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DESIGN OF EXPOSED SEWER PIPES FOR INTERMITTENT USE UNDER FREEZING CONDITIONS

by

D.G. Stephenson

ANALYZED

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PREFACE

Engineering construction in Northern Canada introduces varied technical problems that necessitate modification of many standard engineering techniques. This paper deals with one aspect of these, the protection from freezing of sewage effluent pipes.

This analysis of the heat transfer characteristics of exposed sewer pipes was made by the Division of Building Research in response to an inquiry from the Department of Transport. It is thought that the results may be of interest to others concerned with construction and operation of facilities in the north of Canada.

The author is a member of the Building Services Section of the Division of Building Research, with special interest in thermal flow problems. His work on this problem illustrates the way in which the building science sections of the Division of Building Research serve the sections which are more concerned with the practice of building such as the Northern Section which deals with all questions of northern building coming to the Division.

Ottawa
April 1959

R.F. Legget
Director

DESIGN OF EXPOSED SEWER PIPES FOR INTERMITTENT USE UNDER FREEZING CONDITIONS

by

D.G. Stephenson

In many locations in northern Canada, the presence of permafrost requires sewage effluent pipes from buildings to be located above grade where they are exposed to ambient air temperature. Since the air temperature is well below 32°F for several months each year, it is necessary to protect against freezing. Experience has suggested that this can be done at minimum cost by designing for intermittent flow through the pipe utilizing a siphon method of discharge from the sewage collection tank. This paper analyzes the heat transfer situation and shows how an exposed pipe may be designed for intermittent use so that ice will not restrict the flow.

The study clearly shows that the pipe should have as thin a wall as possible, that it should be made of a material with a low heat capacity, and the number of gallons of liquid flowing during a siphon cycle should be as large as possible. If the minimum required inlet temperature to prevent freezing in a bare pipe is so high that the sewage must be heated, the economics of adding insulation should be studied.

To determine the optimum pipe diameter (D) and the required sewage inlet temperature, it is necessary to calculate these for each specific case. The optimum diameter for a sewer pipe exposed to freezing conditions can be calculated by the following.

$$\frac{\Delta . S}{N} \left(0.314 . L + 549 \quad \alpha^{0.115} \quad \nu^{0.8} \quad D^{1.345}\right)$$

$$= \frac{0.113 \quad h_o \; L}{\alpha^{0.575} \quad D^{2.725}} + \frac{18.1 \quad h_o \quad \nu^{0.8}}{\alpha^{0.460} \quad D^{1.380}}$$

The required inlet temperature for sewage is

$$32 + B+C \ ^{\circ}F$$

where

$$\frac{B+C}{32+A} = \frac{\Delta S}{N} \left(0.314 \ DL + 234 \quad D^{2.345} \quad \alpha^{0.115} \quad \nu^{0.8}\right)$$

$$+ \frac{0.064 \quad h_o \; L}{\alpha^{0.575} \quad D^{1.725}} + \frac{47.6 \quad h_o . \nu^{0.8}}{\alpha^{0.460} \quad D^{0.380}}$$

Figures 1 and 2 give all the powers of α and D which are needed for these calculations. The simplicity of the design procedure is shown in Appendix A. Figure A 1 shows the sensitivity of the required inlet temperature to variations in pipe diameter.

NOMENCLATURE

V	=	velocity (ft/hr)
g	=	acceleration of gravity = 4.17×10^8 (ft/hr^2)
X	=	difference in height of pipe between inlet and outlet (ft)
L	=	length of pipe (ft)
D	=	inside diameter of pipe (ft)
f	=	friction factor = $0.34/(Re)^{0.26}$
Re	=	Reynolds number = $V.D/\nu$
ν	=	Kinematic viscosity (ft^2/hr)
μ	=	absolute viscosity (lb/ft hr)
N	=	volume discharged in one siphon cycle (gallons)
t	=	time taken to discharge N gallons (hr)
Nu	=	Nusselt number = $\frac{h \cdot D}{k}$
Pr	=	Prandtl number = $\frac{c \cdot \mu}{k}$
h_i	=	heat transfer coefficient inside pipe (Btu/ft^2 hr F°)
h_o	=	heat transfer coefficient outside pipe (Btu/ft^2 hr F°)
k	=	thermal conductivity of fluid (Btu/ft hr F°)
c	=	specific heat of fluid (Btu/lb F°)
-A	=	outside air design temperature (°F)
B	=	sewage outlet temperature -32 (F°)
C	=	sewage inlet temperature -(32+B) (F°)
Δ	=	thickness of pipe wall (ft)
S	=	volumetric specific heat of pipe material (Btu/ft^3 F°)
α	=	$\frac{2\ g\ \ X/L}{0.34\ \ \nu^{0.26}}$

DESIGN EQUATIONS

It is assumed that the flow through the pipe is intermittent and that between the times when flow occurs the pipe will cool to an ambient air temperature below freezing. Thus when sewage starts to flow down the pipe it will first form a layer of ice on the inside. The latent heat given up by this freezing will raise the temperature of the pipe to 32°F and it will remain at this temperature until the ice is melted. The rate at which melting will occur depends on the difference between the heat transfer from the liquid to the pipe and the heat loss from the pipe to the atmosphere. The amount of ice formed to begin with depends on the heat-storage capacity of the pipe and the difference between the ambient air temperature and +32°F. To ensure that ice will not accumulate in the pipe it is necessary that the flow continue long enough to melt all the ice that forms initially.

Calculation of Flow Velocity and Reynolds Number

The average velocity for a liquid flowing through a sloping pipe of length L with a total drop of X is given by:

$$V^2 = \frac{2\,g \cdot X}{f \cdot \frac{L}{D} + 1} \qquad (1)$$

Since the friction factor is only slightly dependent on velocity, V can be calculated approximately by assuming a value of f, say 0.02, and then using the value of V to calculate the Reynolds number and a value of f. This more accurate value of f will then give a more accurate value of V and the process may be repeated as often as necessary. It is usually not necessary to repeat the calculation more than once.

The time in hours needed to discharge N gallons of sewage is found from

$$t = \frac{0.204\ N}{D^2 \cdot V} \qquad (2)$$

Calculation of Heat Transfer Coefficient for Fluid to Pipe Heat Transfer

In almost all practical cases the flow Reynolds number will exceed 5000 and the flow can be assumed turbulent. For turbulent flow the heat transfer coefficient is related to the flow conditions and the fluid properties by the following dimensionless equation:

$$Nu = 0.023\ (Re)^{0.8} . (Pr)^{0.4} \qquad (3)$$

For water near the freezing temperature,

$$h_i = \frac{0.021\ (Re)^{0.8}}{D} \qquad (4)$$

$$= \frac{0.021\ V^{0.8}}{\nu^{0.8} . D^{0.2}} \qquad (4a)$$

Heat Loss from Pipe to Atmosphere

For a 30-mph wind blowing across the pipe, the outside heat transfer coefficient is approximately $h_o = 15$ Btu/ft^2 hr F°. When sewage starts to flow through a pipe at a temperature below 32°F a layer of ice will form on the inside of the pipe and the pipe temperature will very rapidly rise to +32°F. Thus the heat transfer to and from the pipe can be calculated assuming that the pipe is always at 32°F.

Calculation of Sewage Temperature at Outlet End of Pipe

It is assumed that the ambient air temperature is -A°F and the temperature of the sewage when it leaves the pipe is (32+B)°F. A heat balance on unit length of pipe leads to:

$$h_i\ (\pi) . D . B . t = h_o . \pi\ (D+2\Delta)\ (32+A)\ t$$

$$+ \pi . \Delta\ (D+\Delta) . S . (32+A).$$

For thin walled pipe, $\Delta \ll D$ so that

$$D \doteqdot D+\Delta \doteqdot D+2\Delta$$

Therefore

$$t \left(\frac{h_i \cdot B}{32 + A} - h_o \right) = \Delta \cdot S \qquad (5)$$

$$\text{or} \quad B = \frac{(\Delta \cdot S + h_o \cdot t)\ (32+A)}{h_i \cdot t} . \qquad (5a)$$

This equation can be used to calculate B when the other quantities are specified.

Calculation of Minimum Sewage Inlet Temperature

The temperature of the fluid drops as it moves along the pipe. To calculate the exact fluid temperature at any position and for any time during the initial transient is a very complicated problem. The required inlet temperature, however, can be estimated as follows.

Assume inlet temperature to be 32+B+C so that the heat given up by the fluid equals

$$10 \cdot N \cdot C = \pi \cdot D \cdot L\ (32+A)\ (\Delta \cdot S + h_o \cdot t) .$$

Therefore

$$C = \frac{\pi \cdot D \cdot L\ (32+A)\ (\Delta \cdot S + h_o \cdot t)}{10 \cdot N} . \qquad (6)$$

When equations (5) and (6) are added and equation (2) is used to eliminate t it gives

$$\frac{B+C}{32+A} = \left(\Delta \cdot S + \frac{0.204\ h_o N}{D^2\ V} \right) \left(\frac{\pi\ D\ L}{10 \cdot N} + \frac{D^2\ V}{0.204\ h_i\ V} \right) \qquad (7)$$

$$= \left(\frac{\Delta \cdot S}{N} \right) \cdot \left(0.314\ D\ L + \frac{4.9\ D^2 V}{h_i} \right) + 0.064\ \frac{h_o\ L}{D\ V} + \frac{h_o}{h_i} .$$

If h_i is replaced by the equivalent expression in equation (4),

equation (7) reduces to

$$\frac{B+C}{32+A} = \left(\frac{\Delta \cdot S}{N}\right) \cdot \left(0.314\ D\ L + 234\ D^{2.2}\ V^{0.2}\ \nu^{0.8}\right)$$

$$+ 0.064\ \frac{h_o\ L}{D\ V} + \frac{47.6\ h_o\ D^{0.2}\ \nu^{0.8}}{V^{0.8}} . \tag{7a}$$

V can be expressed in terms of D and other constants by combining equation (1) and the expression for f

$$V \doteqdot \alpha^{0.575} \cdot D^{0.725} \tag{8}$$

where

$$\alpha = \frac{2g \cdot X/L}{0.34\ \nu^{0.26}} \tag{8a}$$

Equations (7) and (8) can be combined to give

$$\frac{B+C}{32+A} = \left(\frac{\Delta \cdot S}{N}\right) \cdot \left(0.314\ D\ L + 234\ D^{2.345}\ \alpha^{0.115}\ \nu^{0.8}\right)$$

$$+ \left(\frac{0.064\ h_o\ L}{\alpha^{0.575} \cdot D^{1.725}}\right) + \left(\frac{47.6\ h_o\ \nu^{0.8}}{\alpha^{0.460} \cdot D^{0.380}}\right) \tag{9}$$

If equation (9) is differentiated with respect to D and the derivative of the right side set equal to zero, it gives:

$$0 \doteqdot \left(\frac{\Delta \cdot S}{N}\right) \cdot \left(0.314\ L + 549\ \alpha^{0.115}\ \nu^{0.8}\ D^{1.345}\right)$$

$$- \frac{0.113\ h_o\ L}{\alpha^{0.575} \cdot D^{2.725}} - \frac{18.1\ h_o\ \nu^{0.8}}{\alpha^{0.460} \cdot D^{1.380}} \tag{10}$$

Equation (10) can be solved graphically for the optimum pipe diameter. This value of D in equation (9) gives the minimum value of B + C.

When the minimum required inlet temperature for a bare pipe is so high that the sewage must be heated, the economics of adding insulation should be studied. Adding insulation is equivalent to reducing h_o and will reduce the optimum diameter as well as the required sewage inlet temperature.

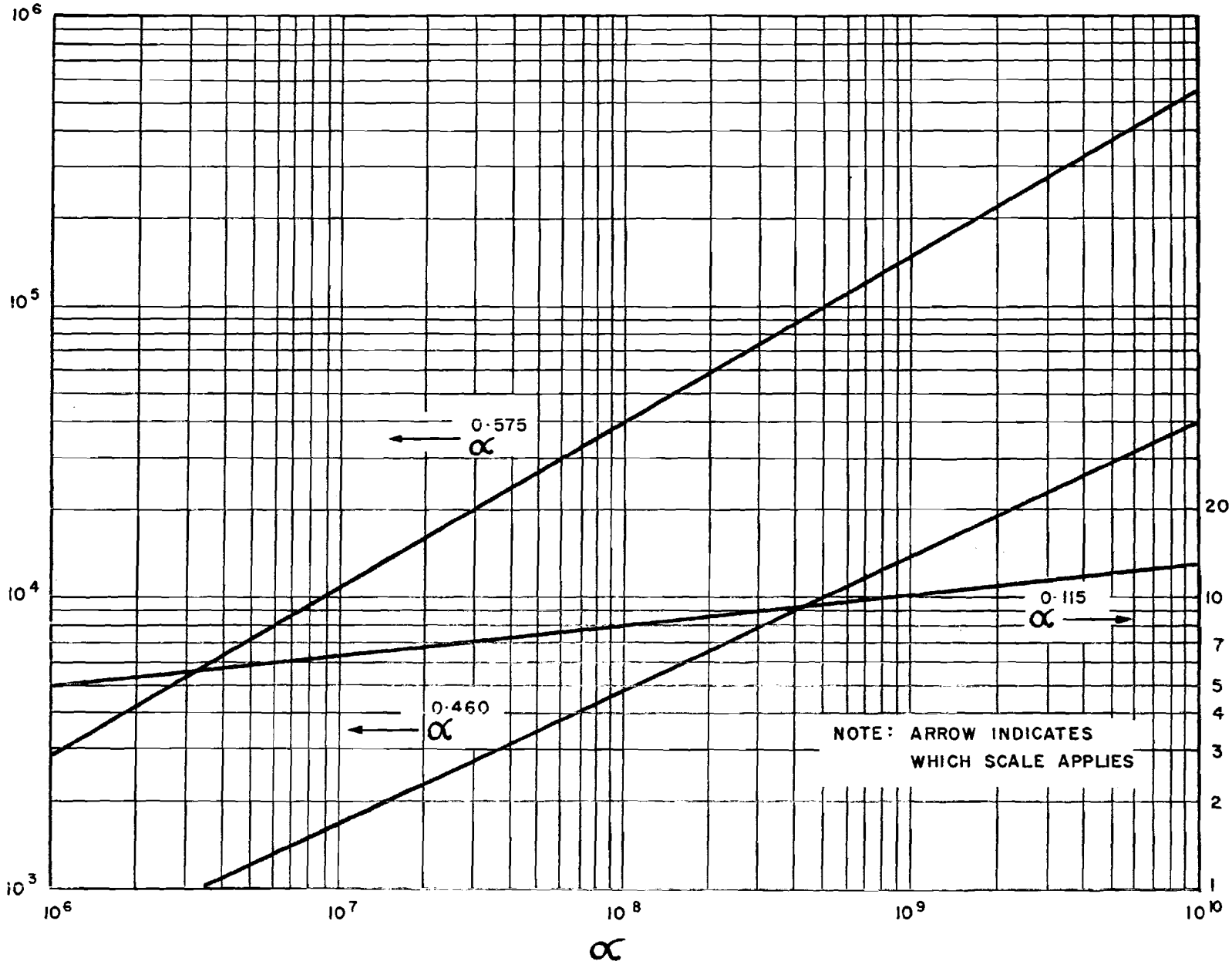

FIGURE 1 POWERS OF α USED IN THE CALCULATION

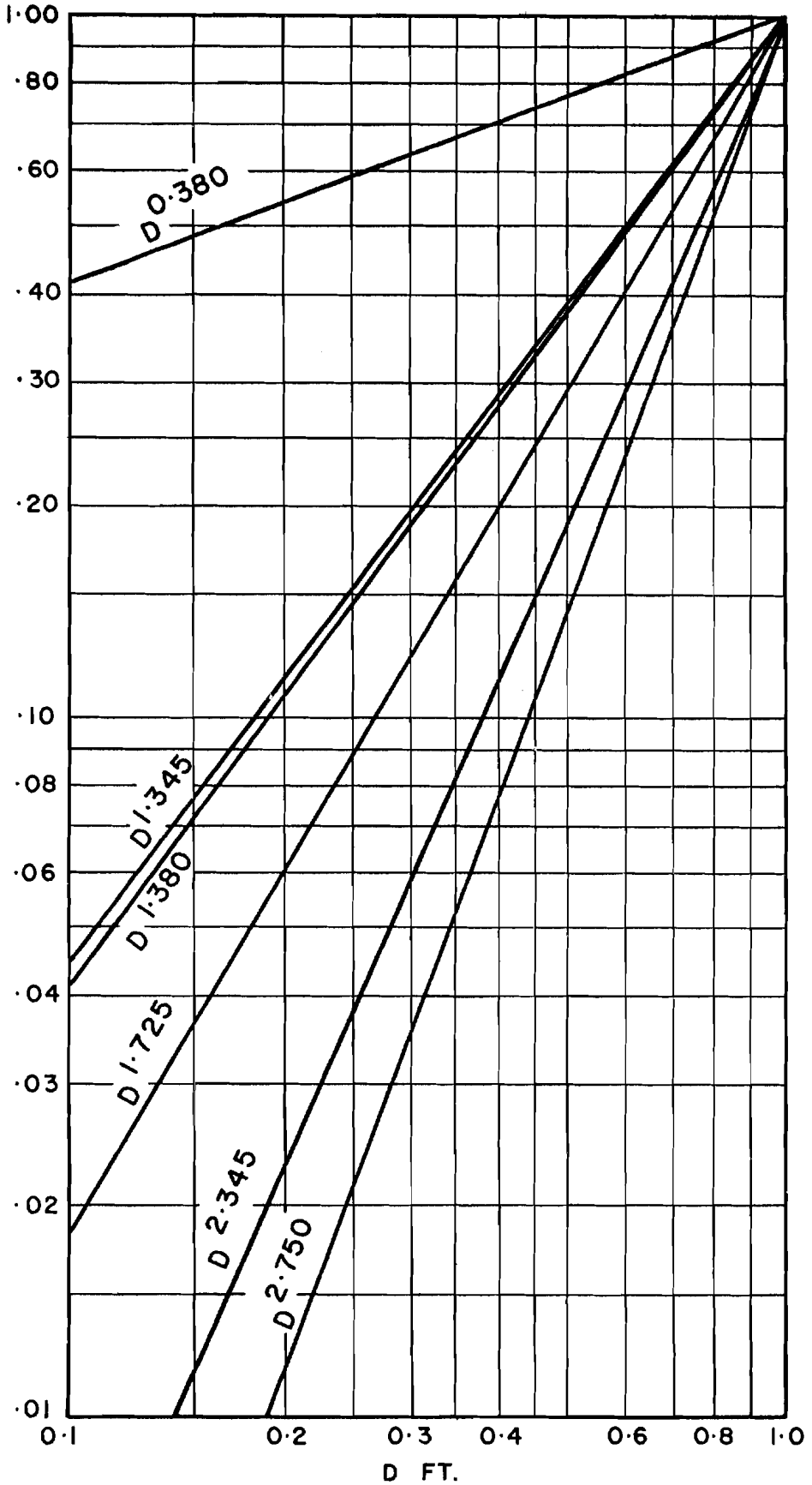

FIGURE 2

POWERS OF D USED IN THE CALCULATION

APPENDIX A

SAMPLE CALCULATION

Data:	Outside air design temperature	-50°F
	Length of exposed pipe	550 ft
	Slope of pipe	0.7%
	Volume flow each siphon cycle	300 gallons

Problem: What standard pipe is best suited for this situation and what temperature must the sewage have at the pipe entrance?

Solution: For this type of installation thin walled aluminum pipe is much better than cast iron or steel pipe because of its low volumetric specific heat ($S = 35$ Btu/ft^3 F°)

Assume $\Delta = 0.134$ in.

$\nu = 0.059$ ft^2/hr

Then $$\frac{\Delta \cdot S}{N} = \frac{0.134}{12} \times \frac{35}{300} = 0.0013$$

$$\alpha = \frac{8.34 \times 10^8 \times 0.007}{0.34 \times 0.48} = 3.58 \times 10^7$$

$$\nu^{0.8} = 0.105$$

$$h_o = 15$$

Therefore

$$\text{R.H.S. Eq.(10)} = 0.224 \times 0.554\, D^{1.345} - \frac{0.0425}{D^{2.725}} - \frac{0.000636}{D^{1.38}}$$

Solving for D when R.H.S. Eq.(10) = zero

D	0.3 ft	0.4 ft	0.5 ft
R.H.S. Eq.(10)	-0.789	-0.129	+0.158

So, the optimum pipe diameter is approximately 0.45 ft.

For D = 0.45 ft.

$$B+C = 82 \left[0.0013 \left(0.314 \times 0.45 \times 550 + 234 \times (0.45)^{2.345} \times (3.58 \times 10^7)^{0.115} \times 0.105 \right) + \frac{0.064 \times 15 \times 550}{(3.58 \times 10^7)^{0.575} \cdot (0.45)^{1.725}} + \frac{47.6 \times 0.105}{(3.58 \times 10^7)^{0.460} \cdot (0.45)^{0.380}} \right]$$

$$= 82 \left[0.0013 \left(0.314 \times 0.45 \times 550 + 234 \times 0.155 \times 7.4 \times 0.105 \right) + \frac{0.064 \times 15 \times 550}{2.18 \times 10^4 \times 0.255} + \frac{47.6 \times 0.105 \times 15}{2.95 \times 10^3 \times 0.745} \right]$$

$$= 82 \left(0.1375 + 0.0950 + 0.0345 \right)$$

$$= 21.9 \text{ F}^\circ$$

Sewage inlet temperature is 32 + B + C = 53.9 F°

$$V^2 = \frac{8.34 \times 10^8 \times 3.85}{(0.020 \times 550/0.45) + 1} = 1.23 \times 10^8$$

$$V = 11{,}090 \text{ ft/hr}$$

$$Re = \frac{11{,}090 \times 0.45}{0.059} = 84{,}500$$

$$f = 0.34/(8.45)^{0.26} \times 10^{1.04} = 0.0178$$

Therefore

$$V^2 = \frac{8.34 \times 10^8 \times 3.85}{(0.0178 \times 550/0.45) + 1} = 1.41 \times 10^8$$

$$V = 11{,}870 \text{ ft/hr}$$

$$Re = \frac{11{,}870 \times 0.45}{0.059} = 90{,}500$$

$$t = \frac{0.204 \times 3.00}{0.45 \times 11{,}870} = 0.01147 \text{ hr.}$$

Figure A 1 shows how the required sewage inlet temperature varies with the pipe diameter for the conditions specified in this problem. If the sewage is normally at a temperature above the minimum, this graph shows the range of pipe diameters which will be ice free for the specified conditions.

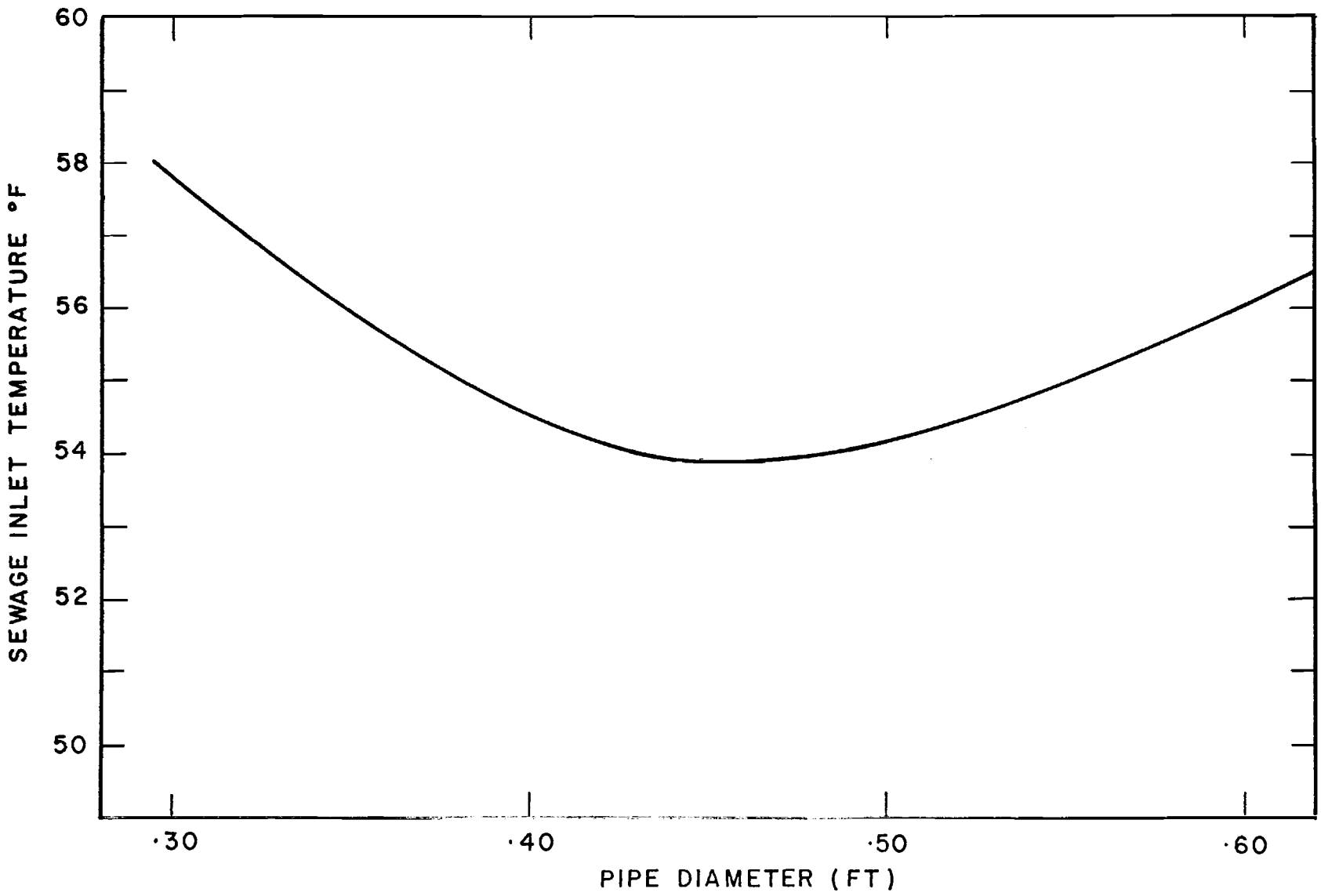

FIGURE A1

REQUIRED SEWAGE INLET TEMPERATURE AS A FUNCTION OF PIPE DIAMETER