable salaries and wages,

$$x_6 = \frac{1}{365\ W} \left(\frac{R_7 H_t}{H_{sa}} + R_8\right) \quad (6)$$

7. Cost of water and water treatment,

$$x_7 = 0.00024 \left(\frac{1 - C}{C}\right) \left(\frac{R_9}{S_{odc}\ L}\right) \quad (7)$$

The analytical expressions are based on the system operating 24 hours per day for 365 days per year. The optimization technique which is presented in the following pages determines the values of C and D which give the minimum cost; all other variables must be specified. The variables $R_3$ and $R_7$ for this analysis have been modified from those used by Hunt. $R_3$ and $R_7$ were defined as functions of additional variables by Hunt; in this analysis they are assigned a constant value determined from economic data recently acquired from Continental Pipe Line Company (4).

The objective function, $X_t$, for the single-line system gives the total cost per ton-mile and can be expressed as a function of C and D in polynomial form by combining the seven cost groups algebraically. The polynomial expression, developed in Appendix C, is given by

$$X_t = (K_1 C^{1.84} + K_2 C^{1.84})\ D^{2.10} + (K_3 C^{-2} + K_4 C^{-3})\ D^{-5} + K_5 D + \frac{K_6}{C} + K_7 , \quad (8)$$

where the coefficients $K_i$, $i = 1$ to 7, are combinations of the variables other than C and D.

The absolute minimum cost for the single-line system is obtained by solving the simultaneous equations

$$\frac{\partial X_t}{\partial C} = 0$$

and

$$\frac{\partial X_t}{\partial D} = 0$$

Hunt investigated the solution of these equations by plotting $\frac{\partial X_t}{\partial C}$ and $\frac{\partial X_t}{\partial D}$ for different pipe sizes versus concentration as shown in Figure 1. He observed that the $\frac{\partial X_t}{\partial C}$ and $\frac{\partial X_t}{\partial D}$ curves intersected close to but never exactly on the zero ordinate and interpreted the intersection of the $\frac{\partial X_t}{\partial C}$ curves with the zero ordinate as sufficiently close to zero to describe a possible minimum condition although the equations for an absolute minimum were not satisfied. The reason these curves are not zero at the same concentration will be discussed later. Hunt was correct in selecting the points where $\frac{\partial X_t}{\partial C} = 0$ as the points of possible minimum costs. He determined which combination of concentration and diameter produced the minimum cost by using a digital computer for:

1. Solving the value of concentration at which $\frac{\partial X_t}{\partial C} = 0$ for a given pipe size
2. Computing the cost for this diameter at its optimum concentration using the seven cost groups
3. Repeating steps 1 and 2 for a given array of pipe sizes and comparing costs at the optimum conditions for each diameter.

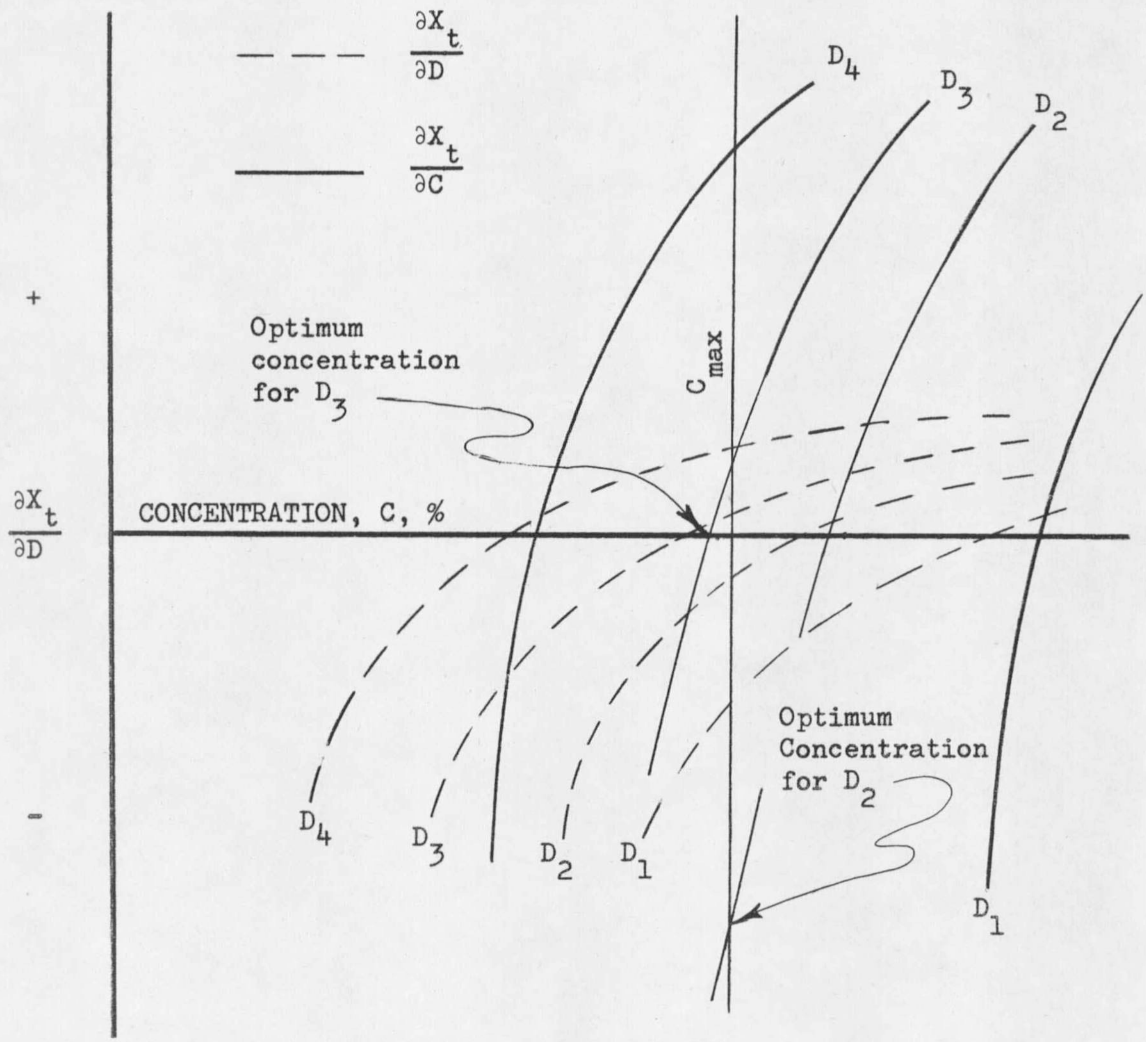


Figure 1. PARAMETRIC CURVES OF $\frac{\partial X_t}{\partial D}$ and $\frac{\partial X_t}{\partial C}$

Analysis of the response surface (13) generated by plotting $X_t$, cost per ton-mile, as a function of the concentration, C, and diameter, D, in a three-coordinate system as shown in Figure 2 offers an improvement of Hunt's method of solution. All surfaces for the single-line model were found to have similar shapes which decend to lower costs with smaller diameters and higher concentrations. The shape of the surface shows no node (a point at which $\frac{\partial X_t}{\partial D}$ and $\frac{\partial X_t}{\partial C}$ are both equal to zero) in the region of physical meaning; therefore, the conditions for an absolute minimum do not occur which indicates why the intersection of the curves $\frac{\partial X_t}{\partial D}$ and $\frac{\partial X_t}{\partial C}$ plotted by Hunt and shown in Figure 1 do not occur at the zero ordinate.

The response surface must be limited to a feasible region describing physical applications with all their limitations and constraints. Such a region is necessary since the concentration of woodchips in a pipeline has a limiting maximum above which it may not be increased without compressing the chips and packing the pipe so that transport is stopped. Faddick found this limit to be 43 percent for four-inch pipe; however, Equation B-5*, which he suggested and on which the economic pipeline model is based, does not contain constraints. This physical limitation on the concentration requires that the feasible region of the response surface be bounded by the planes $C = 0$, $D = 0$, and $C = C_{max}$ where $C_{max}$ is the maximum allowable operating concentration. The value

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*Equation numbers which contain letters refer to equations in the Appendix corresponding to the letter.