ENERGY CONSERVATION IN COAL CONVERSION

Method for Computing the Optimum Economic Pipe Diameter for Newtonian Fluids

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ABSTRACT

A closed form relation is presented for calculating the diameter of a pipe line which yields the minimum life-cycle cost for a wide range of fluid parameters and operating conditions.

A central consideration in the derivation of the relation is that the optimum diameter should reflect the energy costs for overcoming friction losses.

Diameters from the method presented here are compared with a relation developed by DuPont Co. The mean absolute percent difference between the two methods is less than 19%, with the method outlined here yielding larger diameters than the DuPont relation. A 19% increase in diameter represents a 58% decrease in the pumping power required to overcome friction losses.

INTRODUCTION

As the cost of energy and materials continues to increase, more attention is being devoted to optimization methods in a wide range of engineering design problems. A problem amenable to optimization occurs in the selection of a pipe diameter for a flowing fluid, where increasing the pipe diameter decreases the friction losses, hence energy costs, but increases the labor and capital costs. Although a number of constraints such as erosion limitations, allowable pressure drop, process control and compressible flow may dictate the selection of the diameter in a particular situation, there are many cases where the diameter can be optimized for a given set of fluid parameters, and costs.

This section presents a method for calculating the pipe diameter which yields the minimum life cycle cost of a pipe-line for a given set of parameters. A central consideration in the development of this method was that the optimum diameter should reflect the cost of energy required for pumping the fluid. In addition, this method is quite general, and encompasses a wide range of fluid parameters, and operating conditions, since most of the methods for computing the optimum diameter found in the literature[1,2,3,4,5] were restricted to either specific flow regimes, narrow ranges of viscosities, operating temperatures, pressures, or piping materials. The significant parameters for computing the optimum economic diameter are: mass flow rate, fluid viscosity, fluid density, operating pressure, operating temperature, cost of electricity, cost of labor, return on investment, project life, percent utilization, piping material costs, and pump and motor efficiency.

Since the economics are based on a per unit length basis, the length of the piping is not in the list of parameters.

A closed form solution for the optimum economic diameter is derived and has been correlated with a software program which computes the optimum diameter as a function of the parameters above. Optimum pipe diameters for a range of parameters were compared with diameters computed from a well-known relation developed by DuPont.

DEVELOPMENT OF THE METHOD FOR COMPUTING THE OPTIMUM DIAMETER

To find the optimum diameter, it is first necessary to determine how much capital investment in increased pipe cost is justified to save a unit of power. Using the internal rate of return analysis (or discounted cash flow method), the sum of the present values of all cash flows associated with a given project plus the salvage value, is equal to the initial capital investment. This can be expressed as:

$$C = \sum_{n=1}^{N} \frac{CF_n}{(1 + i)^n} \qquad (1)$$

where:

C = capital investment, \$/KW

i = rate of return, fractional

N = economic life, years

CF_n = net cash flow for any year, n, \$/KW.

The factor $\frac{1}{(1 + i)^n}$ transforms each cash flow to its value at time zero. The net cash flow for year n is defined as the savings resulting from a reduction in purchased electricity minus the operation and maintenance costs. This is expressed as:

$$CF_n = CE_n - CO_n - CM_n \qquad (2)$$

where:

CF_n = net cash flow for year n, \$/KW

CE_n = cost of electricity saved for year n, \$/KW

CO_n = operating costs for year n, \$/KW

CM_n = maintenance costs for year n, \$/KW

The cost of electricity saved for year n is:

$$CE_n = CE \times U \times 8760$$

where:

CE = cost of electricity, \$/KW-hr

U = period of operation per year, fractional

We assume that the cash flows are uniform, so (1) can be written using the present worth factor, PW:

$$C = PW(CE_n - CO_n - CM_n) \quad (3)$$

It is assumed that the difference in operation and maintenance costs for an incremental change in diameter are negligible, and there is no salvage value. Therefore, (3) becomes:

$$C = PW(CE_n) \quad (4)$$

This relation is illustrated in Figure 1.

Once the justified capital investment is determined for any given operating life, return on investment, price of electricity, and utilization factor, the optimum diameter is that diameter where the ratio of the incremental pipe cost to the incremental power lost due to friction

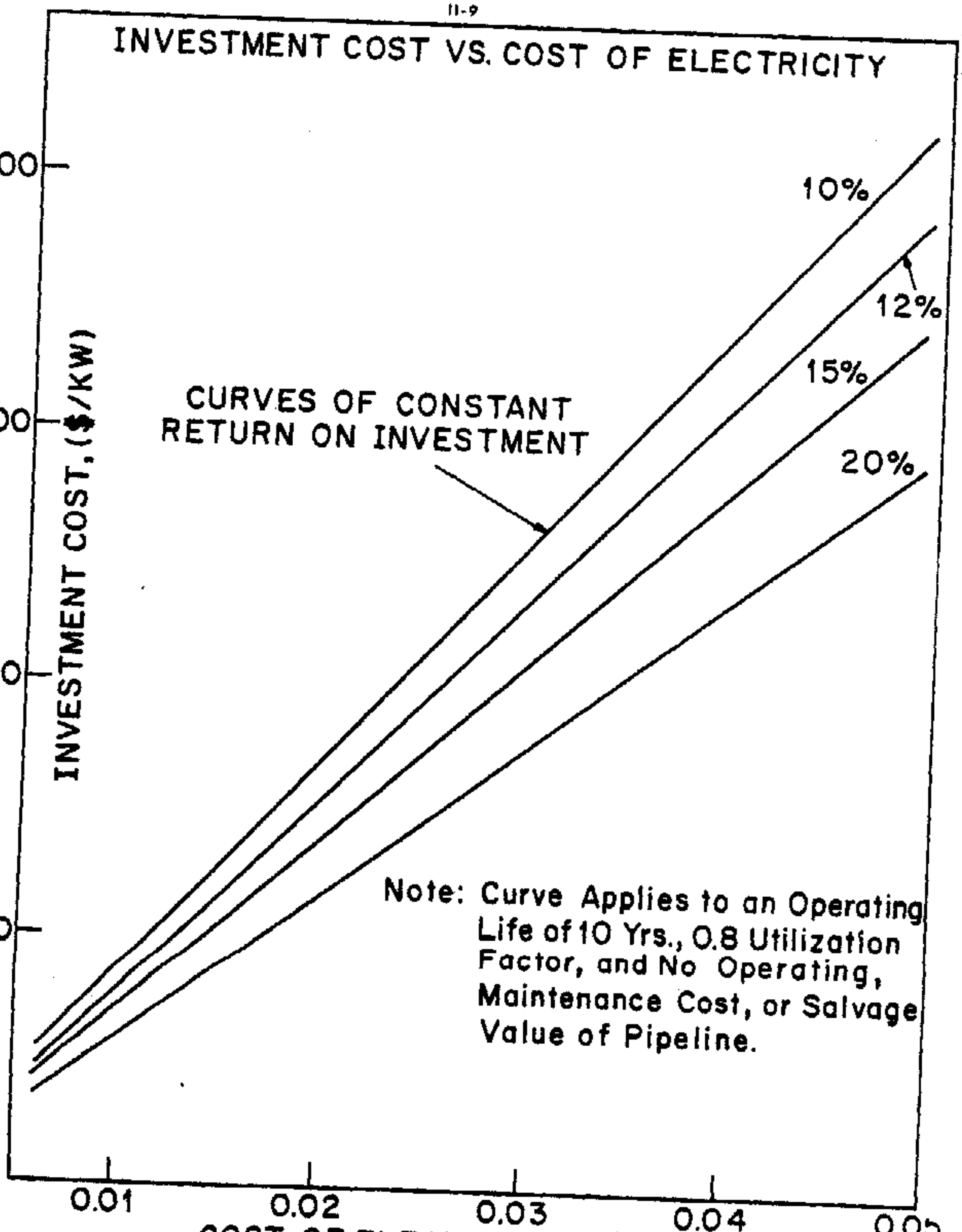

INVESTMENT COST VS. COST OF ELECTRICITY
2000
1500
1000
500
INVESTMENT COST, ($/KW)
10%
12%
15%
20%
CURVES OF CONSTANT
RETURN ON INVESTMENT
Note: Curve Applies to an Operating Life of 10 Yrs., 0.8 Utilization Factor, and No Operating, Maintenance Cost, or Salvage Value of Pipeline.
0.01
0.02
0.03
0.04
0.05
COST OF ELECTRICITY, ($/KW-HR)

FIG. 1

equals the amount of capital investment justified to save a unit of power. Mathematically,

$$C = \frac{\Delta P_c}{\Delta P_f} = \frac{\partial P_c}{\partial D}\Delta D \div \frac{\partial P_f}{\partial D}\Delta D \qquad (5)$$

where:

$\frac{\partial P_c}{\partial D}\Delta D$ is the incremental pipe cost, ΔP_c (\$/Ft)

$\frac{\partial P_f}{\partial D}\Delta D$ is the incremental power loss, ΔP_f (KW/Ft)

C is the capital investment justified to save a unit of power, (\$/KW)

The above expressions are illustrated graphically in Figures 2 and 3. Figure 2 depicts pumping power and pipe cost as a function of diameter. Note that the pumping power decreases inversely to the fifth power of the diameter, whereas, the pipe cost increases linearly with diameter. The ratio of incremental pipe cost to incremental pumping power is the capital investment justified to save a unit of power. A plot of the ratio of incremental pipe cost to incremental power consumption versus diameter for a flow of 6,000 gallons per minute of water is shown in Figure 3. If \$100.00 can be invested to save a kilowatt, it can be seen that the optimum economic diameter is 14.5 inches, while if C = 1000 \$/KW can be invested, the optimum diameter is 21 inches.

From the derivation given in Appendix A, the closed form expression relating the significant variable to the optimum diameter is:

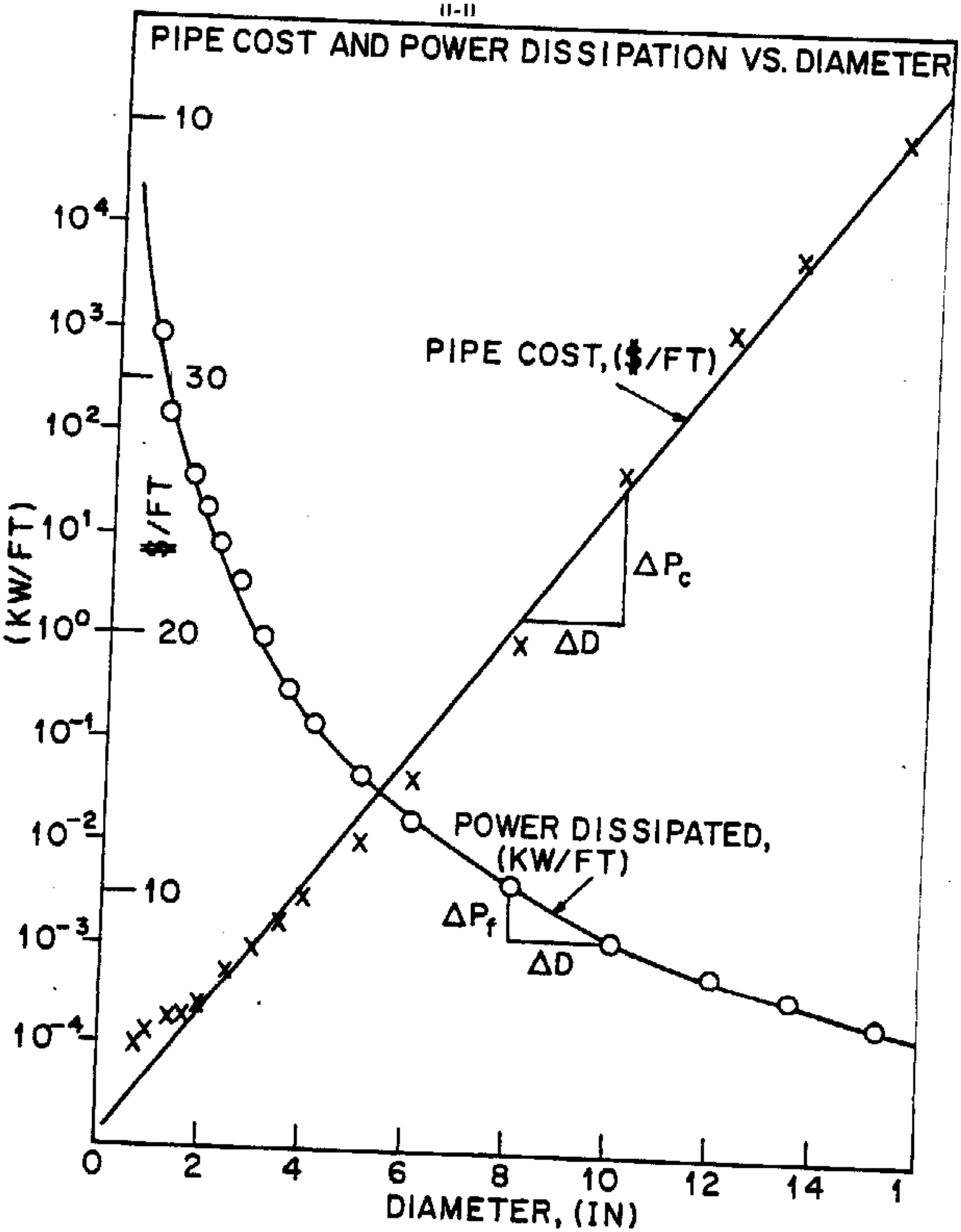

PIPE COST AND POWER DISSIPATION VS. DIAMETER
10
10^4
10^3
30
10^2
10^1
$/FT
(KW/FT)
10^0
20
10^{-1}
10^{-2}
10
10^{-3}
10^{-4}
PIPE COST, ($/FT)
ΔP_c
ΔD
POWER DISSIPATED, (KW/FT)
ΔP_f
ΔD
0
2
4
6
8
10
12
14
1
DIAMETER, (IN)

FIG. 2

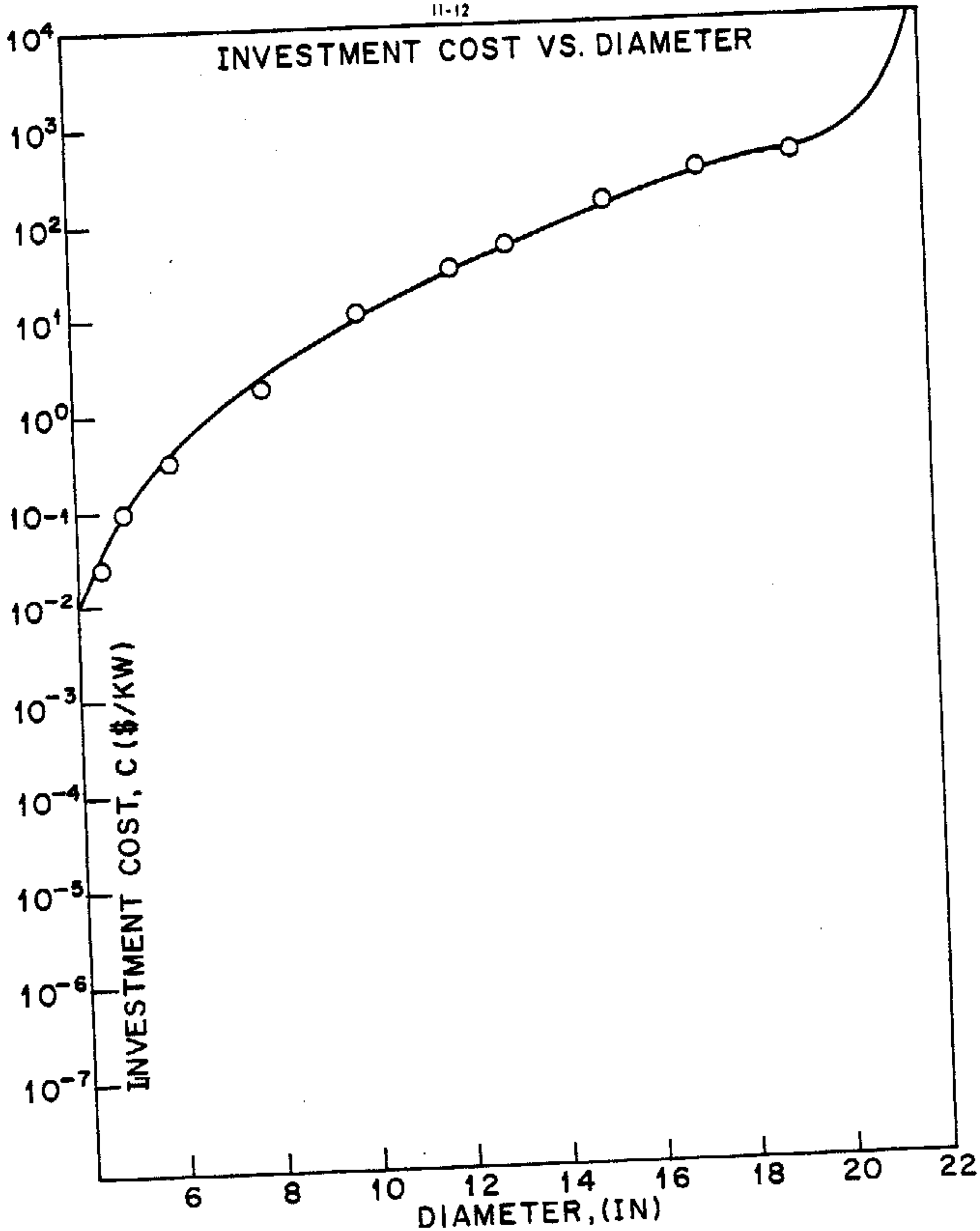

INVESTMENT COST VS. DIAMETER
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
INVESTMENT COST, C ($/KW)
6
8
10
12
14
16
18
20
22
DIAMETER, (IN)

FIG. 3

$$D/D_o = a_1 \gamma^{a_2}$$

where:

$$\gamma = 2.63 \times 10^{-13}\ Cfw^3/EC_p b\rho^2 \qquad (6)$$

and,

C is the capital cost to save a unit of power, \$/KW

f is the friction factor, dimensionless

w is the mass flow rate, lbm/hr

C_p is the pipe cost coefficient, \$/ft-in^2

b relates allowable stress to temperature, dimensionless

ρ is the fluid density, lbm/ft^3

E is the combined pump and motor efficiency, fractional

D_o is the unit diameter, one in.

The complete derivation of γ is given in Appendix A.

To compute the constants a_1 and a_2, a least squares linear regression of γ on D/D_o was performed. The values of D/D_o were computed by a software program with the inputs of:

1. mass flow rate
2. fluid viscosity
3. fluid density
4. operating pressure
5. cost of labor
6. capital investment to save a unit of power
7. piping material
8. pump and motor efficiency.

The program begins at an initial diameter of .5 inches and increments upwards in standard diameters, computing the incremental pipe cost and power consumed in going from one diameter to the next. When the ratio of incremental pipe cost to incremental power consumption is equal to the inputted capital cost to save a unit of power, the optimum diameter is found. A listing of the software program is given in Appendix C.

For the values of parameters in Table 1, 275 optimum diameters were computed by the software program, and the least squares linear regression yielded the constants:

$$a_1 = 2.4$$

$$a_2 = .179$$

giving the expression:

$$D/D_o = 2.4\ \gamma^{.179} \qquad (7)$$

The correlation coefficient for the 275 diameters is r = .94

γ versus D/D_o is presented in Figure 4.

TABLE 1

PARAMETER INPUTS FOR COMPUTER RUNS

RUN 1

Carbon Steel

ρ = .075 lbm/ft^3

T = 300°F

P = 500 psi

μ = .02 cp

W = 1000 lbm/hr
10,000 lbm/hr
15,000 lbm/hr
30,000 lbm/hr
60,000 lbm/hr

C = 100 $/KW (.0025 $/KW-hr)*
500 (.0126)
1000 (.0253)
1500 (.0379)
2000 (.0505)

C_L = 13.00 $/MH

E = .7

RUN 2

Carbon Steel

ρ = 62.5 lbm/ft^3

T = 300°F

P = 500 psi

μ = 1.0 cp

W = 10,000 lbm/hr
15,000 lbm/hr
30,000 lbm/hr
60,000 lbm/hr
120,000 lbm/hr
250,000 lbm/hr
500,000 lbm/hr
750,000 lbm/hr
1,000,000 lbm/hr
3,000,000 lbm/hr
4,500,000 lbm/hr

C = 100
500
1000
1500
2000

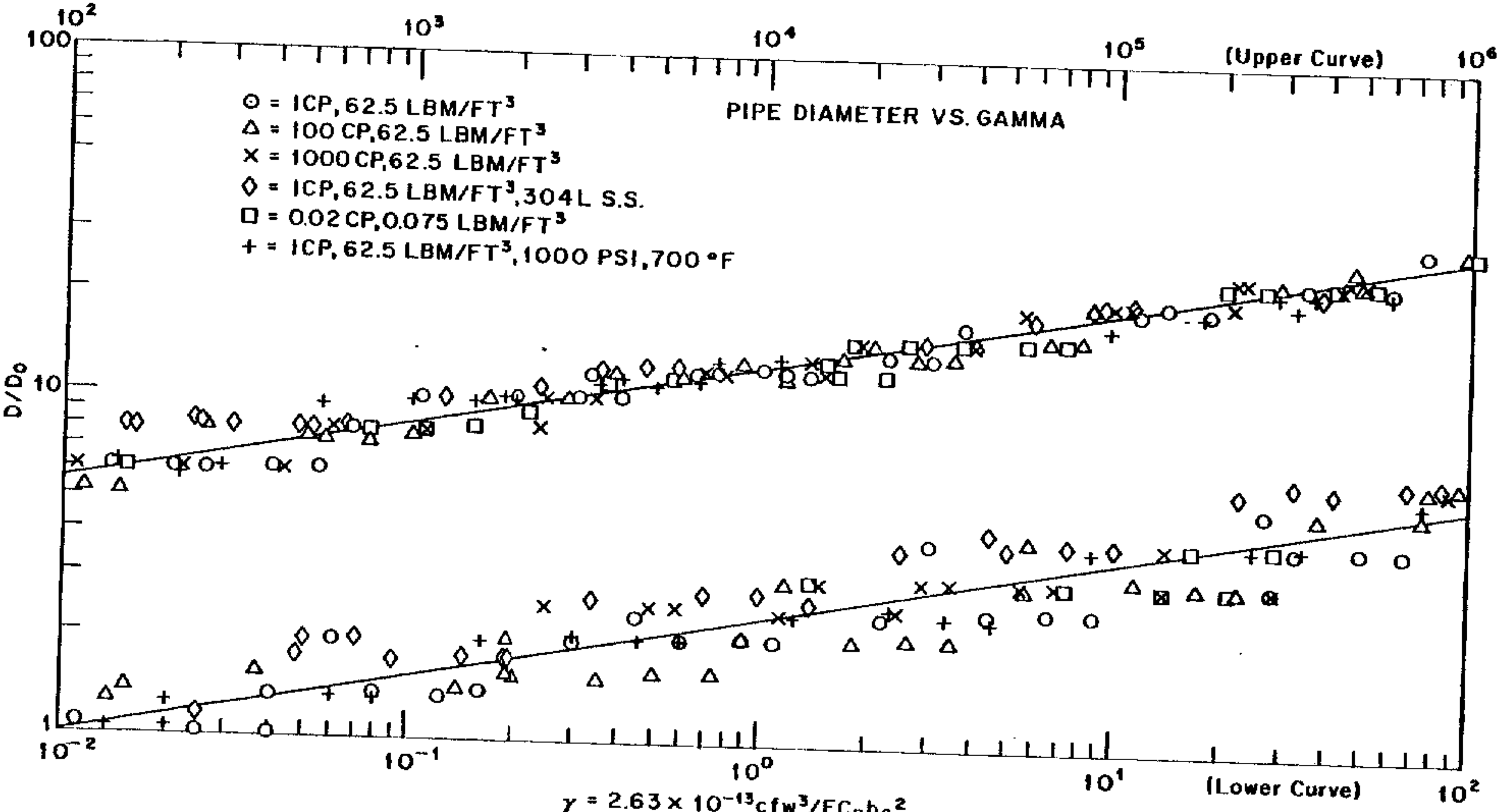
C_L = 13.00

E = .7

* For the computer runs, C is related to $/KW-hr by equation (4), with 12% return on investment over a 10-year operating life, and .8 utilization factor.

TABLE 1 (cont.)

RUN 3	RUN 4	RUN 5	RUN 6
Carbon Steel	Carbon Steel	304L S.S.	Carbon Steel
ρ = 62.5 lbm/ft^3	ρ = 62.5 lbm/ft^3	ρ = 62.5 lbm/ft^3	ρ = 62.5 lbm/ft^3
T = 300°F	T = 300°F	T = 300°F	T = 700°F
P = 500 psi	P = 500 psi	P = 500 psi	P = 1000 psi
μ = 100 cp	μ = 1000 cp	μ = 1 cp	μ = 1 cp
W = same as Run 2	W = same as Run 2	W = same as Run 2	W = same as Run 2
C = same as Run 2	C = same as Run 2	C = same as Run 2	C = same as Run 2
E = .7	E = .7	E = .7	E = .7



PIPE DIAMETER VS. GAMMA
○ = 1CP, 62.5 LBM/FT³
△ = 100 CP, 62.5 LBM/FT³
× = 1000 CP, 62.5 LBM/FT³
◇ = 1CP, 62.5 LBM/FT³, 304L S.S.
□ = 0.02 CP, 0.075 LBM/FT³
+ = 1CP, 62.5 LBM/FT³, 1000 PSI, 700 °F
(Upper Curve)
(Lower Curve)
D/Do
100
10
1
10^2
10^3
10^4
10^5
10^6
10^{-2}
10^{-1}
10^0
10^1
10^2
$\gamma = 2.63 \times 10^{-13} c f w^3 / E C_p b_\rho^2$

FIG. 4

ASSUMPTIONS AND LIMITATIONS

The method for determining the optimum economic diameter is subject to the following assumptions and limitations.

1. The method applies to Newtonian fluids (including incompressible flow of gases).
2. The upper limits for combinations of operating temperatures and pressures are: 700°F and 1800 psi for A53 Gr. B carbon steel, and 1000°F and 2000 psi for 304 L S.S. and 316 L S.S.
3. The material and labor costs for the three piping materials were based on data from Richardson, Process Plant Construction Estimating Standards 1977-1978 Edition[6], and a least squares correlation relating material and labor costs as a function of pipe weight per foot is used in the software program for computing the optimum diameter. Figures 5 and 6 show material cost and labor cost versus weight per foot of pipe.
4. Although the software program computes the optimum economic diameter for straight runs of pipe, the method is not limited to this. To account for the material and labor cost of fittings and valves, a pipe cost constant, C_p is computed. The computation of C_p is detailed in the section: Procedure for Calculating the Optimum Diameter.

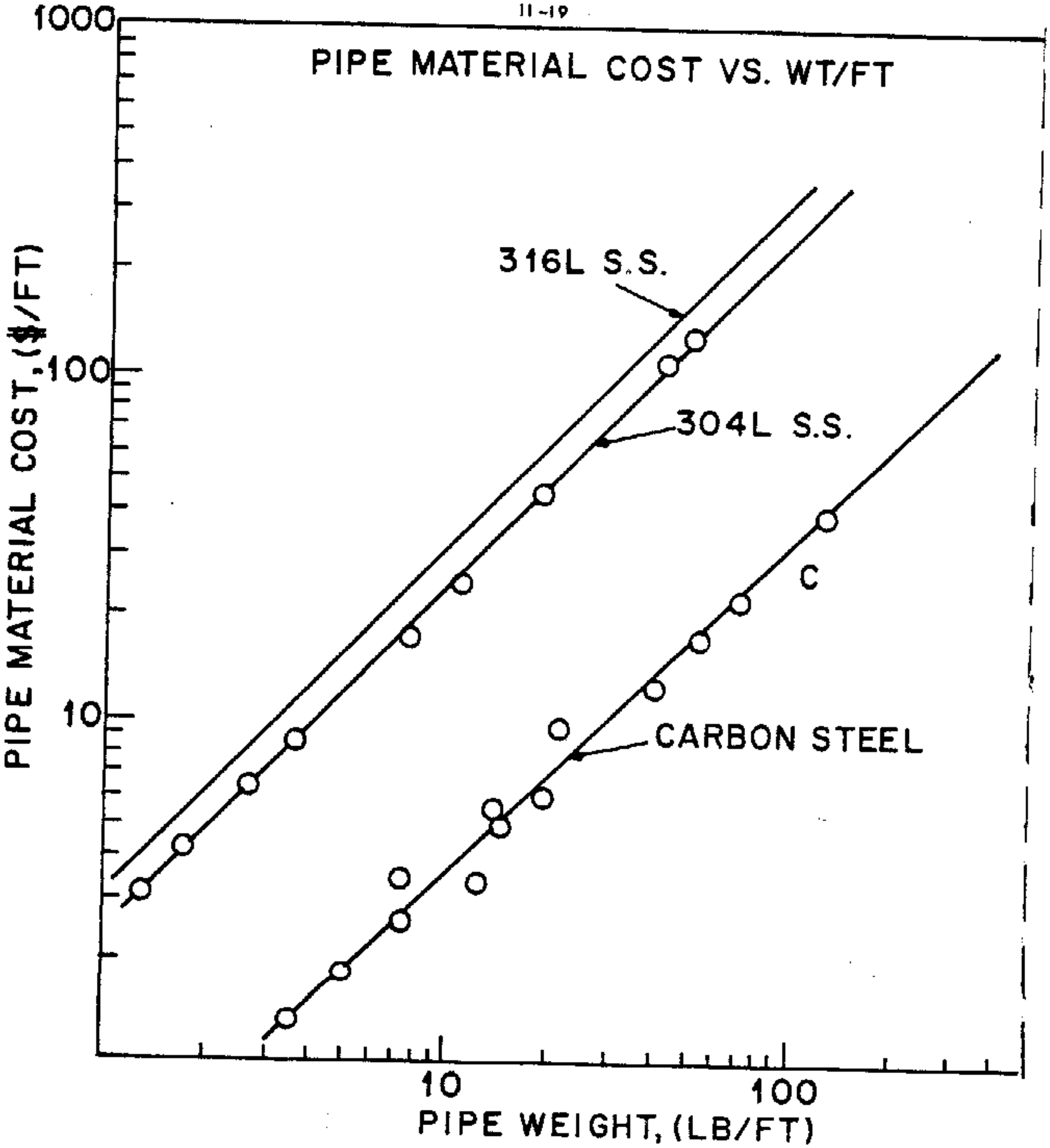
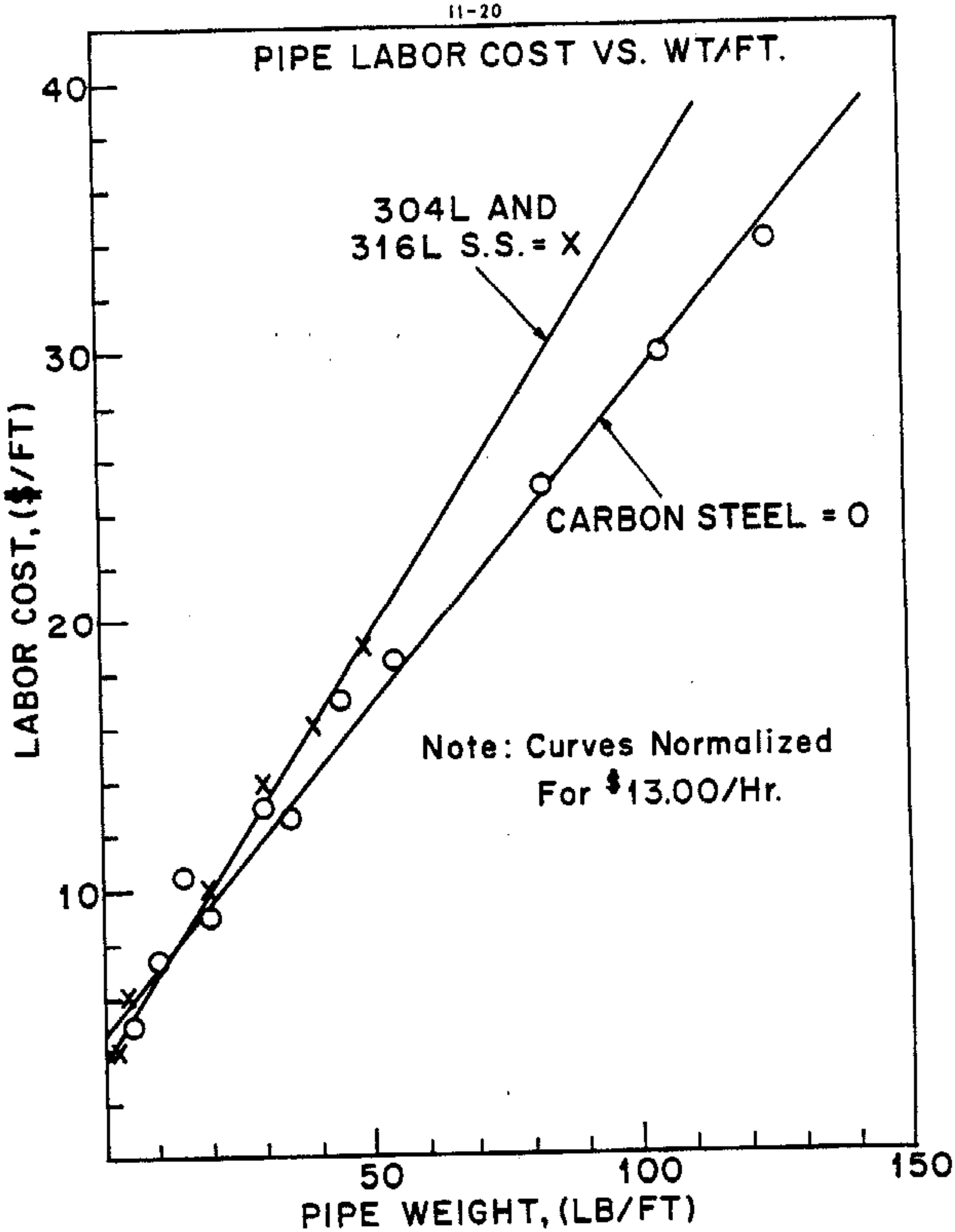

PIPE MATERIAL COST VS. WT/FT
1000
100
10
316L S.S.
304L S.S.
CARBON STEEL
C
PIPE MATERIAL COST, ($/FT)
10
100
PIPE WEIGHT, (LB/FT)

FIG. 5



PIPE LABOR COST VS. WT/FT.
40
30
20
10
LABOR COST, ($/FT)
304L AND
316L S.S. = X
CARBON STEEL = O
Note: Curves Normalized
For $13.00/Hr.
50
100
150
PIPE WEIGHT, (LB/FT)

FIG. 6

5. When sizing pipe, it is common practice to anticipate an increase in friction factor over the life of the pipe. To account for this the friction factor is multiplied by some constant. In the software program the friction factor is multiplied by 2, which corresponds to a value of C = 100, in the familiar William-Hazen formula for friction loss. This value of C if often used for design purposes, however, any value of f can be used in the method presented here.
6. Diameters to a maximum of thirty inches can be computed using this method.

EFFECT OF INFLATION ON THE OPTIMUM DIAMETER

By examining equation (6), it can be seen that the effect of inflation over the operative life of the pipe line would be to increase the cost of electricity, hence the capital investment to save a unit of power, C, would increase, as would the pipe cost coefficient, C_p, leaving the optimum diameter unchanged.

If the cost of electricity changes at a rate different than the material cost, the diameter would be affected as the ratio of the change in capital investment to the change in pipe cost to the .179 power.

PROCEDURE FOR CALCULATING THE OPTIMUM DIAMETER

For the parameters:

1. mass flow rate, W lbm/hr
2. fluid viscosity, μ cp
3. fluid density, ρ lbm/ft^3
4. operating pressure, P psi
5. operating temperature, T °F
6. cost of electricity, CE \$/KW-hr
7. return on investment, i fractional
8. project life, N years
9. utilization factor, U fractional
10. piping material costs, C_p \$/Ft-in^2
11. pump and motor efficiency, E fractional

Steps one through six outline the procedure for calculating the optimum diameter, using the relation:

$$D/D_o = 2.4\ \gamma^{.179} \qquad (7)$$

Step One: The capital investment justified to save a unit of power is calculated from equation (4), which is:

$$C = PW \times CE \times U \times 8760 \qquad (4)$$

Step Two: The quantity,

$$b = P(2(S - .6P) + P)/(S - .6P)^2 \qquad (8)$$

is computed where,

S is the allowable stress at the operating temperature, psi

P is the operating pressure, psi

This equation relates the maximum allowable stress of a given piping material to the operating temperature. Tables excerpted from the ASME pressure vessel code giving allowable stresses versus temperature for various materials are listed on pp. 6-38 to 6-41 of Perry[1].

Step Three: The pipe cost coefficient, C_p, is now computed. This coefficient depends on: (1) the piping material cost, (2) the number and cost of the various fittings and valves, and (3) the labor cost to install the pipe and all the fittings. For the commonly used piping materials, carbon steel, 304L S.S. and 316L S.S., C_p is given as:

$$C_p = .118X + .084\, C_L Y \qquad \text{for carbon steel} \qquad (9)$$

$$C_p = .208X + .162\, C_L Y \qquad \text{for 304L S.S.} \qquad (10)$$

$$C_p = .266X + .162\, C_L Y \qquad \text{for 316L S.S.} \qquad (11)$$

where:

X is the material cost per foot of 12-inch, 3/8" thickness carbon steel pipe, including the cost of fittings and valves. For 304L S.S. and 316L S.S. use 12-inch schedule 10S pipe.

Y is the man hours per foot to install the above 12-inch diameter pipe, including fittings and valves.

C_L is the cost of labor, \$/mhr

To compute X and Y, the fittings and valves in a run of pipe to be optimized are converted to the reference diameter of 12 inches. An estimating guide such as Richardson[6], can be used to determine the material and labor costs for the various valves and fittings, all converted to the reference diameter of 12 inches.

Step Four: For materials other than carbon steel, 304L S.S. or 316L S.S., if material costs can be expressed as a multiple of carbon steel costs, it is only necessary to multiply X by this multiple. Similarly for Y. If the pipe cost is not a direct multiple of carbon steel costs in order to compute C_p, it is necessary to express the pipe cost in the form:

$$P_c = Bwt^n + C_L(Gwt + d) \qquad (12)$$

where:

P_c is the material and labor cost per foot for erecting straight pipe without fittings or valves.

wt is the pipe weight, lbm/ft

From a least squares correlation, B, n, G and d can be determined. B can be expressed as:

$$B = C_m J \qquad \text{or} \qquad C_m = B/J$$

where:

C_m is the material cost coefficient, Ft/lb

J is the material cost per foot for a straight run of 12-inch pipe of the desired material and schedule, exclusive of any fittings or valves.

Similarly:

$$G = Fk \qquad \text{or} \qquad F = G/k$$

where:

F is the labor cost coefficient, ft/lb

k is the manhours per foot to erect the 12-inch pipe above, exclusive of any fittings or valves.

From the derivation given in Appendix A, we have the result:

$$C_p = nC_mC_2X + 2C_LFC_2Y \tag{13}$$

where:

X is the material cost per foot of the 12-inch pipe <u>including</u> all fittings and valves.

Y is the manhours per foot to erect the above pipe fittings and valves.

n is the exponent given in equation (12)

C_2 is the specific weight of the pipe, lb/ft-in^2

C_L is the labor rate, \$/mh.

<u>Step Five</u>: The effect of additional head loss due to fittings and valves (over 100 feet of straight pipe) is accounted for by computing an "equivalent" friction factor, f', to be used in equation (6)

$$f' = 2f(1 + L_e/100) \tag{14}$$

where:

f is the friction factor from the moody chart for a given Reynolds number and pipe diameter

L_e is the equivalent length in feet of pipe due to fitting and valve head loss only.

The factor of 2 was discussed under the section, Assumptions and Limitations, and is used to anticipate increasing friction factor with pipe aging.

Step Six: All the parameters needed to compute $D/D_o = 2.4\ \gamma^{.179}$ are known at this stage with the exception of f'. Since $f' = f(N_{RE}, e/D)$ for turbulent flow, D/D_o cannot be calculated explicitly. Therefore, it is necessary to assume an initial diameter. From this diameter, N_{RE} is calculated, and f is found from the Moody chart. L_e can also be computed, since L_e/D is known from the various fittings and valves. Consequently, f' can be calculated from Step Four. D/D_o can now be computed. Using this value of D, f and L_e are again found, and a new f' is calculated as before. This f' is substituted into Equation (6), and new D is calculated. From this D, the above process is repeated once more, with the resulting D being the optimum diameter. At the most, three calculations of D will be required before the solution converges within ± 3% of the optimum diameter.

Following the procedure outlined above, a numerical example is given in the following section.

CALCULATION OF THE OPTIMUM DIAMETER - AN EXAMPLE

Find the optimum economic diameter given the following parameters:

1. mass flow, W = 750,000 lbm/hr
2. fluid density, ρ = 62.5 lbm/ft^3
3. fluid viscosity, μ = 100 cp
4. operating temperature, T = 300°F
5. operating pressure, P = 300 psi
6. pump and motor efficiency, E = .7
7. utilization factor, U = .8
8. cost of electricity, CE = .038 $/KW-hr
9. return on investment, i = .12
10. operating life of 10 years
11. cost of labor, C_L = 13.55 $/hr
12. A53 Gr B carbon steel piping with the following fittings:

    5 - 90° ELS, 2 - T's, 2 gate valves (fully open),

    5 field butt-welds per 100 foot of pipe

Step One: The capital investment is calculated from Equation (4)

$$C = PW(CE \times U \times 8760)$$
$$= 5.65(.038 \times .8 \times 8760)$$
$$= 1505 \text{ \$/KW}$$

Step Two: The coefficient relating allowable stress to temperature is calculated, with information from pp. 6-38 to 6-41 of Perry[1].

$$b = P(2(S - .6P) + P)/(S - .6P)^2$$
$$= 300(2(18,150 - .6(300) + 300)/(18,150 - .6(300)^2)$$
$$= .034$$

<u>Step Three</u>: The pipe cost coefficient is calculated. The following table is constructed for the 12-inch, 3/8-inch wall thickness reference pipe, based on data from Richardson[6].

Item	Quan.	Material Cost	Man Hours Req'd	Le/D
90° ELS	5	5 x 86.00 = 430.00	5 x 10.6 = 53	150
T'S	2	2 x 149.00 = 248.00	2 x 10.6 = 21.2	40
300#Gate Valves	2	2 x 3119.00 = 6238.00	2 x 5 = 10	20
Pipe	100 ft.	1523.00	68.6	--
Field Welds	5	--	5 x 11.1 = 55.5	--
TOTALS		8489.00	208.3	210

Therefore,

$$X = 8489/100 = 84.9 \text{ \$/ft}$$

and,

$$Y = 208.3/100 = 2.08 \text{ mh/ft}$$

From Equation (9),

$$C_p = .118X + .084C_LY$$
$$= .118(84.9) + .084(13.55)(2.08)$$
$$= 12.38$$

<u>Steps Five and Six</u>: Calculation of f' and D. Assuming an initial diameter of 6 inches yields;

$$N_{RE} = 6.32\ W/\mu D = 6.32(75{,}000)/(100)(6)$$
$$= 7{,}900,$$

and from the Moody chart, f = .034. Therefore,

$$L_e = (210)(.5) = 105 \text{ and from equation (14)}$$
$$f' = 2f(1 + L_e/100) = 2(.034)(1 + 105/100)$$
$$= .139$$

From equation (6),

$$\gamma = 2.63 \times 10^{-13}\ Cf'w^3/EC_p b\rho^2$$
$$= 2.63 \times 10^{-13}\ (1505)(.139)(750{,}000)^3/(.7)(12.38)(.034)(62.5)^2$$
$$= 2.0 \times 10^4$$

Therefore,

$$D/D_o = 2.4\ \gamma^{.179}$$
$$= 2.4\ (2.0 \times 10^4)^{.179}$$
$$= 14.14$$

The Reynolds number is now recalculated.

$$N_{RE} = 6.32(750{,}000)/(100)(14.14)$$
$$= 3352$$

and from the Moody Chart,

$$f = .042$$

$$L_e = (210)(1.17) = 247.5$$

$$f' = (2)(.042)(1 + 247.5/100)$$

$$= .292$$

Therefore,

$$\gamma = (2.63 \times 10^{-13})(1505)(.292)(750{,}000)^3/(.7)(12.38)(.034)(62.5)^2$$

$$= 4.24 \times 10^4$$

and,

$$D/D_o = 2.4(4.24 \times 10^4)^{.179}$$

$$= 16.3$$

Recalculating the Reynolds number once again,

$$N_{RE} = 2926$$

and,

$$f = .0425$$

$$L_e = 285.3$$

$$f' = .326$$

$$\gamma = 4.73 \times 10^4$$

$$D/D_o = 16.5$$

This is the optimum diameter.

CONCLUSION

The method developed here for determining the optimum diameter was compared with a relation developed by DuPont cited in Perry[1] for the range of parameters listed in computer runs one through three of Table 1. DuPont's equation and the assumptions made in the comparison are given in Appendix B. The software program computed the percent difference in diameter (where $\% \Delta D = \frac{D_Y - D_{DuPont}}{D_{DuPont}} \times 100\%$) for 135 diameters, and the results are summarized in Table 2. For each mass flow range of 1,000 - 60,000 lbm/hr listed in Table 2, five diameters were compared, and for each mass flow range of 10,000 - 4,500,000 lbm/hr, eleven diameters were compared. From Table 2 it can be seen that the mean absolute percent difference in diameters between the two methods is less than 19%, with the method presented here yielding larger diameters than the DuPont relation, for diameters over four inches. A 19% increase in diameter represents a decrease of 58% in the pumping power required to overcome friction losses.

The method for computing the optimum diameter is straight forward, and encompasses a wide range of parameters with an emphasis on the cost of energy, as evidenced by the larger diameters produced, relative to another accepted method.

TABLE 2

DIAMETER COMPARISON BETWEEN DUPONT RELATION

AND DIAMETER CALCULATED FROM GAMMA

Mass flow (lbm/hr)	Density (lbm/ft^3)	Viscosity (cp)	Energy Cost ($/KW-hr)	Max %ΔD	Mean Absolute %ΔD
1,000 - 60,000	.075	.02	.0025	- 11.1	6.8
			.0126	27	17.8
			.0253	29	15.7
			.0379	23	12.3
			.0505	19	10.6
10,000 - 4.5 MM	62.5	1.0	.0025	19	8.7
			.0126	37	11.4
			.0253	28.7	14.4
			.0379	21.8	11.5
			.0505	43	14.2
		100	.0025	22.8	10.5
			.0126	35	18.8
			.0253	37	17.6
			.0379	28.5	12.8
			.0505	23	11.6

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APPENDIX A

Derivation of Gamma

The head loss due to friction of fluid flowing in a closed conduit is given by the D' Arcy-Weisbach Equation as:

$$h_L = f\left(\frac{L}{D_1}\right)\frac{V^2}{2g} \qquad (1)$$

In terms of pressure drop per unit length of pipe:

$$\frac{P_1'}{L} = P_1 = \frac{fV^2}{2gD_1}\rho \qquad (2)$$

where,

$$P_1 = LBf/Ft^2 - Ft$$

For laminar flow,

$$f = 64/N_{RE} \qquad (3)$$

and for transition and turbulent flow, the empirical relation,

$$\frac{1}{f} = -2\log_{10}\left(\frac{2.5}{\sqrt{f}\,N_{RE}} + \frac{e}{3.7D_1}\right) \qquad (4)$$

will be used.

The power dissipated as a result of friction loss per unit length is:

$$P_f = \frac{P_f'}{L} = PVA \qquad (5)$$

The power input for a combined pump and motor efficiency, E, in terms of W and D is:

$$P_f = \frac{C_1 f w^3}{E D^5 \rho^2 g} \qquad (6)$$

As a basis for piping costs, Richardson Process Plant Construction Estimating Standards 1977-1978 was used. Using a least squares linear regression, the following correlation was obtained:

$$P_c = C_m X wt^n + C_L(FYwt + d) \qquad (7)$$

where,

C_m = .0228, n = .974, F = .01573, d = .268 (for carbon steel)

C_m = .0375, n = 1.04, F = .0303, d = .188 (for 304L S.S.)

C_m = .048, n = 1.04, F = .0303, d = .188 (for 316L S.S.)

wt = lb/ft

X = $/ft, material cost per foot of 12-inch, 3/8" wall thickness carbon steel pipe. Includes cost of pipe, fittings, and valves. For 304L S.S. and 316L S.S. use 12-inch SCH. 10S pipe.

Y = mh/ft, manhours to install 12-inch, 3/4" wall thickness carbon steel pipe, including all fittings and valves. For 304L S.S. and 316L S.S. use 12-inch, SCH 10S pipe.

C_L = $/mhr, cost of labor.

The pipe cost is a function of weight per length for a given material. This in turn is a function of operating pressure and temperature (unless special considerations require extra wall thickness for abrasion, for example). With no allowance for corrosion, the wall thickness as a function of temperature and pressure is given by the ASME pressure vessel code formula for seamless pipes as:

$$t_m = PD_o/2(S + .4P) \tag{8}$$

or in terms of inside diameter, D, this can be expressed as:

$$t_m = PD/2(s - .6P). \tag{9}$$

Since,

$$wt = c_2(D_o{}^2 - D^2) \tag{10}$$

and,

$$D_o = D + 2t_m. \tag{11}$$

We can combine these expressions, and the weight per length can be expressed as:

$$wt = c_2 D^2 b \tag{12}$$

where,

$$b = P(2(S - .6P) + P)/(S - .6P)^2. \tag{13}$$

Using the case of carbon steel as an example, and substituting (12) into (7) we have:

$$P_c = C_m X\,(C_2 D^2 b)^{.974} + C_L(FYC_2 D^2 b + d) \qquad (14)$$

Computing the incremental pipe cost for a ΔD yields:

$$\Delta P_c \doteq \frac{dP_c}{dD}\Delta D = (1.948C_m \times (C_2 b)^{.974} \times D^{.948} + 2C_L FYC_2 Db)\Delta D \qquad (15)$$

where,

$$\Delta P_c = \$/\text{ft.}$$

The incremental change in the power required for this ΔD is:

$$\Delta P_f \doteq \frac{dP_f}{dD}\Delta D = -\frac{6C_1 fw^2}{ED^6 \rho^2 g}\Delta D\ . \qquad (16)$$

Therefore,

$$C = \frac{\Delta P_c}{\Delta P_f} = \frac{dP_c}{dD}\Delta D \times \frac{dD}{dP_f}\frac{1}{\Delta D}$$

$$= -\frac{ED^6 \rho^2 g(1.948C_M \times (C_2 b)^{.974} \times D^{.948} + 2C_L FYC_2 Db)}{6C_1 fw^3} \qquad (17)$$

Making the approximation:

$$DbC_p \doteq Db(1.948C_M \times C_2 + 2C_L FYC_2) \qquad (18)$$

or,

$$C_p = (1.948C_M \times C_2 + 2C_L FYC_2). \qquad (19)$$

For carbon steel this becomes:

$$C_p = .118X + .084C_L Y \qquad (20)$$

For 304L S.S. this is:

$$C_p = .208X + .162C_L Y \quad (21)$$

and for 316L S.S. this is:

$$C_p = .266X + .162C_L Y \quad (22)$$

We can simplify (17) so that:

$$C = \frac{\Delta P_c}{\Delta P_f} = - EC_p \rho^2 bD^7 g/6C_1 fw^3 \ . \quad (23)$$

For any given investment cost to save a unit of power, C ($/kw), the optimum diameter is:

$$D = (C6C_1 fw^3/EC_p bg\rho^2)^{1/7} \quad (24)$$

Dividing by the unit diameter D_o, inches,

$$D/D_o = (C6C_1 fw^3/D_o^7 EC_p bg\rho^2)^{1/7} \quad (25)$$

Let:

$$C_6 = 3.83 \times 10^{-11} \ in^5/ft^5 \cdot hr^3/sec^3 \cdot kw\text{-}sec/ft\text{-}lbf \cdot 6C_1/EC_p g \quad (26)$$

or:

$$C_6 = 2.63 \times 10^{-13}/EC_p \ , \ kw\text{-}hr^3\text{-}in^7/\$\text{-}lbm\text{-}ft^6 \quad (27)$$

Therefore,

$$D = f(C,f,b,w^3,\rho^2,E,C_6) \quad (28)$$

We define gamma as:

$$\gamma = 2.63 \times 10^{-13}\ Cfw^3/EC_p b\rho^2, \tag{29}$$

which is the quantity relating the significant parameters to the optimum economic diameter. The parameter groups in Table 1 were inputted to the software program, and each combination of parameters yielded an optimum diameter, and a corresponding γ. A least squares linear regression of γ on D/D_o yields:

$$D/D_o = 2.4\ \gamma^{.179} \tag{30}$$

with a correlation coefficient r = .94.

NOMENCLATURE

h_L = head loss, ft

V = velocity, ft/sec

L = ft

P_1 = Lbf/ft^2-ft

D_1 = diameter, ft

e = relative rougness, ft

A = area, ft^2

g = 32.14 ft-lbm/sec^2-lbf

ρ = density, lbm/ft^3

f = friction factor, dimensionless

N_{re} = reynolds number, dimensionless

C_1 = scale factor, dimensionless

P_f = power per unit length, lbf/sec

P_c = pipe cost, $/ft

C_L = labor cost, $/mh

C_M = material cost coefficient, ft/lb

F = labor cost coefficient, ft/lb

η = cost exponent, dimensionless

d = cost constant, mh/ft

D_o = unit diameter, one in.

P = operating pressure, psi

S = allowable stress, psi

t_m = wall thickness, in.

D = inside diameter, in.

U = fractional operation time per year, dimensionless

C_2 = 2.667 lbm/ft-in^2

wt - pipe weight, lbm/ft

b = dimensionless

ΔP_c = $/ft

ΔP_f = lbf/sec

C = $/kw

C_p = $/ft-in^2

γ = dimensionless

E = pump and motor efficiency, fractional, dimensionless

X = material cost, $/ft

Y = labor, mh/ft

w = mass flow rate, lb/hr

APPENDIX B

DuPont Co. Optimum Diameter Relation

The parameters indicated in runs 1 through 3 of Table 1 were inputted to the DuPont formula[1] below, and the diameters calculated were compared with the diameters calculated from the γ correlation. The results of these comparisons are summarized in Table 2.

Both relations computed the optimum diameter for a straight run of schedule 40 carbon steel pipe which included five field butt-welds per hundred feet. The comparison of the two methods was made on a common basis with the parameters below assigned to the DuPont formula, and where applicable, to the γ correlation.

The formula of DuPont which is based on return on incremental investment is given as:

$$D^{4.84+n}/(1+.794L'_e D) = \frac{.000189YKq^{2.84}\rho^{.84}\mu^{.16}\left((1+M)(L-\phi)+\dfrac{ZM}{a'+b'}\right)}{n\,X\,E(1+F)(Z+(a+b)(1-\phi))} \quad (1)$$

where:

D = economic pipe diameter, ft

n = exponent in pipe cost equation ($C = XD^n$)

C = cost of pipe, \$/ft

X = cost of 1 ft, of 1 ft diameter pipe

L_e' = factor for friction in fittings, in pipe diameters per unit length of pipe

$M = (a' + b')EP/(17.9KY)$ ratio of annual cost of pumping installation to annual cost of power delivered to the fluid, dimensionless

E = Combined pump and motor efficiency, dimensionless

P = installed cost of pump and motor, $/Hp

K = cost of power delivered to the motor, $/kw-hr

Y = days of operation per year (24 hr days)

ϕ = factor for taxes, dimensionless

Z = fractional annual rate of return on investment, dimensionless

F = ratio of cost of fittings plus installation cost of fittings and pipe to pipe material cost, dimensionless

a' = fractional annual depreciation on pumping installation, dimensionless

b' = fractional annual maintenance on pumping installation, dimensionless

a = fractional annual depreciation on pipe line, dimensionless

b = fractional annual maintenance on pipe line, dimensionless

q = volumetric flow rate, ft^3/sec

ρ = fluid density, lbm/ft^3

μ = fluid viscosity, cp

The values assigned to the parameters are:

$n = 1.256$	$Y = 292$
$X = 14.1$	$\phi = .55$
$L_e' = 0$	$Z = .12$
$E = .7$	$a' + b' = .4$
$p = 150$	$a + b = .2$

Using a least squares correlation, the following relations were derived for material and labor costs of schedule 40 carbon steel pipe based on data from Richardson[6].

$$\text{Material cost, \$/ft} = 14.1\ D^{1.256}$$

of if D is in inches,

$$\text{\$/ft} = .62\ D^{1.256}$$

also,

$$\text{Labor cost, \$/ft} - 1.22\ D^{.78}$$

assuming labor cost = \$13.00/mhr and welding cost, $/ft = 1.08 $D^{.78}$.

The above expressions are combined to form an expression for 1 + F which is,

$$1 + F = 1 + 3.71\ D^{-.476} \text{ where, D is in.}$$

APPENDIX C

SOFTWARE PROGRAM LISTING

```
C PROGRAM FOR OPTIMIZING PIPE SIZE FOR ANY NEWTONIAN FLUID
C
C
C        ROBERT KRAMEK
C        DEPARTMENT OF MECHANICAL ENGINEERING
C        CARNEGIE-MELLON UNIVERSITY
C        PITTSBURGH PENNSYLVANIA
C
C
         REAL NRE, KNEW,KOLD, LAMBDA, MU,KWHR
         DIMENSION DNOM(30), DOUT(30), TMSTL(30), TMSS(30), CKI(15),
         2 P(10), T(10), Q(30), RHO(10), MU(10), DS(10), C(10),
         3 RHOS(10), CLABOR(10)
C NOMINAL DIAMETERS FOR STANDARD PIPE SIZES ARE:
115      DNOM(1)=.5
         DNOM(2)=.75
         DNOM(3)=1.0
         DNOM(4)=1.25
         DNOM(5)=1.5
         DNOM(6)=2.0
         DNOM(7)=2.5
         DNOM(8)=3.0
         DNOM(9)=3.5
         DNOM(10)=4.
         DNOM(11)=5.
         DNOM(12)=6.
         DNOM(13)=8.
         DNOM(14)=10.
         DNOM(15)=12.
         DNOM(16)=14.
         DNOM(17)=16.
         DNOM(18)=18.
         DNOM(19)=20.
         DNOM(20)=24.
         DNOM(21)=30.
C OUTSIDE DIAMETERS ARE AS FOLLOWS
         DOUT(1)=.840
         DOUT(2)=1.05
         DOUT(3)=1.315
         DOUT(4)=1.66
         DOUT(5)=1.9
         DOUT(6)=2.375
         DOUT(7)=2.875
         DOUT(8)=3.5
         DOUT(9)=4.
         DOUT(10)=4.5
         DOUT(11)=5.56
         DOUT(12)=6.625
         DOUT(13)=8.625
         DOUT(14)=10.75
         DOUT(15)=12.75
         DOUT(16)=14.
         DOUT(17)=16.
         DOUT(18)=18.
```

```
      DOUT(19)=20.
      DOUT(20)=24.
      DOUT(21)=30.
C SCHEDULE 40 WALL THICKNESSES
      TMSTL(1)=.109
      TMSTL(2)=.113
      TMSTL(3)=.133
      TMSTL(4)=.14
      TMSTL(5)=.145
      TMSTL(6)=.154
      TMSTL(7)=.203
      TMSTL(8)=.216
      TMSTL(9)=.226
      TMSTL(10)=.237
      TMSTL(11)=.258
      TMSTL(12)=.28
      TMSTL(13)=.322
      TMSTL(14)=.365
      TMSTL(15)=.375
      TMSTL(16)=.375
      TMSTL(17)=.375
      TMSTL(18)=.375
      TMSTL(19)=.375
      TMSTL(20)=.375
      TMSTL(21)=.375
C THICKNESSESS FOR SS TO BE SCH 10
      TMSS(1)=.065
      TMSS(2)=.065
      TMSS(3)=.065
      TMSS(4)=.065
      TMSS(5)=.065
      TMSS(6)=.065
      TMSS(7)=.083
      TMSS(8)=.083
      TMSS(9)=.083
      TMSS(10)=.083
      TMSS(11)=.109
      TMSS(12)=.109
      TMSS(13)=.109
      TMSS(14)=.134
      TMSS(15)=.156
      TMSS(16)=.156
      TMSS(17)=.165
      TMSS(18)=.175
      TMSS(19)=.188
      TMSS(20)=.218
      TMSS(21)=.250
C THE VALUES FOR PARAMETERS TO BE USED IN DO LOOPS ARE:
      T(1)=0.
      T(2)=100.
      T(3)=300.
      T(4)=500.
```

```
      T(5)=700.
      T(6)=900.
      T(7)=1000.
      T(8)=1300.
      T(9)=1500.
      P(1)=0.
      P(2)=500.
      P(3)=1000.
      P(4)=1500.
      P(5)=1800.
      P(6)=2000.
      P(7)=2500.
      P(8)=3000.
      CLABOR(1)=2.
      CLABOR(2)=8.
      CLABOR(3)=13.
      CLABOR(4)=20.
      CLABOR(5)=50.
      CKI(1)=2.
      CKI(2)=100.
      CKI(3)=500.
      CKI(4)=1000.
      CKI(5)=1500.
      CKI(6)=2000.
      Q(1)=1000.
      Q(2)=5000.
      Q(3)=10000.
      Q(4)=15000.
      Q(5)=30000.
      Q(6)=60000.
      Q(7)=120000.
      Q(8)=250000.
      Q(9)=500000.
      Q(10)=750000.
      Q(11)=1000000.
      Q(12)=3000000.
      Q(13)=4500000.
      MU(1)=.005
      MU(2)=.01
      MU(3)=.02
      MU(4)=.05
      MU(5)=1.0
      MU(6)=5.
      MU(7)=20.
      MU(8)=100.
      MU(9)=1000.
      RHO(1)=.02
      RHO(2)=.075
      RHO(3)=.09
      RHO(4)=40.
      RHO(5)=62.5
      RHO(6)=80.
C DO LOOP INDEXES FOR INPUTTED FLOW PARAMETERS ARE:
C THE TEMPERATURE INDEXES ARE:
      NT=2
      NTF=2
```

```
      NTINC=1
C THE PRESSURE INDEXES ARE:
      NP=2
      NPF=2
      NPINC=2
C THE LABOR RATE INDEXES ARE:
      NL=3
      NLF=3
      NLINC=1
C THE INVESTMENT COST INDEXES ARE:
      NK=3
      NKF=6
      NKINC=1
C THE MASS FLOW RATE INDEXES ARE:
      NQ=3
      NQF=13
      NQINC=1
C THE VISCOSITY INDEXES ARE:
      NMU=5
      NMUF=5
      NMUINC=1
C THE FLUID DENSITY INDEXES ARE:
      NR=5
      NRF=5
      NRINC=1
      TYPE 876
C THE DO LOOPS CALCULATE THE COMBINATIONS OF THE VARIOUS
C FLUID PARAMETERS AND OPERATING CONDITIONS
      DO 877 IND1=NT,NTF,NTINC
      DO 877 IND2=NP, NPF, NPINC
      DO 877 IND3=NL, NLF, NLINC
      DO 877 IND4=NK, NKF, NKINC
      DO 877 IND5=NQ, NQF, NQINC
      DO 877 IND6=NMU, NMUF, NMUINC
      DO 877 IND7=NR, NRF, NRINC
      EFF=.5
C THE PIPE COST COEFFICIENT IS C5
      C5=3.25
      INDEX=1
      ERRNEW=0.
      TM=.1
      KWOLD=9.9E+09
      PCOLD=PCNEW
      SIGMA=0.
      HLOSS1=9.9E+09
C FOR C.S. FLAG2=1, FOR 304LS.S. FLAG2=2, FOR 316L S.S. FLAG2=3
      FLAG2=1
C THE REYNOLDS NUMBER IS CALCULATED
10    IF (INDEX.GT.21) GO TO 951
      ERROLD=ERRNEW
12    D=DOUT(INDEX)-2.0*TM
      V=.16*Q(IND5)/(RHO(IND7)*3.1416*D**2)
14    NRE=124.*D*V*RHO(IND7)/MU(IND6)
      IF (NRE.LT.2100) GO TO 31
```

```
C FRICTION FACTOR FOR TURBULENT FLOW
      RELR=.0018/D
      IT2=1
      FW=.1
 20   A=1/FW**.5
      B=-2*ALOG10(2.51*A/NRE+RELR/3.7)
      ERROR2=ABS(A)-ABS(B)
      IF (ERROR2.LT.0) GO TO 21
      IF (ERROR2.LT.0.04) GO TO 55
      FW=FW+.0001
      GO TO 20
 21   FW=FW-.0001
      IT2=IT2+1
      IF(IT2.EQ.3000) GO TO 951
      GO TO 20
C STOKES LAW FOR LAMINAR FLOW
 31   FW=64/NRE
 55   F=2*FW
C THE HEAD LOSS AND PUMPING POWER IS COMPUTED ASSUMING A PUMP MOTOR EFF
C ICIENCY OF E
 40   HLOSS=.1295*F*RHO(IND7)*V**2/D
 1022 FORMAT (' FRICTION FACTOR IS:',F6.4)
      PPOW=(5.71E-05/EFF)*Q(IND5)*HLOSS/RHO(IND7)
      KWNEW=PPOW
      DELTKW=KWOLD-KWNEW
      KWOLD=KWNEW
      GO TO (81,82,83), FLAG2
C ALLOWABLE PIPE STRESSES COMPUTED BY LEAST SQUARES FIT FROM
C ASME PRESSURE VESSEL CODE. FOR CARBON STEEL PIPING:
 81   IF(T(IND1).GT.1100) TYPE 98, T(IND1)
      IF (T(IND1).GT.900) GO TO 84
      IF (T(IND1).GE.750) GO TO 89
      IF (T(IND1).GE.600) GO TO 86
      IF (T(IND1).GE.100) GO TO 87
      IF (T(IND1).LT.100)  T(IND1)=100.
      GO TO 87
 84   S=8.95E31/T(IND1)**9.52
      GO TO 80
 89   S=8.38E14/T(IND1)**3.76
      GO TO 80
 86   S=2.23E06/T(IND1)**.777
      GO TO 80
 87   S=3.9E04/T(IND1)**.139
      GO TO 80
C FOR 304 SS PIPING ALLOWABLE STRESSES ARE:
 82   IF (T(IND1).GT.1500) TYPE 98, T(IND1)
      IF (T(IND1).GT.1050) GO TO 35
      IF (T(IND1).GE.700) GO TO 36
      IF (T(IND1).GE.100) GO TO 37
      IF (T(IND1).LT.100) T(IND1)=100.
      GO TO 37
 35   S=1.735E25/T(IND1)**7.03
      GO TO 80
 36   S=6.67E05/T(IND1)**.626
      GO TO 80
 37   S=7.49E04/T(IND1)**.29
      GO TO 80
```

```
C FOR 316 SS PIPING THE ALLOWABLE STRESSES ARE:
 83     IF (T(IND1).GT.1500) TYPE 98, T(IND1)
        IF (T(IND1).GT.1100) GO TO 41
        IF (T(IND1).GE.900) GO TO 42
        IF (T(IND1).GE.100) GO TO 43
        IF (T(IND1).LT.100) T(IND1)=100.
        GO TO 43
 41     S=4.783E23/T(IND1)**6.45
        GO TO 80
 42     S=3.232E10/T(IND1)**2.13
        GO TO 80
 43     S=2.54E04/T(IND1)**.062
        GO TO 80
 98     FORMAT (' THE TEMP. IS TOO HIGH; T=',F10.2)
        GO TO (84,35,41), FLAG2
 80     TM=P(IND2)*DOUT(INDEX)/(2*(S+.4*P(IND2)))
        GO TO (75,76,76) FLAG2
 75     IF (TMSTL(INDEX).LE.TM) GO TO 6
        TM=TMSTL(INDEX)
        GO TO 6
 76     IF (TMSS(INDEX).LE.TM) GO TO 6
        TM=TMSS(INDEX)
 6      WT=2.677*((D+2*TM)**2-D**2)
        GO TO (91,92,93),FLAG2
 91     PCOST=36.56*(WT**.974)+CLABOR(IND3)*(1.95*WT+26.87)
        GO TO 200
 92     PCOST=256*(WT**.96)+CLABOR(IND3)*(1.146*WT+12.41)
        2  +CLABOR(IND3)*(4.53*D+6.4)
        GO TO 200
 93     PCOST=332.8*(WT**.96)+CLABOR(IND3)*(1.146*WT+12.41)
        2  +CLABOR(IND3)*(4.53*D+6.4)
 200    PCNEW=PCOST
        IF (ABS(ERRNEW).GT.ABS(ERROLD)) GO TO 900
        DELTPC=PCNEW-PCOLD
        PCOLD=PCNEW
        LAMBDA=DELTPC/DELTKW
        ERRNEW=LAMBDA-CKI(IND4)
        IF (ERRNEW) 4,900,5
C IF THE NEW ERROR IS NEGATIVE, INCREMENT SIZE AND GO THROUGH LOOP
C AGAIN. IF NEW ERROR IS ZERO, FINISHED. IF  NEW ERROR IS POSITIVE.
C CHECK THE ABSOLUTE VALUE OF OLD AND NEW ERROR, AND SELECT MIN ERROR.
 4      INDEX=INDEX+1
        GO TO 10
 5      IF (ABS(ERRNEW).LE.ABS(ERROLD)) GO TO 900
        INDEX=INDEX-1
        GO TO 12
 900    ALEPH=P(IND2)*(2*(S-.6*P(IND2))+P(IND2))
        2  /(S-.6*P(IND2))**2
        GAMMA=2.63E-13*CKI(IND4)*F*Q(IND5)**3
        2 /(EFF*C5*ALEPH*RHO(IND7)**2)
C DUPONT'S RELATION FOR PIPE DIAMETER BASED ON INCRE-
CMENTAL RETURN ON INVESTMENT IS CALCULATED ON AN EQUAL BASIS
```

```
C WITH PIPOP.
C THE CAPITAL OUTLAY JUSTIFIED TO SAVE A KILOWATT IS BASE
C 10 YEAR PROJECT LIFE, .8 UTILIZATION, 12% ROI, NO OPERA
C OR SALVAGE VALUE.
      KWHR=CKI(IND4)/39595.
      ALPH1=2.55*EFF*(1+(1.22*D**.785+1.1*D**.78)/(.62*
      ALPH2=4.386E-12*KWHR*Q(IND5)**2.84*MU(IND6)**.16/
      ALPH3=.45+8.61E-03*EFF/KWHR
      D1=12*(ALPH2*ALPH3/ALPH1)**.164
      DELD=(D-D1)/D1*100
      WRITE (5,878) RHO(IND7), MU(IND6), P(IND2), T(IND
     2  CKI(IND4), CLABOR(IND3), V,D, KWHR, NRE,
     3  GAMMA, F, D1, DELD
      GO TO 907
  876 FORMAT (1X,' RHO',4X,' VISC',2X,' PSI',4X,' TEMP'
     2 9X,' $/KW',2X,' $/MH',1X,' VEL.',1X' DIA',3X,'
     3  10X,' GAMMA',6X,' FF',3X,' D1',2X,' %DIFF'//)
  878 FORMAT (F7.3,1X,F8.3,1X,F6.1,1X,F6.1,1X,F9.1,
     2 4X,F7.1,1X,F6.2,1X,F5.2,1X,F5.2,1X,F7.4,1X,E12.
     3 F6.4,1X,F5.2,1X,F6.2)
  907 GO TO 877
  877 CONTINUE
      GO TO 953
  951 TYPE 952
  952 FORMAT (' TOO MANY ITERATIONS WERE REQUIRED')
      GO TO 877
  953 TYPE 954, IT2, INDEX
  954 FORMAT (' IT2=',I6, ' INDEX=',I6)
      STOP
      END
```