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HYDRAULIC FLOW RESISTANCE FACTORS FOR CORRUGATED METAL CONDUITS

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ABSTRACT

Hydraulic design procedures require a reliable determination of the resistance factors applicable to each shape of corrugation used in the manufacture or fabrication of corrugated metal conduits. These resistance factors vary over a wide range for each of the corrugation shapes now available. In this publication, methods are presented which allow the designer to estimate resistance factors for all available corrugation shapes and methods of manufacture. Variables considered include conduit size and shape, corrugation shape, flow rate, flow depth, and method of manufacture. Resistance factors are presented in terms of the Darcy f or the Manning n, and design charts, geometric tables, and SI conversion factors are included. A method of estimating resistance for untested corrugations is also included, along with design examples.

ACKNOWLEDGMENTS

A number of individuals have contributed to the development of this publication. Mr. Herbert G. Bossy (retired, formerly with the Federal Highway Administration, FHWA), Mr. Frank L. Johnson of the Hydraulics Branch, Bridge Division of FHWA, and the FHWA staff contributed valuable review and comments, all of which were considered and many were incorporated into this text. Mr. Bossy was co-author of the previous publication in 1970, and his many insights into the problems associated with corrugated metal pipe resistance were invaluable. The patience of Mr. Gilbert Trainer and Mr. Robert C. Wood of the FHWA staff, during the delays in preparation of this publication, is also appreciated.

Without the cooperation and help of Ms. Karen Huber, who drafted the figures several times, and Ms. Donna Ettaro, who typed the text and its numerous equations and tables, the preparation of this document would have been impossible. My thanks go to both of them, and to the many others who helped to produce this document.

HYDRAULIC FLOW RESISTANCE FOR CORRUGATED METAL CONDUITS

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U.S. DEPARTMENT OF TRANSPORTATION

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HYDRAULIC FLOW RESISTANCE FACTORS FOR CORRUGATED METAL CONDUITS

By: Jerome M. Normann

INTRODUCTION

Corrugated metal sheets having a variety of corrugation forms are used to fabricate circular pipes and pipe-arch conduits commonly used as highway drainage structures. On the basis of early, limited hydraulic test results, a fixed coefficient, usually a Manning n value of 0.024, was often used to define the hydraulic resistance of all such conduits, regardless of size, shape, corrugation form, flow depth, flow rate, or method of manufacture.

Experimental data are now available for a number of metal corrugation configurations, as shown below:

Types of Corrugated Metal Pipes (C.M.P.)	Nominal Size of Corrugations Pitch (c) x Depth (k) Inches	Nominal Size of Corrugations Pitch (c) x Depth (k) Centimeters	References[1]
Annular	2-2/3 x 1/2	6.8 x 1.3	1,2,3,4,5
	6 x 1	15.2 x 2.5	6
	6 x 2	15.2 x 5.1	3,7,8
	9 x 2-1/2	22.9 x 6.4	6
Helical	1-1/2 x 1/4	3.8 x 0.65	9
	2 x 7/16	5.0 x 1.1	10
	2 x 1/2	5.0 x 1.3	4,6,9,10
	2-2/3 x 1/2	6.8 x 1.3	5,6,11

These data show that the forementioned variables do, in fact, affect the resistance coefficients to varying degrees. Use of a constant coefficient to define hydraulic resistance of all corrugated metal pipes is not justified by the available facts.

[1] Numbers in parentheses refer to corresponding References in Appendix A.

In hydraulic studies in which resistance coefficients have been determined by head-loss measurements for a range of flow rates, resistance data have been obtained, almost exclusively, by tests of circular pipes flowing full. Therefore, a method is needed to estimate the resistance coefficients for untested pipe diameters, untested corrugation types, non-circular sections such as pipe-arches, and partly full flow conditions.

One of the predominant characteristics that determines the C.M.P. resistance factor is relative roughness, in terms of conduit size and depth of corrugation. In selecting a conduit size dimension for a tabular or graphic presentation of resistance factors, either the diameter (D) or the hydraulic radius (R) can be used, as D=4R for circular pipes flowing full.

Because the more reliable hydraulic tests were performed on circular pipes flowing full, pipe diameter, rather than hydraulic radius, has been used as the conduit-size dimension in reports of these investigations. For most engineering applications, it is more convenient to use pipe diameter for circular pipes. Accordingly, in this report, the actual inside diameters, measured between inside corrugation crests, are used for the dimensions of circular pipes and values of the Darcy f and Manning n are related to the diameters.

Similarly, resistance factors for corrugated metal pipe-arch sections, though determined from the respective hydraulic radii, also can be related to 4R for full flow conditions, in which 4R can be considered the effective diameter of the pipe-arch that corresponds to a circular pipe with an equal resistance coefficient. Because of this relationship, the same charts, in which f or n is plotted against circular pipe diameter, can be used for pipe-arches.

In most partly full flow conditions, it is satisfactory to disregard the variation of resistance factor with depth of flow, and to apply the same resistance coefficient to all partial flow depths for a given corrugation type, pipe size, and flow rate. At this time, it is not felt that enough information is available on C.M.P. resistance to permit accurate determinations of resistance for very shallow flow depths, say below d/D = 0.4.

Design information on hydraulic resistance of five forms of annular corrugations and four forms of helical corrugations are presented. This information can be used to select a culvert or storm-drain size for a given rate of flow and conduit slope, or to determine the depth of flow occurring in a long conduit of a given size and at a given flow rate. The usual methods available to hydraulic engineers can be applied for these solutions. The presentation of complete design solutions were not considered essential to the purpose of this publication.

In order to make this publication more useful to designers than the 1970 edition (12), only the design charts are presented in the main body of the text. The procedures used to develop the design charts are contained in Appendix D, Development of Design Charts for Corrugated Metal Conduits. Discussions of the experimental data and methods of estimating the hydraulic resistance of untested corrugation shapes are also found in that appendix.

OBJECTIVES

The objectives of this manual are to: (1) Provide the designer with usable means for estimating the hydraulic resistance factors for five different corrugation shapes used in annular C.M.P. and four different corrugation shapes used in helical C.M.P. and (2) to enable the designer to estimate the resistance factors for new and untested corrugation shapes, should these become available.

HYDRAULIC RESISTANCE FACTORS

The hydraulic resistance factor, or coefficient, applicable to a conduit can be used to determine the rate of energy loss (slope of the total head line) under a given condition of flow rate, conduit size, and depth of flow. The resistance factor also defines the hydraulic capacity, or flow rate, when the other conditions are fixed. Although in the design of less important conduits, the usual practice has been to assume that the resistance factor (commonly the Manning n) is determined by the material forming the walls alone, and does not vary with pipe size or other factors; this simplified assumption is not actually valid.

Resistance factors for C.M.P. depend not only on the shape of corrugation, but also on the pipe diameter, the flow rate, and the helix angle of the corrugations, measured from the pipe axis. For annular C.M.P., the helix angle is 90 degrees.

The fact that the resistance factor decreases as the pipe diameter increases indicates that resistance is significantly affected by the ratio of corrugation depth to the hydraulic radius of the conduit, or relative roughness.

The relative effect of variations in either f or n on the flow capacity of a corrugated metal conduit is evident from the velocity, or discharge, equations for a given energy line slope, S_f. Using the resistance factor n and the Manning Equation in the form:

$$Q = AV = A \frac{1.486}{n} R^{2/3} S_f^{1/2} \quad \text{(English Units)} \text{ - - - - - - - - - - } (1a)$$

$$Q = AV = A \frac{1}{n} R^{2/3} S_f^{1/2} \quad \text{(SI Units)} \text{ - - - - - - - - - - - - } (1b)$$

the discharge varies inversely as n, and a 3 percent reduction in n results in a 3 percent increase in flow capacity. To use the Darcy resistance factor f, the usual form of the equation

$$S_f = \frac{h_f}{L} = \frac{f}{D} \frac{V^2}{2g} \text{ - } (2)$$

can be modified to express flow velocity in terms of the hydraulic radius,

$$V = \left(\frac{2g \; 4R \; S_f}{f} \right)^{1/2}$$

Therefore, the flow rate can also be expressed in terms of the Darcy f,

$$Q = AV = A \frac{16.04}{f^{1/2}} R^{1/2} S_f^{1/2}, \text{ - } (3)$$

which means that a 6 percent reduction in f results in about a 3 percent increase in flow capacity -- comparable to the effect of a 3 percent reduction in n. As indicated by comparing equations (1a) and (3), n varies as $f^{1/2}$ for any particular conduit and flow depth.

These demonstrations of the effects of variations in the resistance factors on the computed discharge capacity of a conduit indicate that some error in estimating these factors is acceptable, especially since there are many variables connected with the flow conditions in C.M.P. In general, any resistance factor determination method resulting in errors of less than 6 percent in f or 3 percent in n can be considered adequately reliable for design computations.

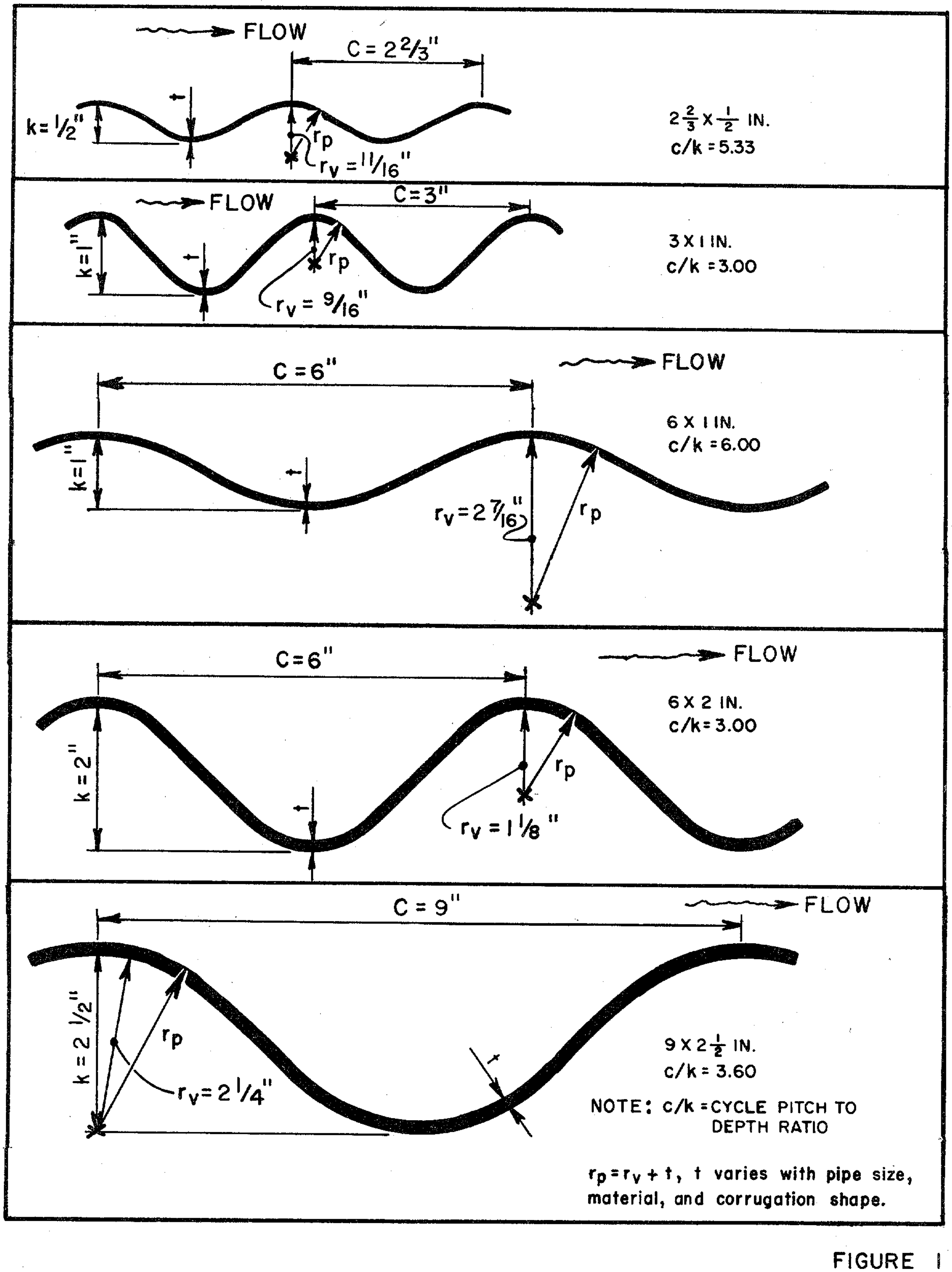
For convenience of presentation, and because the parameters which influence hydraulic flow resistance are different in annular and helical corrugated metal pipes, the two types of corrugations are presented separately in this publication. For annular C.M.P., the main parameters influencing hydraulic resistance are Reynolds number, (related to flow rate, conduit size, and temperature), relative roughness (ratio of corrugation depth to conduit size), and corrugation shape. For all annular C.M.P., the helix angle, measured from the pipe axis, is 90 degrees.

For helical C.M.P., the resistance is determined by the Reynolds number and the helix angle. While it appears that relative roughness and corrugation shape have some influence, these parameters are of little significance until the helix angle approaches 90^{o}.

ANNULAR CORRUGATED METAL PIPES

Corrugation Shapes Considered

The corrugation shapes considered herein for annular C.M.P. are shown in Figure 1. The dimensions presented are nominal dimensions, which are known to vary somewhat from the true dimensions. However, for purposes of estimating resistance coefficients, it is felt that nominal corrugation dimensions are adequate.



1. Shapes of Annular Corrugations

Nominal dimensions are presented below, in inches and centimeters:

Nominal Size of Corrugation Pitch (c) by Depth (k) inches	Radius of Corrugation Valley, r_v, inches	Available Wall Thickness* t, inches	Radius of Corrugation Peak, r_p inches
2-2/3 by 1/2	11/16	0.04-0.168	0.728-0.856
3 by 1	9/16	0.052-0.168	0.615-0.731
6 by 1	2-7/16	0.06-0.164	2.498-2.602
6 by 2	1-1/8	0.109-0.280	1.234-1.405
9 by 2-1/2	2-1/4	0.100-0.300	2.35-2.55

Nominal Size of Corrugation Pitch (c) by Depth (k), (cm)	Radius of Corrugation Valley, r_v, (cm)	Available Wall Thickness* t, (cm)	Radius of Corrugation Peak, r_p, (cm)
6.8 x 1.3	1.7	.102-.427	1.85-2.17
7.6 x 2.5	1.4	.132-.427	1.56-1.86
15.2 x 2.5	6.2	.152-.417	6.34-6.61
15.2 x 5.1	2.9	.278-.711	3.13-3.57
22.9 x 6.4	5.7	.254-.762	5.97-6.48

*Not available in all pipe sizes or materials.

Note that the 6 by 1 inch (15.2 x 2.5 cm) corrugations have a large corrugation radius in terms of corrugation height. For example; in terms of corrugation depth (k), the 6 by 1 inch corrugations have an average r_p/k ratio of 2.55, while the 3 by 1 inch (7.6 x 2.5 cm) corrugations have an r_p/k ratio of 0.673. The more rounded shape of the 6 by 1 inch corrugations has the effect of lowering the hydraulic resistance for pipes with this corrugation as compared with pipes with more peaked corrugations and the same relative roughness.

Bolt and Seam Resistance

Some of the annular corrugation shapes (6 by 2 inch (15.2 x 5.1 cm) and 9 by 2-1/2 inch (22.9 x 6.4 cm)) considered herein are field fabricated into structural plate C.M.P., using bolts and nuts to assemble the metal plates. The bolt heads or nuts protrude into the pipe and create additional resistance to flow over that found in riveted or helically fabricated C.M.P.

In Appendix D, methods for estimating bolt and seam resistance are discussed, and the results have been incorporated into the following resistance factor figures. The discontinuities in the resistance curves for the 6 by 2 inch and 9 by 2-1/2 inch corrugations are due to bolt resistance effects, which are in turn related to the number of plates and bolts used in fabricating the particular conduit. Seam resistance is related to the thickness of the metal plates used to fabricate the conduit, and a reasonable thickness has been assumed for each conduit size.

Flow Rates

As it is shown in Appendix D that Reynolds Number affects the hydraulic resistance of all C.M.P., and since Reynolds number is a function of conduit size, flow depth, flow rate, and temperature, it was necessary to select certain flow rates for use in the design curves. Use of $Q/D^{2.5}$ is a convenient means of representing flow rate, since it is essentially a dimensionless ratio based on pipe size. ($Q/D^{2.5}$ is truly dimensionless if divided by gravitational acceleration, g, to the 1/2 power. Since $Q/D^{2.5}$ is not dimensionless, a different value results in the SI System. All values in this text are based on the English System; however, conversion to the SI System can be accomplished using the conversion factors given in Appendix E).

In general, at their design flow rates, highway storm drains operate at a $Q/D^{2.5}$ value of about 2.0 and culverts operate at a $Q/D^{2.5}$ of about 4.0. Therefore, these two flow ratios have been depicted in the following design curves. Interpolation between the two flow values, and some limited extrapolation is justified. The curves of Appendix D can be used to develop accurate curves for other flow rates.

Darcy Resistance Factors, f

Figures 2-5 may be used to determine the Darcy f for use in the following equations:

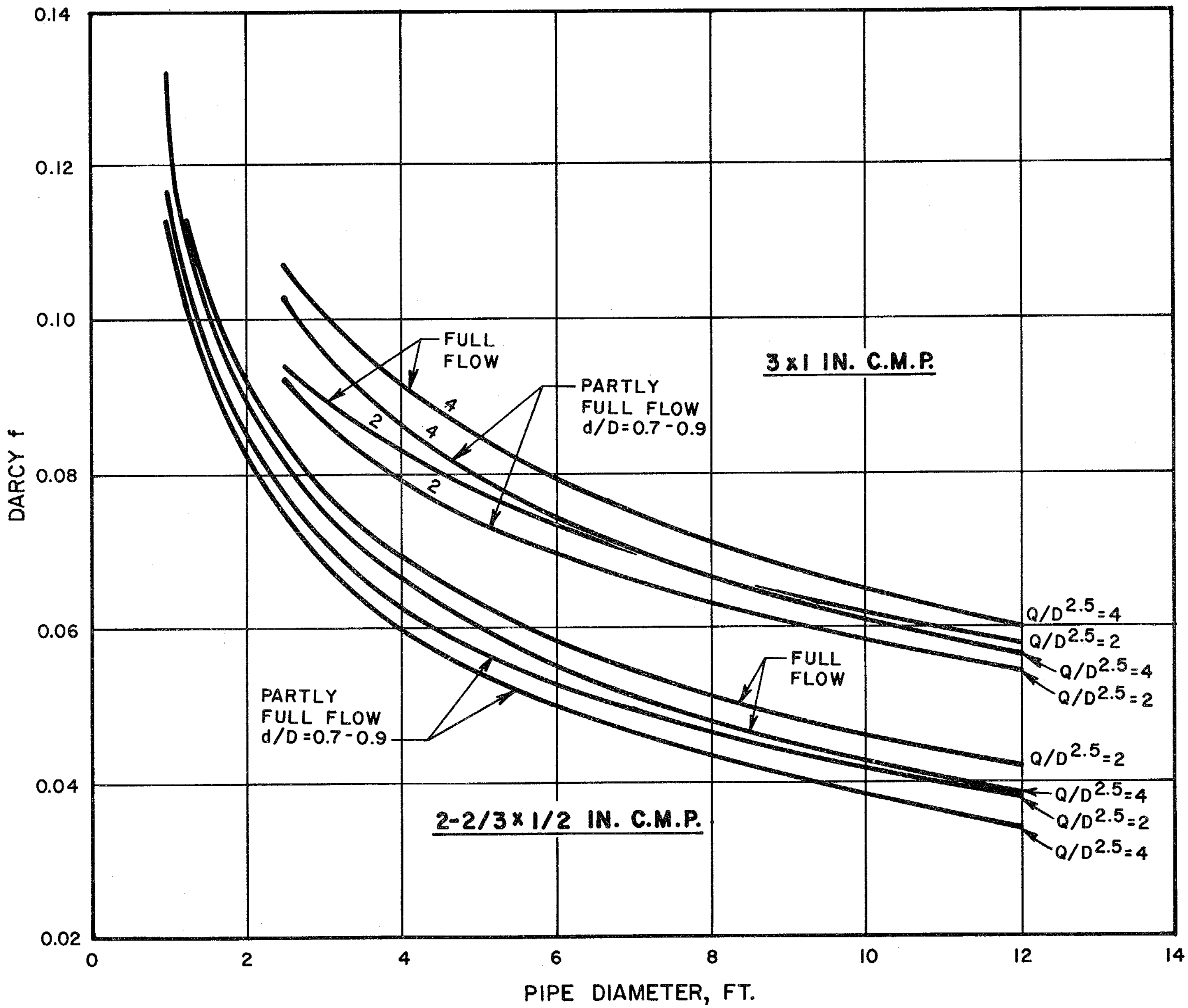


FIGURE 2

2. Darcy f Versus Diameter for 2-2/3- by 1/2-inch and 3- by 1-inch Annular Corrugated Metal Pipe

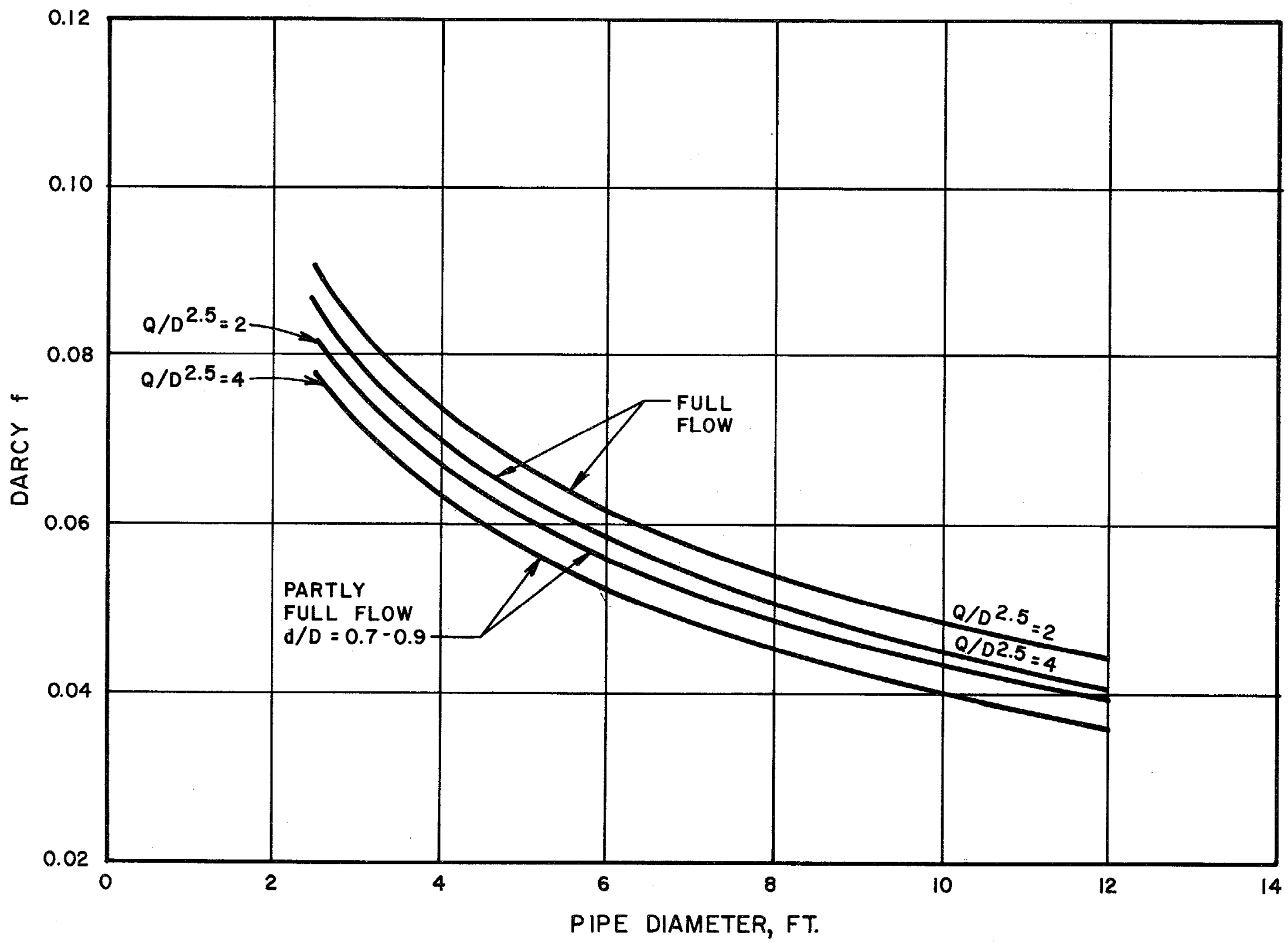


FIGURE 3

3. Darcy f Versus Diameter for 6- by 1-inch Annular Corrugated Metal Pipe

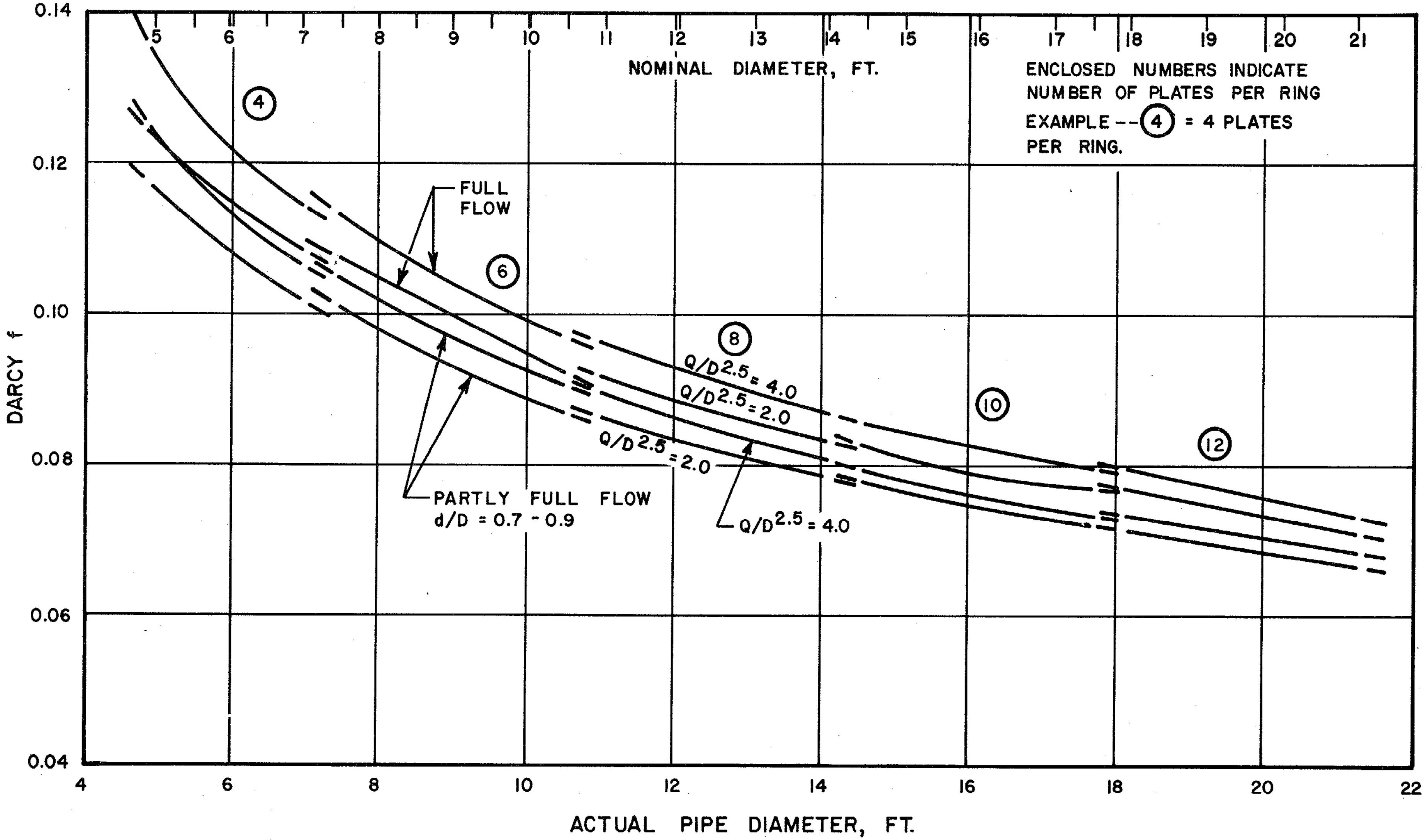
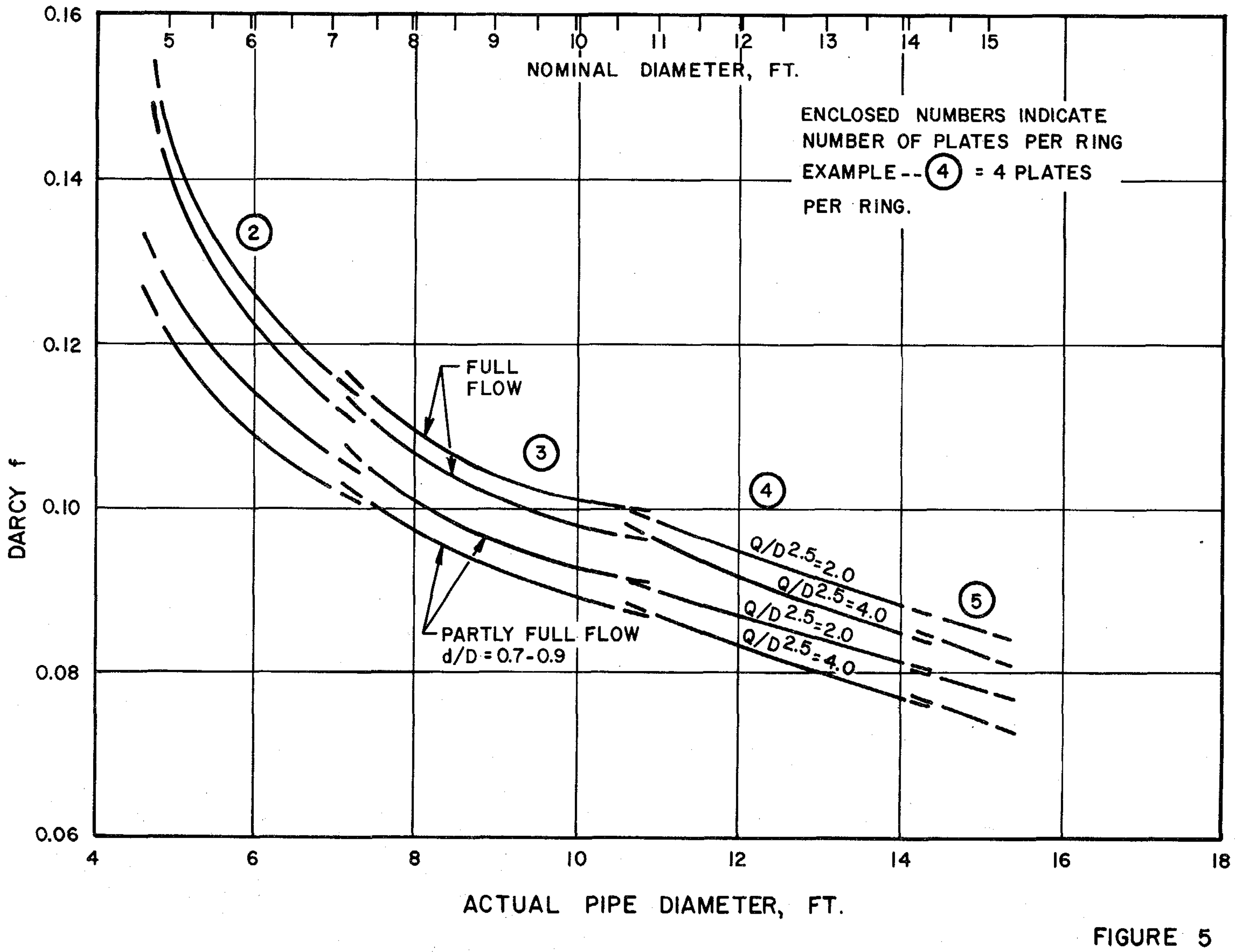


FIGURE 4

4. Darcy f Versus Diameter for 6- by 2-inch Annular Structural Plate Corrugated Metal Pipe



5. Darcy f Versus Diameter for 9- by 2-1/2-inch Annular Structural Plate Corrugated Metal Pipe

$$S_f = \frac{h_f}{L} = \frac{f}{D}\frac{V^2}{2g} = \frac{f}{4R}\frac{V^2}{2g} \qquad (2)$$

and

$$Q = AV = A\,\frac{16.04}{f^{1/2}}\,R^{1/2}\,S_f^{1/2} \qquad (3)$$

where
- Q is the flow rate in cfs (m^3/sec),
- S_f is the friction slope or slope of the energy grade line,
- h_f is the friction head loss, ft. (m),
- L is the pipe length, ft. (m),
- V is the mean velocity, fps. (m/sec),
- g is the gravitational acceleration, and
- A is the flow area in square feet (m^2).

Figure 2 is for 2-2/3 by 1/2 inch (6.8 x 1.3 cm) and 3 by 1 inch (7.6 x 2.5 cm) corrugations. Figure 3 is for 6 by 1 inch (15.2 x 2.5 cm) corrugations, Figure 4 is for 6 by 2 inch (15.2 x 5.1 cm) corrugations, and Figure 5 is for 9 by 2-1/2 inch (22.9 x 6.4 cm) corrugations. The latter two corrugations are used in bolted structural plate C.M.P. The curves are based on actual inside diameters, measured between the inside crests of corrugations. Nominal diameters are represented by tick marks at the top of Figures 4 and 5. For the other corrugations, it is assumed that the nominal diameter is equal to the actual inside diameter.

Manning Resistance Factors, n

Manning n values are presented in Figures 6 - 9, in the following order:

Figure	Corrugation
6	2-2/3 by 1/2 inch (6.8 x 1.3 cm) and 3 by 1 inch (7.6 x 2.5 cm)
7	6 by 1 inch (15.2 x 2.5 cm)
8	6 by 2 inch (15.2 x 5.1 cm) (structural plate)
9	9 by 2-1/2 inch (22.9 x 6.4 cm) (structural plate)

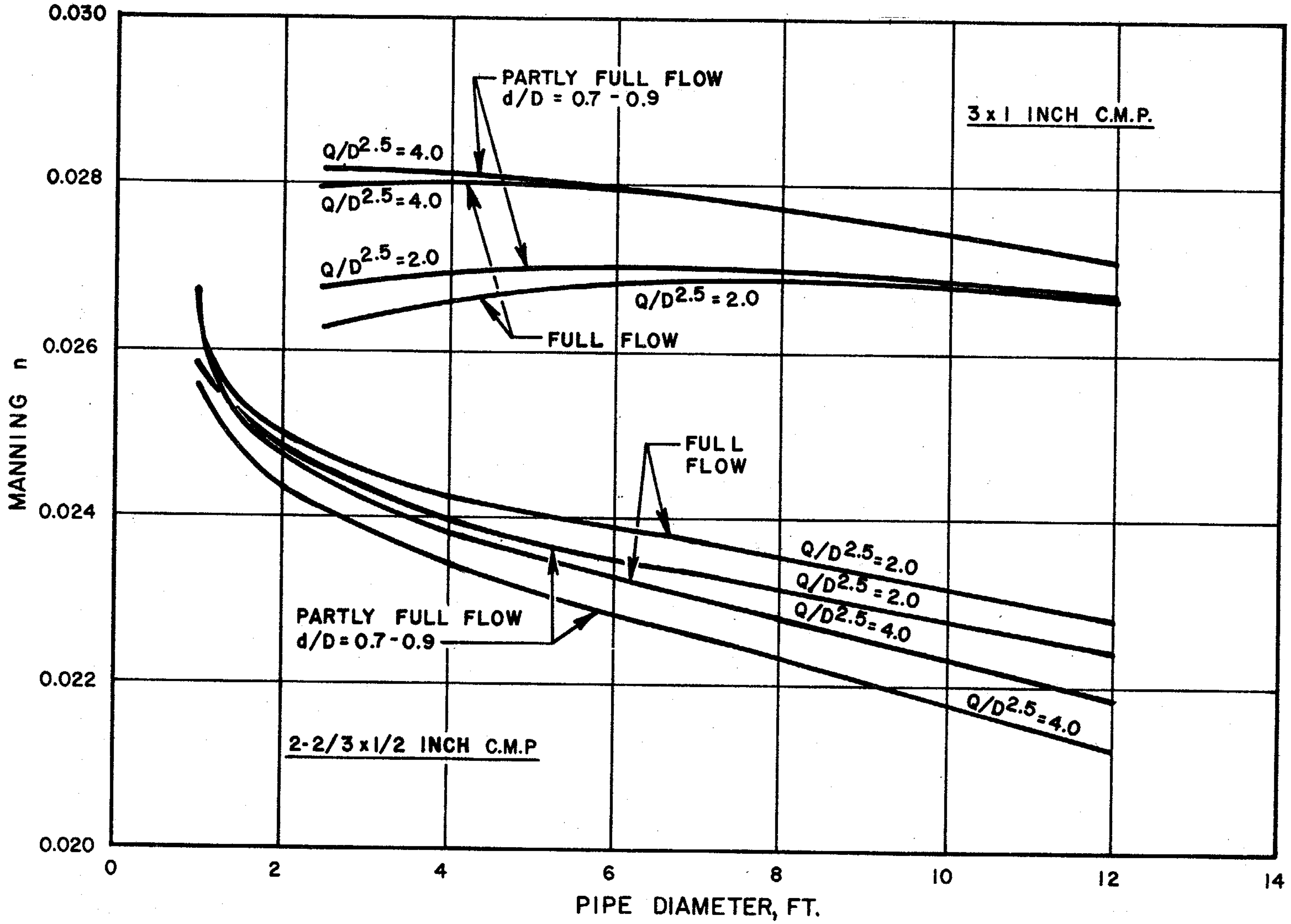


FIGURE 6

6. Manning n Versus Diameter for 2-2/3- by 1/2-inch and 3- by 1-inch Annular Corrugated Metal Pipe

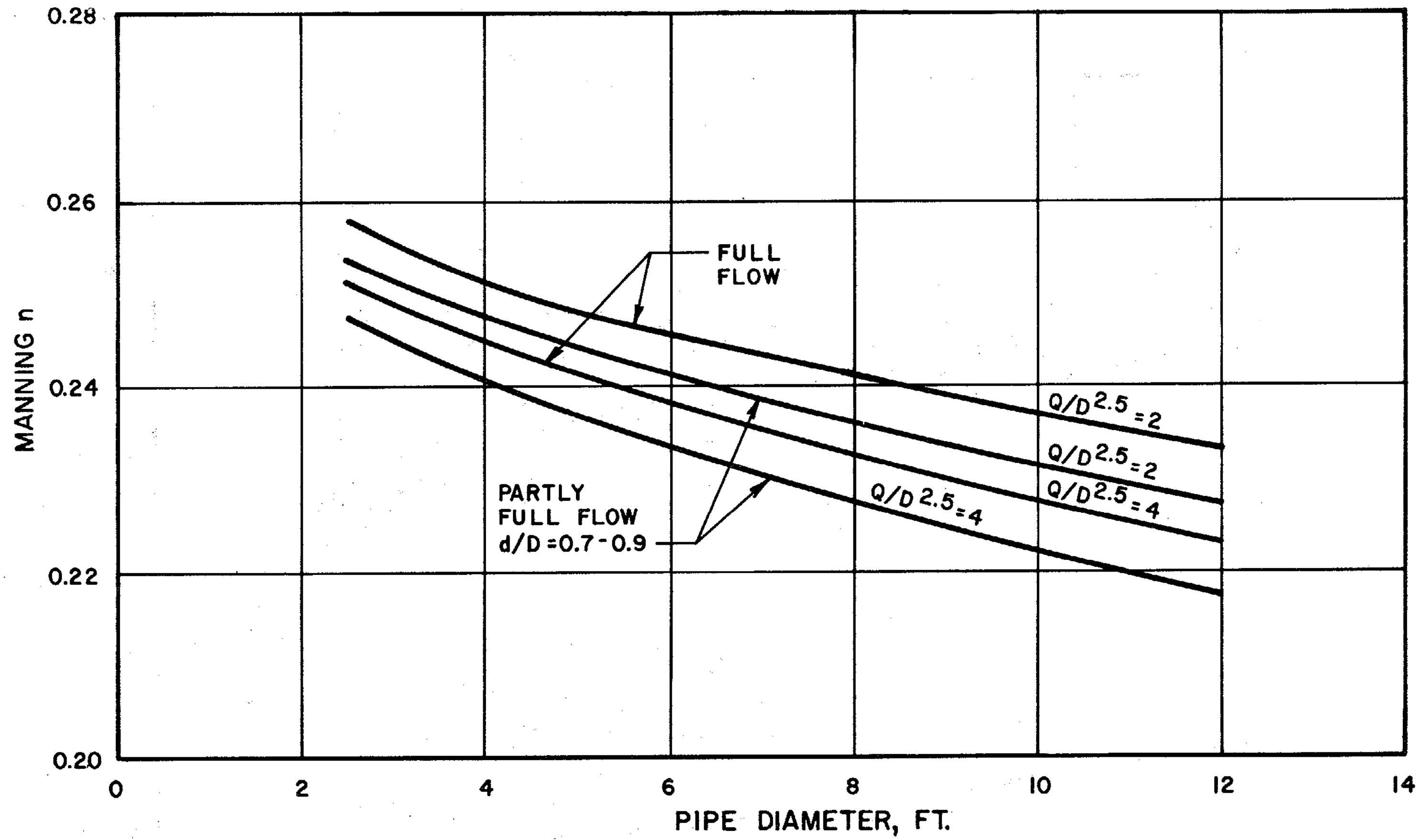


FIGURE 7

7. Manning n Versus Diameter for 6- by 1-inch Annular Corrugated Metal Pipe

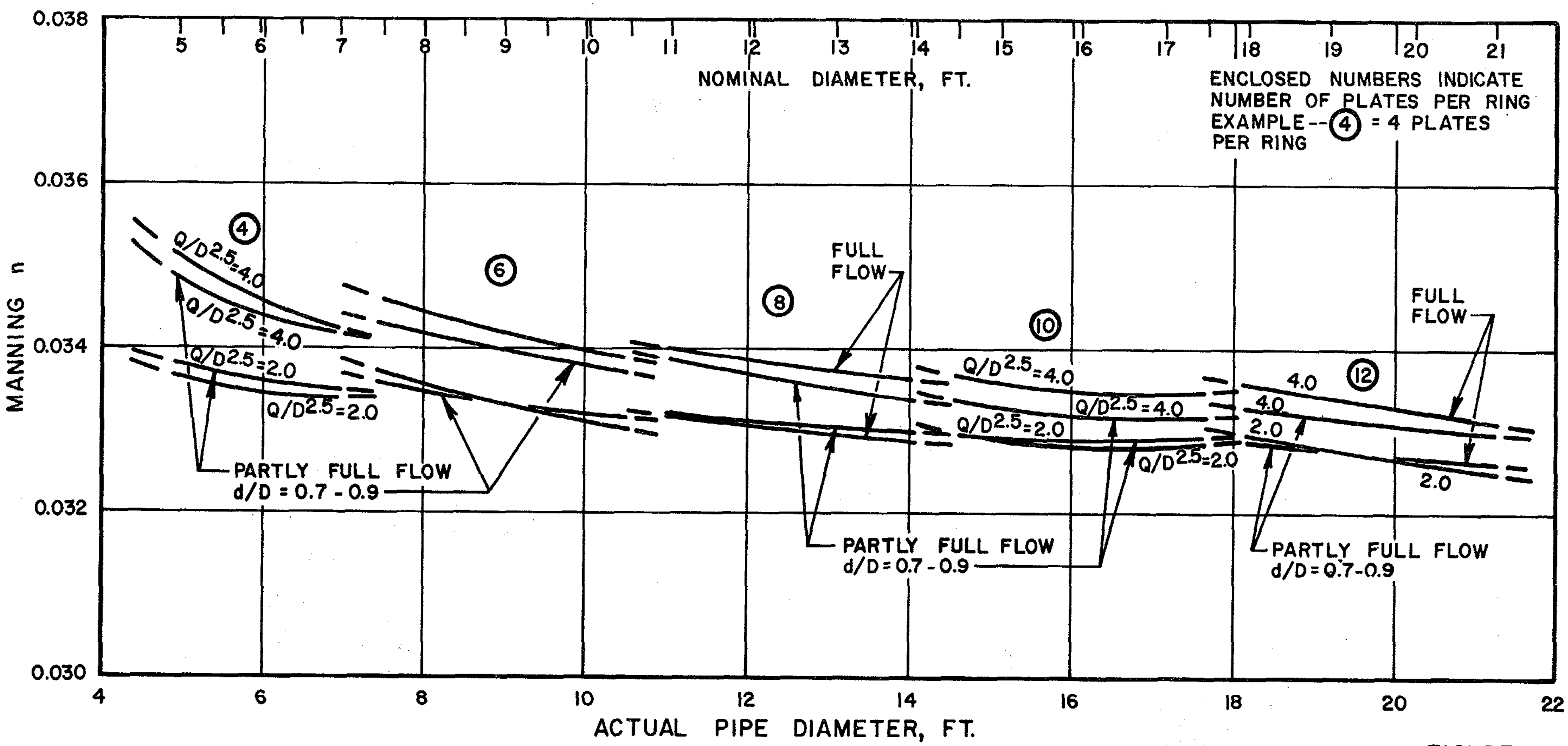


FIGURE 8

8. Manning n Versus Diameter for 6- by 2-inch Annular Structural Plate Corrugated Metal Pipe

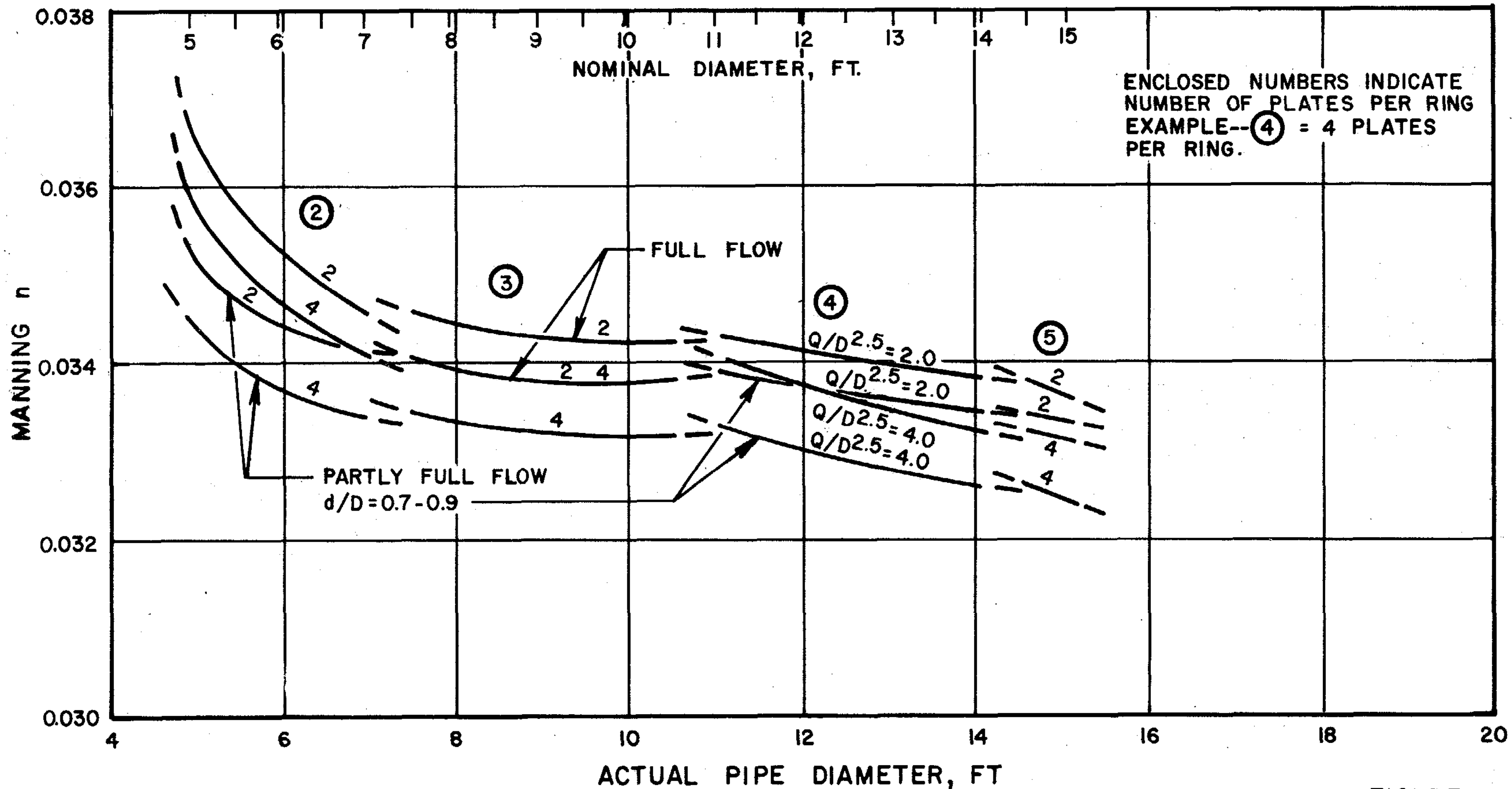


FIGURE 9

9. Manning n Versus Diameter for 9- by 2-1/2-inch Annular Structural Plate Corrugated Metal Pipe

The Manning n values are applied using the following, well known equation:

$$V = \frac{1.486}{n} R^{2/3} S_f^{1/2} \quad \text{-----------------------} \quad (4)$$

where 1.486 is a constant, equal to 1.0 in SI units,
V is the flow velocity, fps (mps),
R is the hydraulic radius, ft. (m), and
S_f is the friction slope.

From continuity (Q=AV), Equation (1) results.

Figures 8 and 9, for structural plate C.M.P., have the nominal diameters represented by tick marks at the top of the graph.

Conversion of the Darcy f, obtained by the analytical process, to the Manning n was accomplished by use of the following equation:

$$n = 0.0926 \ (R)^{1/6} \ (f)^{1/2} \quad \text{-------------------} \quad (5)$$

which may be derived by equating the Darcy and Manning equations for velocity.

Note that for some of the pipes shown, a constant Manning n value could be used for a given flow rate and flow depth with very little error. For example, in Figure 6 for 3 by 1 inch C.M.P., a Manning n value of about 0.027 could be used for all pipe sizes flowing full or partly full with $Q/D^{2.5} = 2.0$.

Use of Resistance Factor Versus Diameter Curves (Figures 2-9)

To obtain the Darcy f or Manning n value for a given circular pipe size, corrugation shape, and flow rate ($Q/D^{2.5}$), simply enter the appropriate graph with the diameter and read the f value from the full or partly full flow curve for $Q/D^{2.5} = 2.0$ or 4.0; for other flow rates interpolate or extrapolate. The partly full flow curves (d/D = 0.7 to 0.9) have been presented for the designer's convenience since storm drains are often designed to flow partly full within this depth range.

For non-circular conduits, such as pipe arches, obtain the equivalent pipe diameter D_e from the full flow hydraulic radius. Then enter the appropriate graph with $D_e = 4R_{full}$ and read the full or partly full resistance factor from the appropriate $Q/D^{2.5}$ curve. For pipe arches, use $Q/BD_a^{1.5}$ in place of $Q/D^{2.5}$, where B is the pipe-arch span and D_a is the pipe-arch rise.

For depths of flow outside the ranges shown (full or d/D = 0.7 - 0.9), determine the hydraulic radius for the partly full flow prism, determine the equivalent diameter, $D_e = 4R$, enter the appropriate graph and read the resistance from the appropriate full flow curve. Do not use the partly full flow curves for this procedure, and do not apply the technique if d/D is less than 0.4. It is not felt that the state-of-the-art permits accurate determination of hydraulic resistance for very shallow flow depths. Note that since C.M.P. resistance is affected by Reynolds number, the resistance factors obtained by the latter technique are approximate, but the errors will not be significant.

<u>Summary of Methods for Use of Figures 2-9</u>

1. From the tables of Appendix C or from Reference 13, "Computation of Uniform and Nonuniform Flow in Prismatic Conduits," determine the true diameter for circular pipes or the effective diameter, $D_e = 4R_{full}$, for non-circular conduits such as pipe-arches.

2. Determine $Q/D^{2.5}$ for circular pipes or $Q/BD_a^{1.5}$ for pipe arches. Values of $D^{2.5}$ and $BD_a^{1.5}$ are given in Appendix C and in Reference 13.

3. For <u>Full Flow</u>, enter the appropriate figure and read the resistance factor from the Full Flow curve. Use the closest $Q/D^{2.5}$ curve, or interpolate. (Note: if the $Q/D^{2.5}$ value falls outside the $Q/D^{2.5} = 2$ to 4 range, refer to Figures D5 to D9 in Appendix D for guidance on the potential variation in the resistance factor.)

5. For partly full flow, with a depth between d/D = 0.7 and d/D = 0.9, enter the appropriate figure and read the resistance factor from the appropriate partly full flow curve. (Note: for pipe arches use d/D_a rather than d/D).

6. For partly full flow, with a depth between $d/D = 0.4$ and $d/D = 0.7$, determine the equivalent diameter, D_e, for the partly full flow prism by the equation $D_e = 4\ R$, where R is the hydraulic radius of the flow prism. Then enter the appropriate figure and read the resistance factor from the Full Flow curve.

7. For partly full flow with a depth between $d/D = 0.9$ and full flow, interpolate between the full flow and partly full flow curves.

Examples of Use of Figures 2-9

1. Circular C.M.P.

Given: 6 ft. (1.8 m) diameter C.M.P. with 3- by 1-inch (7.6 x 2.5 cm) corrugations and a flow of 176 cfs (5.0 m^3/sec).

Required: Resistance factors f and n for full flow and partly full flow. Assume that the partly full flow depth will vary between $d/D = 0.7$ and $d/D = 0.9$.

1) True diameter = nominal diameter = 6 ft. (1.83 m).

2) $D^{2.5} = 88.18\ ft.^{2.5}$ (From Table C-1, Appendix C)

$Q/D^{2.5} = 176/88.18 = 2.0$

3)

d/D	f (Fig. 2)	n (Fig. 6)
1.0 (Full)	0.0735	0.0268
0.7-0.9	0.0700	0.0270

To estimate the resistance factors for other depths of flow, compute the equivalent diameter of the partly full flow prism at the desired depth, enter the appropriate graph, and read the resistance factor from the Full Flow curve.

For example, for the above pipe, suppose the resistance factor at d/D = 0.6 is required with $Q/D^{2.5} = 2.0$. At d/D = 0.6, R/D = 0.2776 (from Table C-2, Appendix C).

Then $D_e = 4R = (4)\ (R/D)\ (D) = (4)\ (.2776)\ (6) = 6.66$ ft. (2.03 m)

From Fig. 2, f = 0.0710
From Fig. 6, n = 0.0269

These latter values are approximate, since the resistance factors vary with Reynolds number.

2. Circular Structural Plate C.M.P.

Given: 12 foot (3.6 cm) (nominal diameter) structural plate C.M.P. with 6- by 2-inch (15.2 x 5.1 cm) corrugations. Flow rate = 1515 cfs (42.9 m^3/sec).

Required: Resistance factors f and n for full and partly full flow.

Partly Full Flow Range: d/D = 0.7 - 0.9.

1) True diameter = 12.06 ft. (3.676 m)

2) $D^{2.5} = 505.1\ ft.^{2.5}$ (Table C-3, Appendix C)

$Q/D^{2.5} = 1515/505 = 3.0$

3)

d/D	f (Fig. 4)	n (Fig. 8)
1.0 (Full)	0.0910	0.0335
0.7-0.9	0.0850	0.0334

The above values were obtained by interpolation between $Q/D^{2.5} = 2$ and $Q/D^{2.5} = 4$.

3. Corrugated Metal Structural Plate Pipe-Arch

Given: Structural Plate Corrugated Metal Pipe-Arch with 9 x 2-1/2 inch corrugations. (28.8 inch (73.2 cm) corner radius).

Nominal size: Span (B) = 10 ft. - 5 in. (3.18 m).
Rise (D_a) = 7 ft. - 3 in. (2.21 m).

Flow rate = 760 cfs (21.5 m^3/sec)

Required: Resistance factors, f and n, for full flow and partly-full flow (d/D_a = 0.7 - 0.9).

1) From Table C-10, Appendix C,

R = 2.085 ft. (0.636 m) (full flow hydraulic radius)

$BD_a^{1.5} = 190.2$

De = 4R = 4 (2.085) = 8.34 ft. (2.54 m).

2) $Q/BD_a^{1.5} = 760/190.2 = 4.0$

3) Enter figures with D_e = 8.34 ft and $Q/BD_a^{1.5} = 4.0$

d/D	f (Fig. 5)	n (Fig. 9)
1.0	0.104	0.0338
0.7-0.9	0.095	0.0333

HELICALLY CORRUGATED METAL PIPES

Corrugation Shapes Considered

Corrugated metal pipe manufactured by the lock seam process, known as helical C.M.P., is available in the same range of sizes as the riveted or spot welded C.M.P. with annular corrugations and seams.

The following corrugation shapes are presented in the design figures of this section:

Nominal Size of Corrugations Pitch (c) by Depth (k) Inches	(cm)	Finished Plate Width Inches	(cm)
1-1/2 x 1/4	3.8 x 0.65	12	30.5
2 x 7/16	5.0 x 1.1	20	50.8
2 x 1/2	5.0 x 1.3	16,20	40.6,50.8
2-2/3 x 1/2	6.8 x 1.3	24	61.0

Factors Affecting Hydraulic Resistance

Relative roughness (k/D) and corrugation shape appear to have little effect on the hydraulic resistance of helically corrugated metal pipes flowing full until the helix angle approaches 90 degrees. The resistance varies primarily with the helix angle of the corrugations, Θ, and secondarily with Reynolds number (flow, cross sectional area, and temperature). At higher Reynolds numbers, the resistance values seem to reach a constant value for full flow in circular conduits.

The helix angle is dependent upon the method of manufacture of the helically corrugated metal pipes. Coiled sheet metal is fed into a pipe mill which forms the corrugations and rolls the metal into a spiral pipe with a lock or welded seam. A fixed width of metal is used; therefore, the angle at which the metal is fed into the machine, and thus the helix angle, varies with the diameter of the pipe being produced. Since the pipe seam must move ahead one finished strip width per complete revolution, the tangent of the helix angle equals the pipe circumference divided by the finished strip width:

$$\tan \Theta = \frac{\pi D}{L_s} \qquad (6)$$

where Θ is the helix angle, degrees (radius),

D is the pipe diameter, inches (cm), and

L_s is the finished strip width, inches (cm).

The finished plate width is defined as the distance between seam center lines on the fabricated pipe, measured parallel to the pipe axis.

In Table 1, helix angles computed by Equation (6) are presented for various combinations of corrugation forms, plate widths, and pipe diameters. These angles, of course, are subject to manufacturing tolerances.

Darcy Resistance Factors, f

Figure 10 depicts Darcy f versus pipe diameter for helically corrugated metal pipes, flowing full, with finished plate widths of 12, 16, 20, and 24 inches (30.5, 40.6, 50.8, and 61.0 cm). The corrugation shapes corresponding with these plate widths are shown on the figure. For the smaller pipe sizes, there is a large reduction in resistance for the helical pipes as compared with annular C.M.P. As the pipe size increases, the helical C.M.P. resistance also increases, and is assumed to approach the resistance of annular C.M.P. for larger pipe sizes.

Flow rates are covered using the parameter $Q/D^{2.5}$, in the same manner as for annular C.M.P. Values of $Q/D^{2.5} = 2$ and 4 are presented. For higher flow values, use the $Q/D^{2.5} = 4$ curves. For lower $Q/D^{2.5}$ values, resistance values can increase drastically, so Figure D10 should be consulted for guidance.

TABLE 1

HELIX ANGLES IN DEGREES FOR CORRUGATED PIPES OF VARIOUS DIAMETERS

Pipe Diameter in inches	Corrugations, inches			
	1-1/2x1/4 Finished Plate Width = 12 inches	2x1/2 Finished Plate Width = 16 inches	2x1/2 Finished Plate Width = 20 inches	2-2/3x1/2 and 3x1 Finished Plate Width = 24 inches
6	58			
8	64			
10	69			
12	72	67	62	58
15		71	67	63
18		74	70	66
21		76	73	70
24		78	75	72
30		80	78	76
36		82	80	78
42		83	81	80
48		84	82	81
54		85	83	82
60		85	84	83
66		86	84	83
72		86	85	84
78		86	85	84
84		87	86	85
90		87	86	85
96		87	86	85

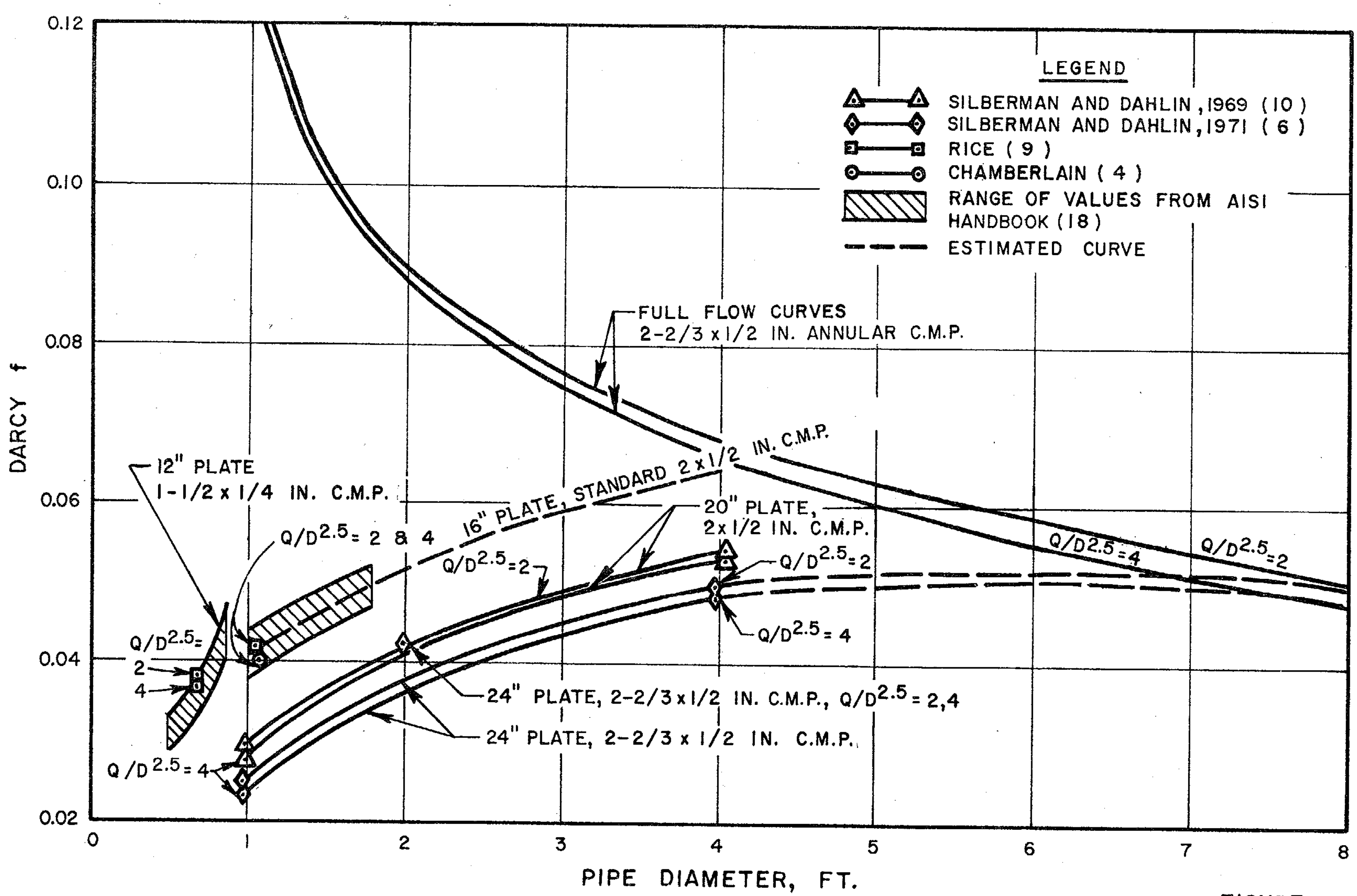


FIGURE 10

10. Darcy f Versus Diameter for Helically Corrugated Metal Pipe

While all corrugation shapes are not shown, it is felt that the resistance of other, untested shapes may be adequately estimated using the finished plate width and pipe diameter as parameters. For example, if 6 by 1 inch helical C.M.P. is fabricated with a 24 inch finished plate width, the same curves can be used as for 2-2/3 by 1/2 inch corrugations with a 24 inch plate width.

Manning Resistance Factors, n

Manning n values for helical C.M.P. are shown on Figure 11. The same curves are presented as were given in Figure 10 for Darcy f values.

Re-Corrugated Annular Rings

For helical C.M.P. joined with re-corrugated annular rings on the end (a short section of annular C.M.P. at the ends to facilitate joining the pipes), add 10.5 percent to the Darcy f determined from Figure 10 or 6 percent to the Manning n from Figure 11.

Limitations

While it is true that helical C.M.P. may have much lower resistance values than annular C.M.P., care should be exercised in the use of the reduced resistance values.

Since the low values depend on the development of spiral flow across the entire cross-section of the pipe, the designer must assure himself that fully developed spiral flow can occur in his design situation. It is recommended that care be taken when the following conditions exist:

1. Partly full flow in the conduit.

2. When high sediment loads can cause sedimentation in the pipe invert during low flow periods. This sediment may hinder the development of spiral flow in the conduit until the sediment is washed out of the conduit.

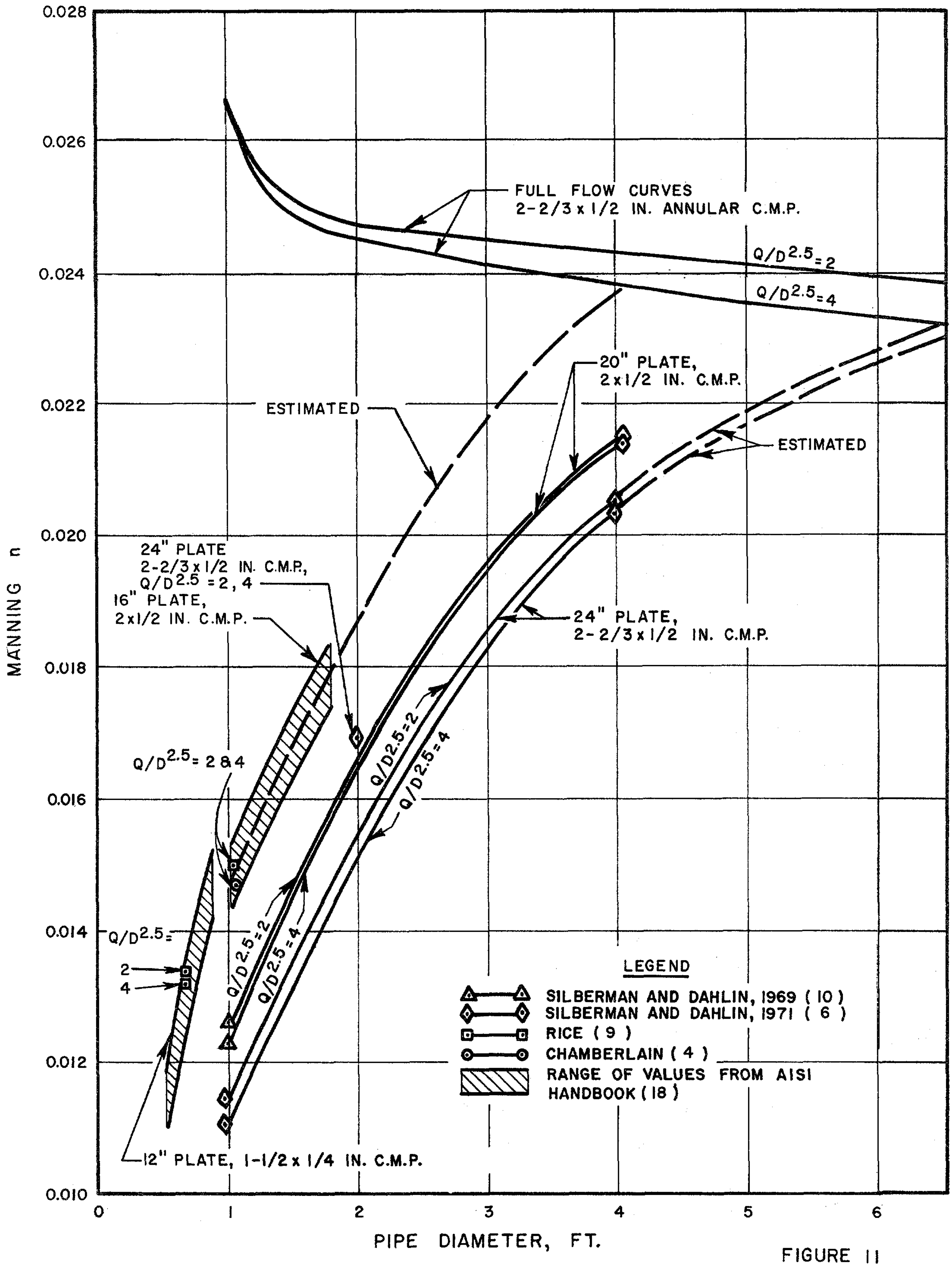


FIGURE 11

11. Manning n Versus Diameter for Helically Corrugated Metal Pipe

Regarding condition 1 above, partly full flow design conditions should be avoided in helically corrugated metal pipes. Otherwise, the partly full resistance coefficient for an annular C.M.P. of the same size and corrugation type should be used rather than the lower resistance coefficient applicable to full flow in helical C.M.P.

Condition 2 is not as great a problem, since sediment is usually washed out of a helical C.M.P. rather rapidly. However, if other pipes in the area have sediment deposits which are of significant depth, it would be prudent to consider that fact in the design of helical C.M.P., and possibly use the higher resistance value for an equivalent annular C.M.P.

If the following conditions exist, use the full flow resistance factor for the annular C.M.P. with the same corrugation shape, pipe size, and flow rate. It is felt that it is better to introduce some conservatism and extra capacity into the pipe design than to risk flooding by depending on a flow condition which will not develop.

3. Short culverts, less than about 20 diameters long, where the spiral flow cannot fully develop.

4. Non-circular conduits, such as pipe-arches.

5. When the helical C.M.P. is partly lined.

For condition 5, use the resistance factor for a partly lined annular C.M.P. of the same size and corrugation type.

Examples of Use of Figures 10 and 11

To illustrate the use of helical C.M.P. resistance factors, two examples will be presented. The first will involve a storm drainage system and the second a culvert. In the first case, it is usually safe to utilize the lower resistance coefficients for helical C.M.P. In culverts, partly full flow often exists, so that the lower helical C.M.P. resistance factors must be applied with care.

1. Given: A storm drain is to be designed to convey 31.0 cfs (0.89 m^3/s). Design is for "just full flow". That is, the hydraulic grade line is assumed to coincide with the roof of the pipe. Use circular helical C.M.P. with 2-2/3 by 1/2 inch (6.8 by 1.3 cm) corrugations and a 24 inch (61 cm) plate width. The slope is 0.0045 ft/ft. Sediment is not considered to be a problem, and the conduit is to be 300 ft (91.5 m) long.

Solution: Since the pipe will flow full at design conditions, has no significant sediment buildup, is long (L greater than 20 D), is circular, and is unlined, the lower resistance coefficients for helical C.M.P. may be used.

First, determine the flow capacities for several pipe sizes. Either Equation (1a) or (3) can be used, depending on whether the Manning n or Darcy f resistance coefficient is chosen.

D,ft.	D,m.	$D^{2.5}$,$ft.^{2.5}$ (Table C-1)	$Q/D^{2.5}$	Darcy f (Figure 10)	Manning n (Figure 11)
2.5	0.76	9.882	3.1	0.041	0.0171
3.0	0.91	15.59	2.0	0.045	0.0187
3.5	1.07	22.92	1.4	0.048*	0.0199*

*Extrapolated.

Use the Manning Equation (1a):

$$Q = A \frac{1.486}{n} R^{2/3} S_f^{1/2} \quad \text{- - - - - - - - - - - - - - - - - -} \quad (1a)$$

D	A/D^2 (Table C-2)	A,ft^2	R/D (Table C-2)	R,ft.	n	S_f	Q, cfs	Q, m^3/s
2.5	0.7854	4.91	0.2500	0.625	0.0171	0.0045	20.9	0.59
3.0	"	7.07	"	0.75	0.0187	"	31.1	0.88
3.5	"	9.62	"	0.875	0.0199	"	44.1	1.25

Therefore, a 3 foot (0.91 m) helical C.M.P. is adequate for this design situation. Note that if the conduit were designed with annular corrugations, the full flow Manning n would be 0.0245 (Figure 6), and the flow capacity would be 23.7 cfs (0.67 m^3/s), or only slightly more than the capacity of a 2.5 foot (0.76 m) diameter helical C.M.P.

2. Given: A culvert is to be designed to convey 62 cfs (1.76 m^3/s). Use circular helical C.M.P. with 2-2/3 by 1/2 inch (6.8 x 1.3 cm) corrugations and a 24 inch (61 cm) plate width. The slope is 0.005 ft/ft. The culvert length is about 200 feet (61 m). Sediment deposition does not appear to be a problem. The culvert entrance is square edged in a headwall, and the allowable headwater is 7.0 feet (1.83 m). Use the culvert design procedures of Hydraulic Engineering Circular No. 5, Hydraulic Charts for the Selection of Highway Culverts (20).

Solution: First check inlet control, which is unaffected by barrel conditions including the corrugation shape.

From Chart 5 of Reference 20, the following inlet control headwater depths are determined:

D,ft.	D,m.	Q cfs	Q m^3/s	HW*/D	HW,ft.	HW,m.
2.5	0.76	62	1.76	3.4	8.5	2.59
3.0	0.91	"	"	1.7	5.1	1.55
3.5	1.07	"	"	1.2	4.2	1.28
4.0	1.22	"	"	0.9	3.6	1.10

*HW = headwater depth, inlet control.

Next, checking outlet control, use full flow n values from Figure 11 for helical C.M.P. and partly full n values from Figure 6, for annular C.M.P. The latter values assume that spiral flow cannot develop in a partly full helical C.M.P.

In outlet control, the barrel roughness does influence culvert capacity, and the corrugation type and method of pipe manufacture (annular or helical) must be considered.

The total losses through the barrel (inlet, outlet, and friction) are computed using the following equation from Reference 20:

$$H = \left[1 + k_e + \frac{29\ n^2\ L}{R^{1.33}} \right] \frac{V^2}{2g} \qquad (7)$$

where,
- H is the total loss through the culvert barrel
- k_e is the entrance loss coefficient (0.5 for square edged inlets)
- n is the Manning resistance factor
- L is the barrel length
- R is the full flow hydraulic radius (D/4 for circular pipes); and
- V is the full flow velocity

Equation (7) is derived by rearranging Equation (4) from the main text and adding the entrance and exit losses. For purposes of illustration, both full flow helical C.M.P. and partly full annular C.M.P. resistance factors will be investigated.

The following tables contain the development of the parameters needed to solve Equation (7):

D,ft.	$Q/D^{2.5}$ (Table C-1)	$Q/D^{2.5}$	Full Flow Darcy f (Figure 10)	Full Flow Manning n (Figure 11)	Partly Full Flow Darcy f (Figure 2)	Partly Full Flow Manning n (Figure 6)
2.5	9.882	6.3	0.041*	0.0169	0.072**	0.0237**
3.0	15.59	4.0	0.044	0.0184	0.069	0.0238
3.5	22.92	2.7	0.047	0.0197	0.065	0.0239
4.0	32.00	1.9	0.050	0.0207	0.063	0.0240

*Use $Q/D^{2.5}$ = 4.0 curve.

**Extrapolated.

D,ft.	A/D^2 (Table C-2)	A, ft^2	Full Flow V,fps	$\frac{V^2}{2g}$,ft.	R/D (Table C-2)	R,ft.	$R^{1.33}$
2.5	0.7854	4.91	12.63	2.48	0.2500	0.625	0.535
3.0	"	7.07	8.77	1.20	"	0.75	0.682
3.5	"	9.62	6.44	0.64	"	0.875	0.837
4.0	"	12.57	4.93	0.38	"	1.00	1.00

Using the Manning Equation (1a) to determine the total barrel losses:

D,ft.	Full Flow		Partly Full Flow	
	H,ft.	m	H,ft.	m
2.5	11.4	3.5	18.8	5.7
3.0	5.3	1.6	7.6	2.3
3.5	2.7	0.8	3.5	1.1
4.0	1.5	0.5	1.8	0.5

Then, $HW_o = H + H_o - L\ S_o$ - (8)

Where,

HW_o = the headwater depth in outlet control

H = barrel losses

$h_o = \frac{d_c + D}{2}$

L = barrel length

S_o = barrel slope

d_c = critical depth

D = barrel diameter

Using Equation (8), for full flow:

D,ft.	H,ft.	d_c (Chart 16,Ref. (2))	h_o,ft.	$L\ S_o$,ft.	HW_o,ft.
2.5	11.4	2.5	2.5	1.0	12.9
3.0	5.3	2.5	2.8	"	6.8
3.5	2.7	2.4	3.0	"	4.7
4.0	1.5	2.3	3.2	"	3.7

For partly full flow, using the larger resistance factors for annular C.M.P.:

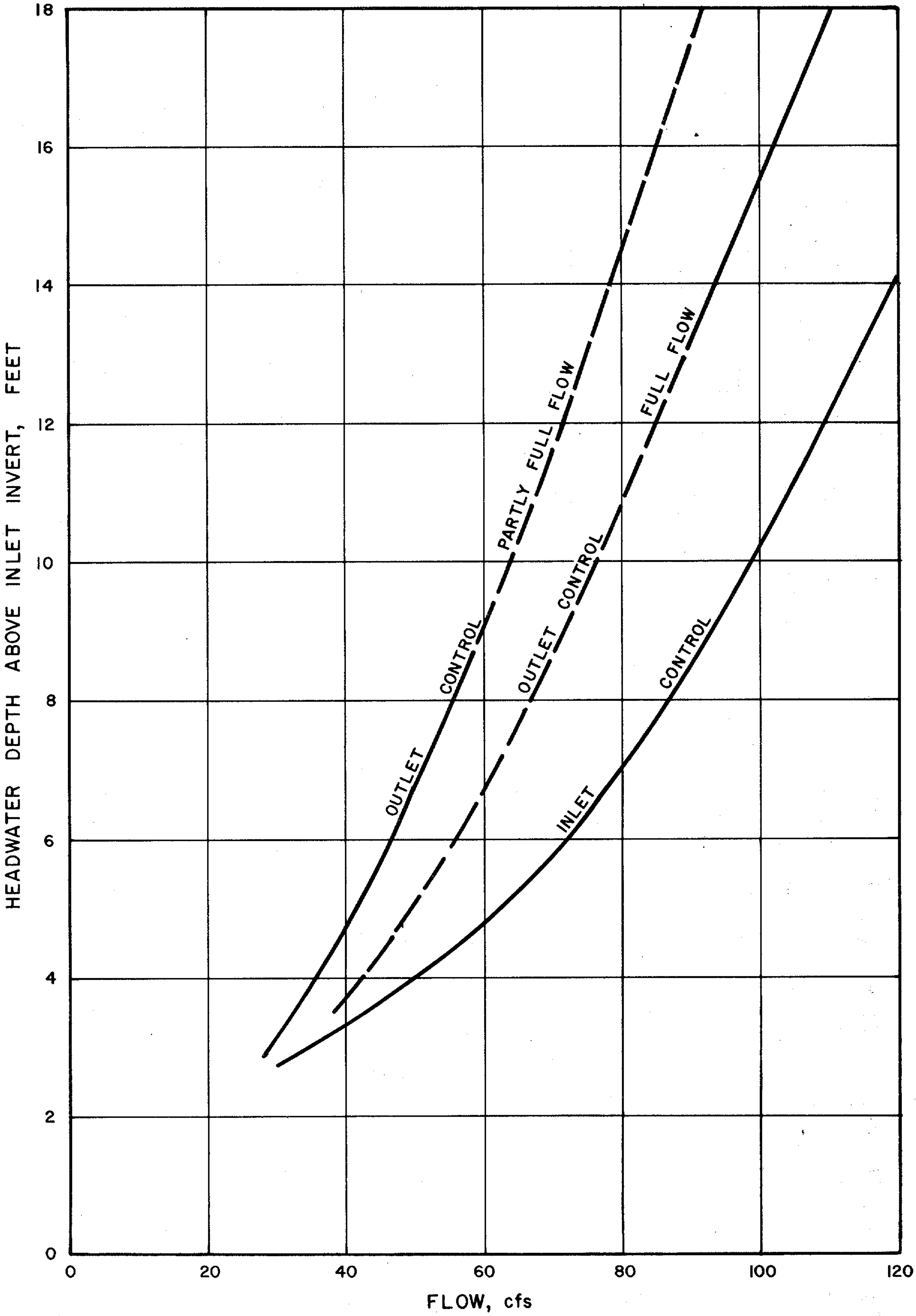
D,ft.	H,ft.	h_o,ft.	L S_o,ft.	HW_o,ft.
2.5	18.8	2.5	1.0	20.3
3.0	7.6	2.8	"	9.4
3.5	3.5	3.0	"	5.5
4.0	1.8	3.2	"	4.0

From the above, it is seen that the 2.5 foot (0.76 m) pipe will flow full, with a flow rate of 62 cfs (1.76 m^3/s) and a headwater depth of 12.9 feet (3.93 m). The 3.0 foot (0.91 m) pipe is partly full at the outlet end; however, it is probably safe to assume full flow since the barrel will flow full throughout most of its length. Also, if the actual flow exceeds the design flow, the pipe will be forced into a completely full flow condition, and the lower Manning n values will certainly be appropriate.

The large 3.5 foot (1.07 m) and 4.0 foot (1.22 m) diameter pipes are definitely partly full under the design flow rate, and the outlet control headwaters are 5.5 feet (1.68 m) and 4.0 feet (1.22 m), respectively.

For this culvert installation, a 3.0 foot (0.91 m) helical C.M.P. barrel is adequate. It should be noted that the headwater could exceed 6.8 feet (2.07 m) if full flow is not maintained. However, as the headwater rises, the barrel will be forced into full flow and the lower resistance factors will be assured.

A set of performance curves for this culvert follows. Note that the inlet control curve is well below the outlet control curves; thus, the culvert operates in outlet control over the range of flows of interest. The full flow outlet control curve is based on helical C.M.P. resistance factors, while the partly full curve is based on annular C.M.P. resistance factors. Above 90 cfs, the pipe is definitely full, since critical depth at the pipe outlet exceeds the pipe diameter. Also, below 30 cfs, the pipe is certain to be partly full, since the headwater depth is below the top of the pipe. However, in the range between 30 and 90 cfs, it is not known where full flow will prevail and the lower resistance factors will be justified. A conservative answer would require use of the partly full flow curve, but it is probably reasonable to utilize the full flow curve from about 60 cfs upward. A definite solution to this problem is not possible at this time, due to the lack of test data on such flow conditions. The designer's judgement must be used to select those cases where a conservative solution is indicated versus those cases where potential damages are low and some increased risk can be assumed.



EXAMPLE 2

PERFORMANCE CURVES 3 FOOT DIAMETER HELICAL CORRUGATED METAL PIPE 2 2/3 x 1/2 INCH CORRUGATIONS, 24 IN. PLATE WIDTH, LENGTH = 200 FT., SLOPE = 0.005, INLET : SQUARE EDGE IN HEADWALL

APPENDIX A - REFERENCES

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APPENDIX B - DEFINITIONS OF TERMS

A = area of flow, feet^2 (m^2).

a = average projected area of an obstruction, such as a bolt head or nut, normal to flow, feet^2 (m^2).

B = pipe-arch span, feet (m).

C_D = coefficient of drag estimated to equal 1.1 for structural plate bolts and 1.0 for structural plate seams.

c = pitch of corrugation, feet (m).

D = pipe diameter, feet (m).

D_a = pipe-arch rise, feet (m).

D_e = equivalent circular pipe diameter, based on 4R, feet (m).

d = depth of flow, feet (m).

d_c = critical depth, feet (m).

f = Darcy resistance factor.

f_p = peak Darcy resistance factor, based on f vs. N_{Rw} curves.

g = gravitational acceleration = 32.16 feet/second^2 or 9.807 meters/second^2.

H = total losses through a culvert barrel (inlet, exit, and friction), feet (m).

HW = inlet control headwater for a culvert, measured above inlet invert, feet (m).

HW_o = outlet control headwater for a culvert, measured above the inlet invert, feet (m).

h_f = friction head loss, feet (m).

h_o = elevation of full flow hydraulic grade line at culvert outlet, approximately equal to $\frac{d_c + D}{2}$, feet (m).

k = depth of corrugation, feet (m).

k_e = entrance loss coefficient

L = length of conduit, feet (m).

L_s = finished plate width, helically corrugated metal pipe, inches (cm).

N = number of structural plate bolts per length, L.

N_R = pipe Reynolds number = $VD/\nu = 4VR/\nu$.

N_{Rw} = wall Reynolds number = $v^* k/\nu$.

n = Manning resistance factor.

P = perimeter of conduit, feet (m).

p = wetted perimeter of conduit, feet (m).

Q = flow rate, feet^3/second (m^3/sec).

R = hydraulic radius = $A/P = D/4$ for full flow in circular pipes, feet (m).

r = distance measured from a pipe axis outward, feet (m).

r_o = radius of a circular pipe, feet (m).

r_p = radius of corrugation peak, feet (m) = $r_v + t$.

r_v = radius of corrugation valley, feet (m).

S_f = friction slope -- slope of total energy line, equal to slope of the hydraulic grade line in pipes flowing full.

S_o = culvert barrel slope, feet/feet

T = temperature, ^oF (^oC).

t = thickness of corrugated metal, feet (m).

V = mean velocity, Q/A, feet/second (m/sec).

v^* = mean shear velocity, $(RS_f g)^{0.5}$, feet/second (m/sec).

w = density of water = 62.37 pounds/foot^3 (9797.6 N/m^3) at 60^{o}F (15.6^{o}C).

y = distance measured from a conduit wall inward, feet (m). For C.M.P., the origin is at a corrugation crest.

Δf = incremental Darcy resistance factor resulting from structural plate bolts or seams.

Θ = helix angle, measured from the pipe axis, degrees (radians).

ν = kinematic viscosity = 1.217×10^{-5} feet^2/second (1.131×10^{-6} m^2/sec) for water at 60°F (15.6°C).

ρ = mass density of water = w/g = 1.939 pound second^2/feet^4 (999.3 kg/m^2) for water at 60°F (15.6°C).

τ_o = unit shear stress in a fluid at the conduit wall, pound/feet^2 (kg/m^2).

APPENDIX C - DIMENSIONAL GEOMETRIC, AND HYDRAULIC FACTORS FOR CORRUGATED METAL CONDUITS

This appendix contains tables of geometric and hydraulic properties for circular and pipe-arch corrugated metal conduits in terms of the actual dimensions rather than the nominal dimensions. Manufacturing standards govern actual dimensions, and small tolerances are to be allowed and should be expected. Information on some corrugation types and conduit shapes covered in the main text are not included here for one of two reasons. First, actual dimensions for some conduits, such as 6- by 1-inch pipe-arches (28.8 inch corner radius), flowing partly full are not available at present. True dimensions for 9- by 2-1/2-inch structural plate C.M.P. with 31 inch corner radius have not been obtained. Use of nominal dimensions given in manufacturers' catalogs for these conduits probably will produce no significant errors in the determination of resistance coefficients. Secondly, some circular conduits, notably the riveted 2-2/3- by 1/2-inch, 3- by 1-inch, and 6- by 1-inch C.M.P., have actual diameters equal to the nominal diameters. For these conduits, standard tables and formulas can be used to determine geometric and hydraulic properties. (See Tables C-1 and C-2).

A more complete set of tables of geometric data for conduits of various shapes may be found in Reference 13, "Computation of Uniform and Non-Uniform Flow in Prismatic Conduits." The tables given herein are for the designers' convenience in utilizing this publication.

The $D^{2.5}$ values for circular pipes and $BD_a^{1.5}$ values for pipe-arches, presented in the accompanying tables, are for use in computing conduit flow factors in terms of either $Q/D^{2.5}$ or $Q/BD_a^{1.5}$. This flow factor is required to determine resistance coefficients for the 2-2/3- by 1/2-inch and 6- by 1-inch corrugated metal conduits. Notice that the flow factor would be dimensionless if divided by $g^{0.5}$, a constant.

Pipe-arches, in general, are not geometrically similar, and the area and hydraulic radius of each pipe-arch section, flowing full or partly full, must be determined individually from its dimensions. However, it has been found that for all pipe-arch sections, the dimensionless ratios for these properties, R/D_a and A/BD_a at a given relative depth, d/D_a, deviate little from an average value. Mean values of these dimensionless ratios for 2-2/3- by 1/2-inch pipe-arches are given in Table C-6 and similar average ratios for 6- by 2-inch structural plate pipe-arches are given in Table C-9. Table C-9 is to be used for both the 18-inch corner radius and 31-inch corner radius 6- by 2-inch pipe-arches, as the averages of the R/D_a and A/BD_a ratios for conduits of both corner radii are about equal at any given relative depth of flow. The 6- by 2-inch structural plate pipe-arches with 18-inch corner radii comprise a large range of sizes and thus deviate from the mean value more than the arches with 31-inch corner radii. The errors involved in using means are still less than 5 percent for determination of A or R from full flow down to a relative depth of 0.4.

Similar average dimensionless ratios R/D_a and A/BD_a were computed from available data for 9- by 2-1/2-inch structural plate corrugated pipe-arches with 28.8 inch corner radius, flowing partly full. The values so determined at various relative depths d/D are nearly identical with those of Table C-9 for 6- by 2-inch arches with the two different corner radii. The values of Table C-9 can be used for determination of resistance factors without introducing significant error.

To convert the English units presented in the following tables to SI units, utilize the conversion factors given in Appendix E.

TABLE C-1 - $D^{2.5}$ VALUES FOR A RANGE OF PIPE DIAMETERS

True Diameter Inches	True Diameter Feet	$D^{2.5}$, feet$^{2.5}$
	1.0	1.000
		1.747

TABLE C-2 - GEOMETRIC FACTORS FOR

(d=Depth of Flow, D=Pi-

TABLE C-1 - $D^{2.5}$ VALUES FOR A RANGE OF PIPE DIAMETERS

True Diameter Inches	True Diameter Feet	$D^{2.5}$, feet$^{2.5}$
12	1.0	1.000
15	1.25	1.747
18	1.5	2.756
21	1.75	4.051
24	2.0	5.657
30	2.5	9.882
36	3.0	15.59
42	3.5	22.92
48	4.0	32.00
54	4.5	42.96
60	5.0	55.90
66	5.5	70.94
72	6.0	88.18
78	6.5	107.72
84	7.0	129.64
90	7.5	154.0
96	8.0	181.0
102	8.5	210.6
108	9.0	243.0
114	9.5	278.2
120	10.0	316.2

TABLE C-2 - GEOMETRIC FACTORS FOR CIRCULAR CONDUITS, FULL OR PARTLY FULL

(d=Depth of Flow, D=Pipe Diameter, R=Hydraulic Radius, and A=Area of Flow)

$\frac{d}{D}$	$\frac{R}{D}$	$\frac{A}{D^2}$	$\frac{d}{D}$	$\frac{R}{D}$	$\frac{A}{D^2}$
1.00	0.2500	0.7854	0.50	0.2500	0.3927
0.95	0.2865	0.7707	0.45	0.2331	0.3428
0.90	0.2980	0.7445	0.40	0.2142	0.2934
0.85	0.3033	0.7115	0.35	0.1935	0.2450
0.80	0.3042	0.6736	0.30	0.1709	0.1982
0.75	0.3017	0.6319	0.25	0.1466	0.1535
0.70	0.2962	0.5872	0.20	0.1206	0.1118
0.65	0.2882	0.5404	0.15	0.0929	0.0739
0.60	0.2776	0.4920	0.10	0.0635	0.0409
0.55	0.2649	0.4426	0.05	0.0325	0.0147

TABLE C-3 - DIMENSIONS AND $D^{2.5}$ VALUES FOR 6- BY 2-INCH STRUCTURAL PLATE CORRUGATED CIRCULAR PIPES, FULL-FLOW CONDITION

Nominal Diameter Feet	True Diameter Feet	Plates Per Ring Number	$D^{2.5}$ $Feet^{2.5}$
5.0	4.93	4	53.97
5.5	5.43	4	68.71
6.0	5.94	4	85.99
6.5	6.45	4	105.66
7.0	6.97	4	128.26
7.5	7.48	6	153.0
8.0	7.98	6	179.9
8.5	8.49	6	210.0
9.0	9.00	6	243.0
9.5	9.51	6	278.9
10.0	10.02	6	317.8
10.5	10.53	6	359.8
11.0	11.04	8	405.0
11.5	11.55	8	453.4
12.0	12.06	8	505.1
12.5	12.57	8	560.2
13.0	13.08	8	618.8
13.5	13.58	8	679.6
14.0	14.09	8	745.2
14.5	14.60	10	814.5
15.0	15.11	10	887.5
15.5	15.62	10	964.3
16.0	16.13	10	1044.9
16.5	16.64	10	1130.0
17.0	17.15	10	1218.0
17.5	17.66	10	1310.8
18.0	18.17	12	1407.0
18.5	18.67	12	1506.0
19.0	19.18	12	1611.0
19.5	19.69	12	1720.0
20.0	20.21	12	1836.0
20.5	20.72	12	1954.0
21.0	21.22	12	2074.0

TABLE C-4 - DIMENSIONS AND $D^{2.5}$ VALUES FOR 9- BY 2-1/2-INCH STRUCTURAL PLATE CORRUGATED CIRCULAR PIPES, FULL FLOW CONDITION

Nominal Diameter Feet	True Diameter Feet	Plates Per Ring Number	$D^{2.5}$
5.0	4.89*	2	52.9
7.0	5.40*	2	67.8
6.0	5.91*	2	84.9
6.5	6.42	2	104.4
7.0	6.93	2	126.4
7.5	7.44	3	151.0
8.0	7.96	3	178.8
8.5	8.46	3	208.2
9.0	8.97	3	241.0
9.5	9.48	3	276.7
10.0	9.99	3	315.4
10.5	10.50	3	357.2
11.0	11.01	4	402.2
11.5	11.52	4	450.4
12.0	12.04	4	503.0
12.5	12.52	4	554.6
13.0	13.05	4	615.2
13.5	13.57	4	678.3
14.0	14.08	4	743.9
14.5	14.59	5	813.1
15.0	15.10	5	886.0

*Estimated

Other pipe sizes range up to 21 feet in diameter; however, dimensional data are not presently available for these pipes.

TABLE C-5 - DIMENSIONS AND HYDRAULIC PROPERTIES OF 2-2/3- BY 1/2-INCH CORRUGATED METAL PIPE-ARCHES, FULL-FLOW CONDITION

Nominal Size Span B Inches	Nominal Size Rise D_a Inches	True Size Span B Feet	True Size Rise D_a Feet	Hydraulic Radius R Feet	Area A $Feet^2$	$BD_a^{1.5}$
18	11	1.51	0.92	0.282	1.11	1.338
22	13	1.81	1.11	0.338	1.59	2.106
25	16	2.11	1.29	0.394	2.17	3.099
29	18	2.41	1.48	0.451	2.83	4.329
36	22	3.01	1.85	0.564	4.42	7.566
43	27	3.61	2.22	0.676	6.37	11.93
50	31	4.22	2.59	0.789	8.67	17.53
58	36	4.82	2.96	0.902	11.3	24.49
65	40	5.42	3.33	1.014	14.3	32.88
72	44	6.02	3.70	1.127	17.7	42.78
79	49	6.62	4.06	1.240	21.4	54.27
85	54	7.23	4.43	1.352	25.5	67.48

TABLE C-6 - GEOMETRIC FACTORS FOR 2-2/3- BY 1/2-INCH CORRUGATED METAL PIPE-ARCHES, FULL OR PARTLY FULL FLOW MEAN VALUES FOR ALL STANDARD SIZES

(d=Depth of Flow, D_a=Rise of Pipe-Arch, R=Hydraulic Radius

A=Area of Flow, and B=Span of Pipe-Arch)

$\frac{d}{D_a}$	$\frac{R}{D_a}$	$\frac{A}{B\ D_a}$	$\frac{d}{D_a}$	$\frac{R}{D_a}$	$\frac{A}{B\ D_a}$
1.00	0.305	0.795	0.50	0.319	0.459
0.95	0.346	0.783	0.45	0.300	0.412
0.90	0.361	0.762	0.40	0.277	0.363
0.85	0.369	0.736	0.35	0.252	0.315
0.80	0.372	0.704	0.30	0.222	0.264
0.75	0.370	0.668	0.25	0.189	0.214
0.70	0.365	0.632	0.20	0.154	0.165
0.65	0.358	0.592	0.15	0.117	0.117
0.60	0.348	0.549	0.10	0.076	0.069
0.55	0.335	0.505	0.05	0.037	0.028

TABLE C-7 - DIMENSIONS AND HYDRAULIC PROPERTIES OF 6- BY 2-INCH STRUCTURAL PLATE CORRUGATED METAL PIPE-ARCHES WITH 18-INCH CORNER RADIUS, FULL-FLOW CONDITION

Section No.	Nominal Size Span (B) Ft-In	Rise (D_a) Ft-In	Plates Per Ring Number	Span B Feet	Rise D_a Feet	Hydraulic Radius R Feet	Area A $Feet^2$	$BD_a^{1.5}$
1	6-1	4-7	5	6.08	4.58	1.299	22.09	59.60
2	6-4	4-9	5	6.33	4.76	1.353	24.09	65.77
3	6-9	4-11	5	6.77	4.91	1.405	26.14	73.66
4	7-0	5-1	5	7.02	5.09	1.460	28.39	80.59
5	7-3	5-3	6	7.25	5.27	1.515	30.60	87.72
6	7-8	5-5	6	7.70	5.42	1.567	32.92	97.17
7	7-11	5-7	6	7.93	5.60	1.622	35.39	105.07
8	8-2	5-9	6	8.15	5.78	1.677	37.95	113.28
9	8-7	5-11	7	8.62	5.92	1.726	40.40	124.1
10	8-10	6-1	7	8.83	6.11	1.781	43.10	133.3
11	9-4	6-3	7	9.32	6.26	1.832	45.83	146.0
12	9-6	6-5	7	9.52	6.44	1.887	48.70	155.6
13	9-9	6-7	7	9.72	6.62	1.940	51.64	165.5
14	10-3	6-9	7	10.22	6.77	1.989	54.51	180.0
15	10-8	6-11	7	10.70	6.91	2.037	57.46	194.3
16	10-11	7-1	7	10.92	7.09	2.092	60.70	206.2
17	11-5	7-3	7	11.40	7.24	2.142	63.87	222.1
18	11-7	7-5	8	11.62	7.42	2.196	67.23	234.8
19	11-10	7-7	8	11.82	7.61	2.250	70.68	248.1
20	12-4	7-9	8	12.32	7.75	2.298	74.05	265.8
21	12-6	7-11	8	12.52	7.93	2.352	77.64	279.6
22	12-8	8-1	8	12.70	8.12	2.406	81.34	293.9
23	12-10	8-4	8	12.87	8.31	2.461	85.20	208.3
24	13-5	8-5	9	13.40	8.44	2.507	88.74	328.6
25	13-11	8-7	9	13.93	8.58	2.555	92.55	350.1
26	14-1	8-9	9	14.12	8.77	2.608	96.53	366.7
27	14-3	8-11	9	14.28	8.96	2.664	100.73	383.0
28	14-10	9-1	9	14.82	9.10	2.713	104.75	406.8
29	15-4	9-3	9	15.33	9.23	2.758	108.65	429.8
30	15-6	9-6	10	15.53	9.42	2.813	113.1	449.0
31	15-8	9-7	10	15.70	9.61	2.866	117.5	467.7
32	15-10	9-10	10	15.87	9.80	2.922	122.2	486.4
33	16-5	9-11	10	16.42	9.93	2.968	126.4	513.8
34	16-7	10-1	10	16.58	10.12	3.023	131.2	533.7

TABLE C-8 - DIMENSIONS AND HYDRAULIC PROPERTIES OF 6-BY 2-INCH STRUCTURAL PLATE CORRUGATED METAL PIPE-ARCHES WITH 31-INCH CORNER RADIUS, FULL-FLOW CONDITION

Section No.	Nominal Size Span (B) Ft-In	Nominal Size Rise (D_a) Ft-In	Plates Per Ring Number	Span B Feet	Rise D_a Feet	Hydraulic Radius R Feet	Area A Feet^2	$BD_a^{1.5}$
1	13-3	9-4	8	13.28	9.36	2.715	98.30	380.3
2	13-6	9-6	8	13.52	9.53	2.764	102.00	397.8
3	14-0	9-8	8	13.97	9.68	2.811	106.00	420.8
4	14-2	9-10	8	14.22	9.87	2.857	110.88	441.0
5	14-5	10-0	8	14.40	10.04	2.927	115.28	458.1
6	14-11	10-2	9	14.88	10.19	2.967	119.6	484.0
7	15-4	10-4	9	15.35	10.34	3.031	124.0	510.4
8	15-7	10-6	10	15.58	10.52	3.093	129.0	531.6
9	15-10	10-8	10	15.80	10.71	3.139	133.8	553.8
10	16-3	10-10	10	16.28	10.85	3.187	138.0	581.8
11	16-6	11-0	10	16.50	11.03	3.242	143.0	604.4
12	17-0	11-2	10	16.97	11.18	3.296	148.0	634.3
13	17-2	11-4	10	17.18	11.36	3.348	153.1	657.8
14	17-5	11-6	10	17.40	11.54	3.400	158.5	682.1
15	17-11	11-8	10	17.88	11.69	3.446	163.4	714.7
16	18-1	11-10	10	18.10	11.87	3.492	168.0	740.3
17	18-7	12-0	10	18.58	12.01	3.558	174.0	772.9
18	18-9	12-2	10	18.78	12.20	3.600	179.0	800.2
19	19-3	12-4	10	19.28	12.34	3.646	184.7	835.8
20	19-6	12-6	11	19.50	12.52	3.696	190.0	863.8
21	19-8	12-8	11	19.70	12.71	3.755	196.2	892.6
22	19-11	12-10	11	19.88	12.89	3.818	202.4	920.0
23	20-5	13-0	12	20.40	13.03	3.866	207.8	959.4
24	20-7	13-2	12	20.58	13.22	3.919	214.0	989.3

TABLE C-9 - GEOMETRIC FACTORS FOR 6- BY 2-INCH
STRUCTURAL PLATE CORRUGATED METAL PIPE-ARCHES
WITH 18-INCH OR 31-INCH CORNER RADIUS, FULL OR PARTLY FULL FLOW
MEAN VALUES FOR ALL SIZES, BOTH CORNER RADII

(d=Depth of Flow, D_a=Rise of Pipe-Arch, R=Hydraulic Radius,

A=Area of Flow, and B=Span of Pipe-Arch)

$\frac{d}{D_a}$	$\frac{R}{D_a}$	$\frac{A}{B\ D_a}$	$\frac{d}{D_a}$	$\frac{R}{D_a}$	$\frac{A}{B\ D_a}$
1.00	0.294	0.788	0.50	0.306	0.443
0.95	0.336	0.775	0.45	0.286	0.393
0.90	0.349	0.754	0.40	0.264	0.346
0.85	0.356	0.726	0.35	0.239	0.295
0.80	0.358	0.693	0.30	0.211	0.246
0.75	0.357	0.657	0.25	0.179	0.197
0.70	0.353	0.618	0.20	0.144	0.148
0.65	0.345	0.577	0.15	0.107	0.101
0.60	0.335	0.534	0.10	0.068	0.056
0.55	0.321	0.489	0.05	0.030	0.020

TABLE C-10 - DIMENSIONS AND HYDRAULIC PROPERTIES OF 9- BY 2-1/2-INCH STRUCTURAL PLATE CORRUGATED METAL PIPE-ARCHES WITH 28.8-INCH CORNER RADIUS, FULL-FLOW CONDITION

Section No.	Nominal Size Span (B) Ft-In	Nominal Size Rise (D_a) Ft-In	Plates Per Ring Number	Span B Feet	Rise D_a Feet	Hydraulic Radius R Feet	Area A $Feet^2$	$BD_a^{1.5}$
1	5-11	5-4	2	5.91	5.32	1.415	25.16	72.52
2	6-3	5-5	2	6.28	5.46	1.472	27.37	80.13
3	6-8	5-7	2	6.65	5.60	1.533	29.73	88.11
4	6-11	5-9	2	6.96	5.76	1.590	32.11	96.19
5	7-4	5-11	2	7.34	5.91	1.646	34.55	105.48
6	7-8	6-1	2	7.65	6.08	1.704	37.13	114.67
7	8-0	6-2	3	8.04	6.19	1.760	39.75	123.8
8	8-4	6-4	3	8.33	6.34	1.816	42.48	132.9
9	8-7	6-6	3	8.64	6.54	1.874	45.35	144.5
10	9-0	6-8	3	9.04	6.64	1.924	48.09	154.7
11	9-4	6-10	3	9.32	6.82	1.982	51.13	166.0
12	9-9	6-11	3	9.73	6.94	2.026	52.90	177.9
13	10-0	7-1	3	10.03	7.11	2.085	57.13	190.2
14	10-5	7-3	3	10.45	7.24	2.141	60.38	203.6
15	10-9	7-5	3	10.73	7.41	2.193	63.61	216.4
16	11-2	7-6	3	11.15	7.54	2.243	66.85	230.8
17	11-5	7-8	3	11.44	7.71	2.296	70.29	244.9
18	11-8	7-10	3	11.69	7.84	2.360	74.14	256.6
19	12-2	8-0	3	12.15	8.01	2.392	77.06	275.4
20	12-5	8-2	3	12.40	8.15	2.451	80.90	288.5
21	12-10	8-3	4	12.91	8.39	2.517	85.11	313.7
22	13-1	8-5	4	13.09	8.42	2.541	87.97	319.8
23	13-7	8-7	4	13.57	8.58	2.601	92.13	341.0
24	13-10	8-9	4	13.81	8.73	2.657	96.23	356.2
25	14-3	8-10	4	14.28	8.88	2.699	99.90	377.8
26	14-6	9-0	4	14.55	9.06	2.760	104.4	396.8
27	14-9	9-2	4	14.77	9.16	2.790	107.8	409.4
28	15-3	9-4	4	15.20	9.26	2.838	111.9	428.3
29	15-6	9-6	4	15.52	9.52	2.916	117.3	455.8
30	16-0	9-7	4	15.97	9.64	2.954	121.2	478.0
31	16-2	9-9	4	16.22	9.80	3.005	125.7	497.6
32	16-8	9-11	4	16.70	9.92	3.045	129.8	521.7
33	16-11	10-1	4	16.90	10.04	3.080	133.8	537.6

APPENDIX D - DEVELOPMENT OF DESIGN CURVES FOR CORRUGATED METAL CONDUITS

CONTENTS

<u>APPENDIX D - LIST OF FIGURES</u>

APPENDIX D - DEVELOPMENT OF DESIGN CURVES FOR CORRUGATED METAL CONDUITS

INTRODUCTION

In order to present the methodology involved in developing the design curves of the main text without posing undue obstacles to its use for design, this appendix is presented. Herein, the background information and methodology are presented. It will be necessary for the user to read and understand this material if design information for new or untested corrugation shapes must be developed.

Annular and helical C.M.P. are discussed in separate sections of this Appendix.

ANNULAR CORRUGATED METAL PIPES

Background Information

Most early experimental investigations of resistance factors in corrugated metal conduits dealt with 2-2/3 by 1/2-inch (6.8 by 1.3 cm) corrugations. Notable among these studies are those of the U.S. Army Corps of Engineers at the North Pacific Division Hydraulic Laboratory, (1)[1], formerly Bonneville Hydraulic Laboratory, and the earlier work of Straub and Morris at the St. Anthony Falls Hydraulic Laboratory (2). These tests were concerned with corrugated pipes from 1.5- to 7-feet (0.46 to 2.13 m) in diameter. Other tests on smaller 2-2/3 by 1/2 inch corrugated pipes were conducted by C. R. Neill (3) on a 15-inch (0.38 m) pipe and by Chamberlain (4) and Garde (5) on a 12-inch (0.30 m) pipe, although the data from these experiments exhibit somewhat more scatter than those of the North Pacific Division and St. Anthony Falls Hydraulic Laboratories, possibly due to the greater relative roughnesses of the smaller diameter pipes.

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[1]Numbers in parentheses refer to corresponding references in Appendix A.

Recognizing the errors that might result from applying the standard 2-2/3- by 1/2-inch C.M.P. results to other corrugation types, especially to 6- by 2-inch (15.2 x 5.1 cm) structural-plate corrugated pipe, the U.S. Army Engineer Waterways Experiment Station (WES) in 1958 began hydraulic model studies of corrugated pipes with a 3:1 pitch-to-depth ratio. Relative corrugation depths corresponding to 2-inch by 5.1 cm) deep corrugations in 5-, 10-, and 20-foot (1.52 m, 3.05 m, and 6.10 m) diameter pipes were investigated. These tests, sponsored by both the U.S. Army, Office, Chief of Engineers, and the U.S. Department of Commerce, Bureau of Public Roads (BPR, now the U.S. Department of Transportation, Federal Highway Administration) resulted in a report published in 1966 (7).

In addition to the results of model tests on corrugations with a 3:1 pitch-to-depth ratio, the WES report (7) also included the results of studies on a 1:4 scale model of a 5-foot (1.52 m) diameter standard 2-2/3 by 1/2-inch C.M.P. These data differed from full-scale tests results (1) both in velocity distribution and resistance coefficient. A possible explanation for this deviation is that it is difficult to precisely reproduce the 1/2-inch corrugations, which are only 1/8-inch deep when modeled at a 1:4 scale ratio. Also, plate 1 of the WES report indicates that the model may have had more sharply peaked corrugations than the full-size pipe. Therefore, the WES model studies of the 5-foot diameter standard 2-2/3- by 1/2-inch C.M.P. are excluded from the analysis here, and only the full-size standard C.M.P. results are considered.

Two separate hydraulic studies have been conducted on full-size 6- by 2-inch (15.2 by 5.1 cm) structural plate C.M.P. Neill (3) performed two series of tests on full-size 60-inch (1.52 m) structural plate C.M.P., and Bauer Engineering, Inc. (8), tested a 14-foot (4.27 m) diameter power plant cooling water intake pipe in Baileytown, Indiana. These studies produced several resistance factors at various Reynolds numbers for the two pipe sizes, which will be discussed later. Data points for these factors are not illustrated in the accompanying figures, but the discussion will show that they generally verify the analysis methods of this report.

Edward Silberman and W. G. Dahlin (6) conducted full scale tests on 48-inch and 66-inch C.M.P. with 6 by 1 inch (15.2 by 2.5 cm) corrugations at the University of Minnesota, St. Anthony Falls Hydraulic Laboratory (SAF). Also tested was a 66 inch (1.68 m) structural plate C.M.P. with 9 by 2-1/2 inch (22.9 by 6.4 cm) corrugations. Both of these test series were at relatively high Reynolds numbers. Unfortunately, the water temperature was near freezing for two of the test series; otherwise, even higher Reynolds numbers could have been achieved. The test results appear very consistent except at low Reynolds numbers where large scatter occurs.

Some hydraulic flow tests were performed at low Reynolds numbers by A. H. Gibson (14) on a 1.8-inch (4.6 cm) diameter corrugated copper pipe, by Rolf Kellerhals (15) on a 3.6-inch (9.1 cm) plastic model of the 60-inch (1.52 m) structural plate C.M.P. tested by Neill, and by E. R. Zeigler on 4-inch (10.2 cm) diameter corrugated plastic tubing. In these tests, the Reynolds number range was below the practical limit for highway drainage design use, and therefore, were not included in the discussion and analysis reported herein. However, these tests do serve to confirm the general pattern of the Darcy f versus Reynolds number (or wall Reynolds number) plots shown in Figures D5 through D9.

Comparison with Previous Methodology

In the previous issue of this publication in 1970 (12), the model studies reported by the Corps of Engineers Waterways Experiment Station (WES) in 1966 (7) for 6 by 2-inch (15.2 by 5.1 cm) C.M.P. were given a large weight, equal to the other tests on 2-2/3 by 1/2 inch (6.8 by 1.3 cm) corrugations (1, 2, 3, 4, 5). The new full scale tests by Silberman and Dahlin (6) costs serious doubt on the estimating methods used earlier to predict resistance factors for other corrugations. For one thing, the trend of Darcy f values as presented in Figure 4 of the 1970 publication were not confirmed for either the 6 by 1-inch (15.2 by 2.5 cm) or the 9 by 2-1/2 inch (22.9 by 6.4 cm) corrugations.

After long deliberation, it was decided to discount the 1966 (7) results in favor of the tests on full scale pipe, including those of Neill on 6 by 2 inch (15.2 by 5.1 cm) C.M.P. (3). It is judged that the WES tests did not adequately define the Reynolds number versus f curves for the 5, 10 and 20 ft. (1.52 m, 3.05 m, and 6.10 m) pipe models, at least at high values of Reynolds number. This may have been due to (1) lack of flow capacity to reach a high enough Reynolds number to attain the peak f, or (2) a basic lack of agreement between the model and the prototype due to a scale factor which was not recognized.

Possibly, the WES model of the 5 foot (1.52 m) pipe did reach a region of constant f with increasing Reynolds number. However, the scatter of the data is such that it is not possible to verify that the test series actually attained the peak f value. The model of the 10 ft. (3.05 m) and 20 ft. (6.10 m) pipes definitely did not reach their peak f values. Thus, while the WES pipe curves are utilized herein to help define the shape of the Reynolds number versus f curves, it seems clear that the earlier FHWA report did underestimate the maximum resistance factor for 6 by 2 inch (15.2 by 4.1 cm) and 3 by 1 inch (7.6 by 2.5 cm) C.M.P.

The methodology used by Silberman and Dahlin to define resistance values for annular C.M.P. in their 1971 SAF Report (6) was also evaluated. Due to the fact that only "peak" f values were considered and the effects of Reynolds number were discounted, the equations developed are judged deficient to adequately define annular C.M.P. resistance over a range of flow conditions.

Therefore, a new method of systematizing and predicting annular C.M.P. resistance was needed.

Full-Size Hydraulic Tests of Structural Plate C.M.P.

In Neill's studies of full-size 60-inch (1.52 m) structural plate C.M.P. (3), most of the tests were performed under partly full flow conditions, making an accurate resistance factor determination difficult. All tests in the first series were in a free-surface condition; however, two tests in the second series were in a full-flow condition owing to the submerged outlet. The resistance factors, in terms of the Darcy f, averaged about 0.14 which seemed high when compared with other estimates.

In Bossy's discussion (16) of Neill's paper, the following three suggestions were given to explain the possible over-estimation of the resistance coefficients:

- The nominal diameter (5.0 ft. or 1.52 m) was used in resistance coefficient calculations rather than the actual diameter (4.93 ft. or 1.50 m).

- The weir coefficient used in determining flow rate may be too low, resulting in an under-estimation of Q.

- The free surface determinations of n include inlet and outlet effects that increase the apparent slope of the water surface profiles.

Neill, in his closure (17), presents revised resistance coefficients based on the true pipe diameter. The following f values were computed for full flow tests S2 and S3, including bolt and seam effects, and without correction of the weir coefficient:

Test	Velocity ft./sec.	Velocity m/sec.	N_{Rw}	Revised f
S2	6.91	2.11	13,000	0.130
S3	7.60	2.32	14,400	0.132

The Bauer Engineering tests (9) were conducted on a completely submerged full-size 6- by 2-inch (15.2 by 5.1 cm) structural plate C.M.P., 1,526 feet (465.1 m) long and 14 feet (4.3 m) in diameter. Two flow rates, based on the capacity of the power plant intake pumps, were studied. The flow rates were determined from velocity-distribution measurements obtained from both horizontal and vertical scans for the lower flow rate and from a horizontal scan only for the higher flow rate. Most velocity-distribution measurements were derived from current meter readings, but a pitot tube was also used in the horizontal scans as a check.

The total head loss, including pipe friction as well as minor inlet, bend, and outlet losses, was determined by measuring the difference between the water levels upstream and downstream of the pipe. Flow rates for the two tests were quite low, 338 cfs (9.6 m^3/sec) and 540 cfs (15.3 m^3/sec). These represent $Q/D^{2.5}$ values of 0.46 and 0.74 respectively.

A subsequent analysis of the Bauer data by the BPR (now the Federal Highway Administration) staff produced higher f values. The main modification in the re-analysis was in the evaluation of the minor loss velocity head coefficients, which appeared to have been overestimated in the Bauer report. The overestimation of the minor losses caused an underestimation of the pipe friction head loss, producing a low f value. The revised f values computed by the BPR staff were 0.0675 for the low flow tests and 0.0650 for the high flow test. The high flow test is suspect, because only one velocity scan was made and because the data exhibit a downward trend at low, increasing, values of wall Reynolds number (N_{Rw}), whereas all other data show an opposite trend.

Silberman and Dahlin (6) conducted full scale laboratory controlled tests of a 66-inch (1.68 m) (nominal) circular C.M.P. with 9 by 2-1/2 inch (22.9 by 6.4 cm) corrugations. For comparison with other results on non-bolted pipes, bolt and seam effects were estimated ($\Delta f_{bolts} = 0.0051$, $\Delta f_{seams} = 0.0036$ at f peak) and deducted from the test results for purposes of comparison. This test shows total f to increase with N_{Rw} to a peak value of 0.137 at N_{Rw} = 16,000, including bolt and seam effects. Water temperatures were low, about 34^{o}F (1.1 ^{o}C) during this test series, which limited the attained Reynolds number to some extent.

Tests of full size structural plate C.M.P. are necessarily limited because of the large size of the conduits, which require high flow capacities. However, it would be beneficial to obtain further data for larger pipe sizes, perhaps through instrumentation of existing or planned installations. Until further information becomes available, the estimates of this manual should be adequate for design use.

Systematization of Available Data

The available experimental results emphasize the dependence of the annular C.M.P. resistance factor on the pipe Reynolds number, $N_R = VD/\nu$, where V is the mean velocity of flow, D is the pipe diameter, and ν is the kinematic viscosity of water. A comparison of available data shows that the Darcy f value for a particular pipe and corrugation shape probably first increases with increasing Reynolds number, peaks, and then declines with further Reynolds number increases. Whether the decline continues, in a manner similar to the "smooth pipe curve" or whether the f value will eventually reach a constant value with increasing Reynolds number is not clear at this time due to the lack of tests at high Reynolds numbers.

However, it was determined that the use of a wall Reynolds number, N_{Rw}, in place of the pipe Reynolds number, N_R, aided in systematizing the data, as the maximum value of the Darcy f would occur at about the same N_{Rw} for all pipe sizes with a given corrugation shape. For example, f values for all pipes with 2-2/3 by 1/2 inch corrugations peak at a N_{Rw} value of about 1600. (Further examination of the data by H. G. Bossy indicates that this is not exactly true, but should be close enough for practical purposes.)

The wall Reynolds number is defined as:

$$N_{Rw} = \frac{v^*k}{\nu} = \frac{(RS_f g)^{0.5}}{\nu} \qquad \text{(D1)}$$

Where,

v^* is the mean shear velocity, ft/sec. (m/sec) = $(RS_f g)^{0.5}$,

R is the hydraulic radius, ft. (m), = D/4 for full flow in circular pipes

S_f is the friction slope (slope of the total energy line), equal to the slope of the hydraulic grade line in pipes flowing full,

g is the gravitational acceleration, 32.16 ft./sec.^{2}, (9.80 m/sec^2)

k is the corrugation depth, ft. (m), and

ν is the kinematic viscosity, ft.^{2}/sec. (m^2/sec).

One reason for the differing views of the relationship between Reynolds number (or wall Reynolds number) and f is thought to be the fact that for any given set of flow tests, only a portion of the f versus N_{Rw} curve is seen. This is because the test results are governed by available flow capacity and head at the particular test facility. Thus, only a portion of the curve is obtained. This leads some investigators to conclude that their data indicate an increasing f with increasing Reynolds number, some a decreasing f, and some a constant f. Another problem is that data are restricted to a few, or even only one pipe diameter, for a corrugation type. In the past 10 years, only three new sets of data for annular C.M.P. are known to have been obtained.

The following table summarizes the available data on annular C.M.P. True dimensions are shown where available; otherwise nominal dimensions are presented. In some cases, peak f values or the N_{Rw} corresponding to the peak f value are not known. The estimated peak f values are unadjusted, first estimates. Also, bolt and seam effects have been removed by using the calculation method presented later in this appendix to facilitate comparisons between the several corrugations shapes.

TABLE D1

SUMMARY OF AVAILABLE TESTS ON ANNULAR C.M.P., WITH DIMENSIONS

Corrugation	D, ft	k, ft	c, ft	r_p, ft	D/k	c/k	c/r_p	Estimated Peak f	Estimated N_{Rw} at Peak f	Ref.
2 2/3 by 1/2 in	1.008	.04167	.2225	.0635	24.2	5.34	3.50	0.133	1330	4,5
	1.25	"	"	.066	30.0	"	3.37	.114	1830	3
	1.5	"	"	"	36.0	"	"	.1013	1420	2
	2.0	"	"	"	48.0	"	"	.0910	1580	2
	3.0	"	"	"	72.0	"	"	.0766	1790	1,2
	4.95	"	"	"	118.8	"	"	.064	1480	1
	7.05	"	"	"	169.2	"	"	.054	1540	1
	5.0[3]	.0468	.2224	.0658	106.8	4.75	3.38	.068	1640	7
6 by 1 in.	3.97	.0798	0.5	0.2093	49.8	6.26	2.39	-	-	6
	5.45	.0784	0.5	.2118	69.5	6.38	2.36	-	-	6
6 by 2 in.[1]	4.925	0.1667	0.5	0.1028	29.5	3.00	4.86	0.1215	>13,000	3
	4.925	"	"	"	"	"	"	.1235	>14,400	3
6 by 2 in.[4]	4.99	0.1665	0.4994	0.1074	30.0	3.00	4.65	-	-	7
	10.0	.156	.500	.104	64.1	3.21	4.81	-	-	7
	20.0	.157	"	.1025	127.4	3.18	4.88	-	-	7
9 by 2 1/2 in.[2]	5.38	0.207	0.75	0.1958	26.0	3.62	3.83	0.132	16,000	6

[1] Full scale, bolt effects deleted. 2 points only.

[2] Full scale, bolt effects deleted.

[3] Model. Corrugations not to scale.

[4] Models. No bolt effects included.

In order to study all data for annular C.M.P. on one plot, Figure D1 was prepared. The model test for the 5 ft. (1.52 m) pipe with 2-2/3 by 1/2 inch (6.8 by 1.3 cm) corrugations was deleted, since adequate information is otherwise available for these corrugations. The lines shown are curves which represent the data points from the respective references. No extrapolation beyond the available data has been performed.

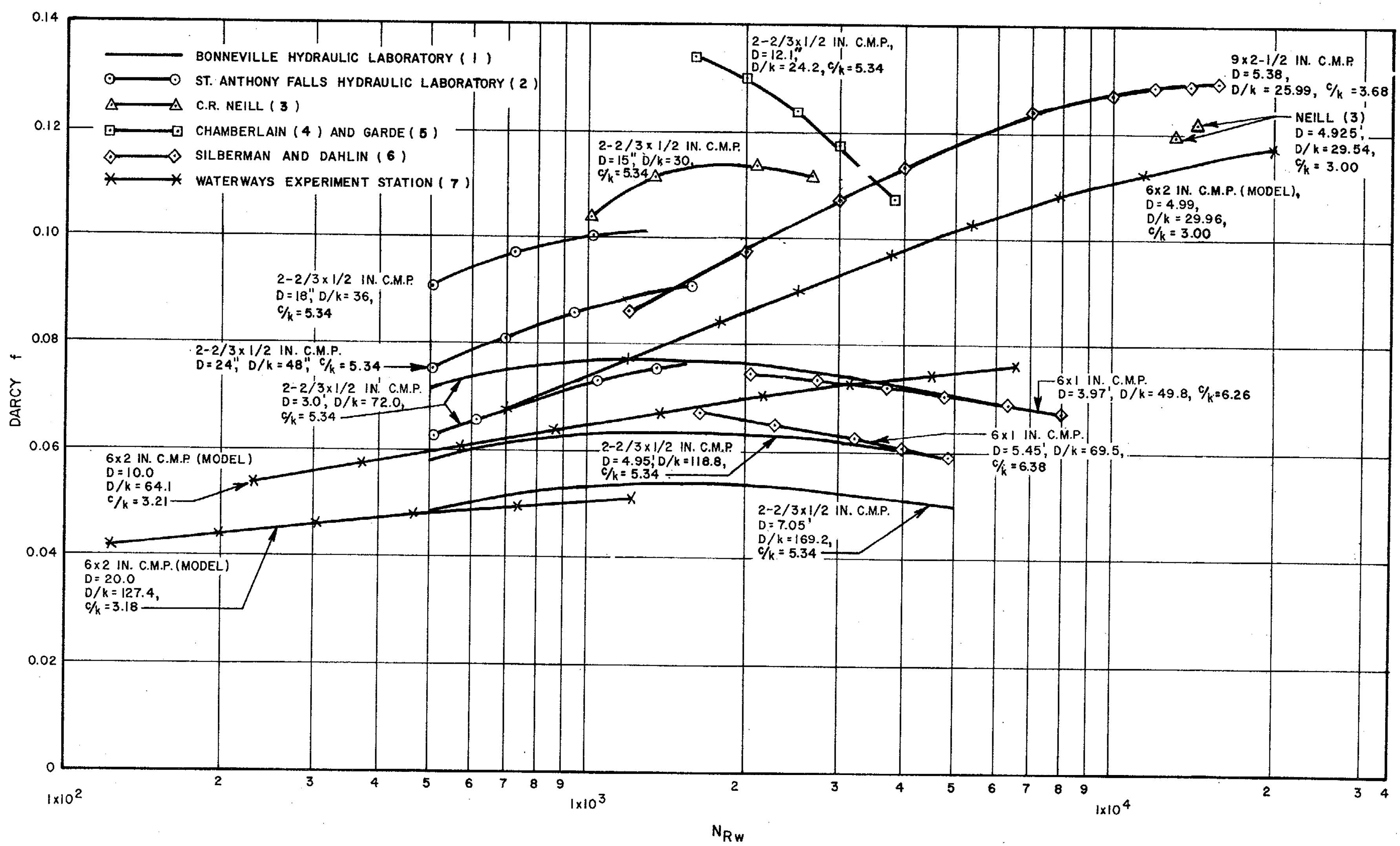
The curves of Figure D1 are based on wall Reynolds numbers computed from the true kinematic viscosity, ν, of the water during each test. In applying the relationships of figure 1 to general solutions, it is convenient to use an average kinematic viscosity for water, at a temperature of $60^{\circ}F$, for which,

$$\nu = 1.217 \times 10^{-5} \ ft^2/sec. \qquad (1.1305 \times 10^{-6} \ m^2/sec)$$

This is permissible as it can be shown that differences in water temperature of $\pm 10^{\circ}F$ ($\pm 5.6^{\circ}C$) affect resistance factors by insignificant amounts.

From Figure D1, it is obvious that peak f values must occur at different values of wall Reynolds number for different corrugation shapes. Since it would be desirable to utilize all available data in defining the shapes of the f vs. N_{Rw} curves, the next step was to estimate the N_{Rw} corresponding to the peak f value. After a great deal of trial and error, it was found that the N_{Rw} at peak f could be approximated by the line shown on Figure D2. Thus, the magnitude of N_{Rw} at peak f is indicated to be a function of the corrugation pitch to depth ratio. The development of this figure required discounting previously defined N_{Rw} at peak f magnitudes for the model 6 by 2 inch (15.2 by 5.1 cm) structural plate C.M.P. (7, 12). However, due to the good definition of peak f location for 2-2/3 by 1/2 inch corrugations and the fair definition for 9 by 2-1/2 inch corrugations, this seems justified.

As the next step, the available data on annular C.M.P. was plotted with a common peak f position, using the same log cycle scale as for the plots of Figure D1. (In all cases, the graph paper used was 2 cycle by 70 division semi-logorithmic paper. A 5 inch log cycle was used, and f was represented on a scale of 1 inch for a Δf of 0.02). Figure D3 shows the results of



D1 Darcy f Versus N_{Rw} for Annular Corrugated Metal Conduits, Based on Test Results

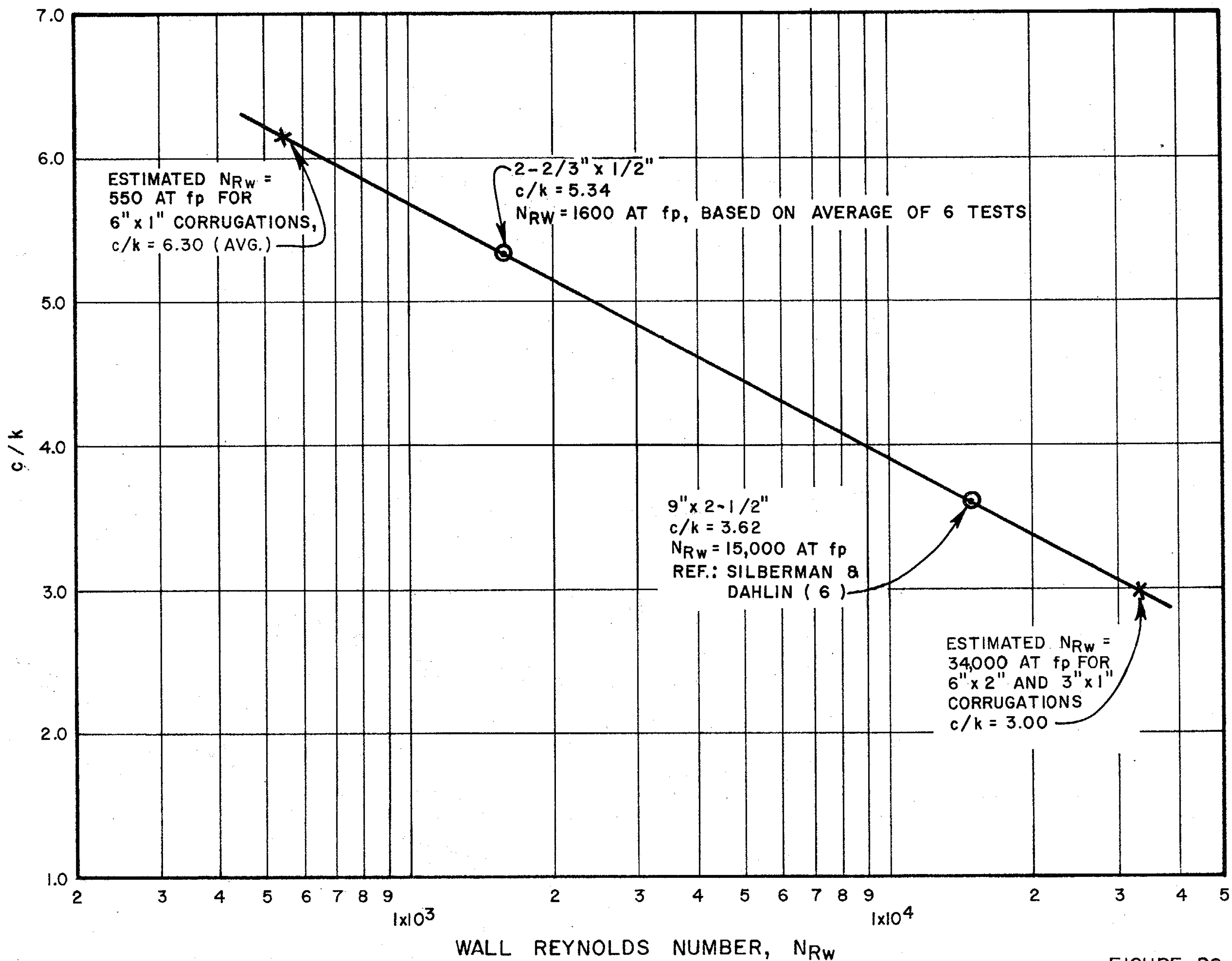


FIGURE D2

D2 Estimate of N_{Rw} at Peak Darcy f Values Based on Length to Depth Ratio of Corrugations (c/k)

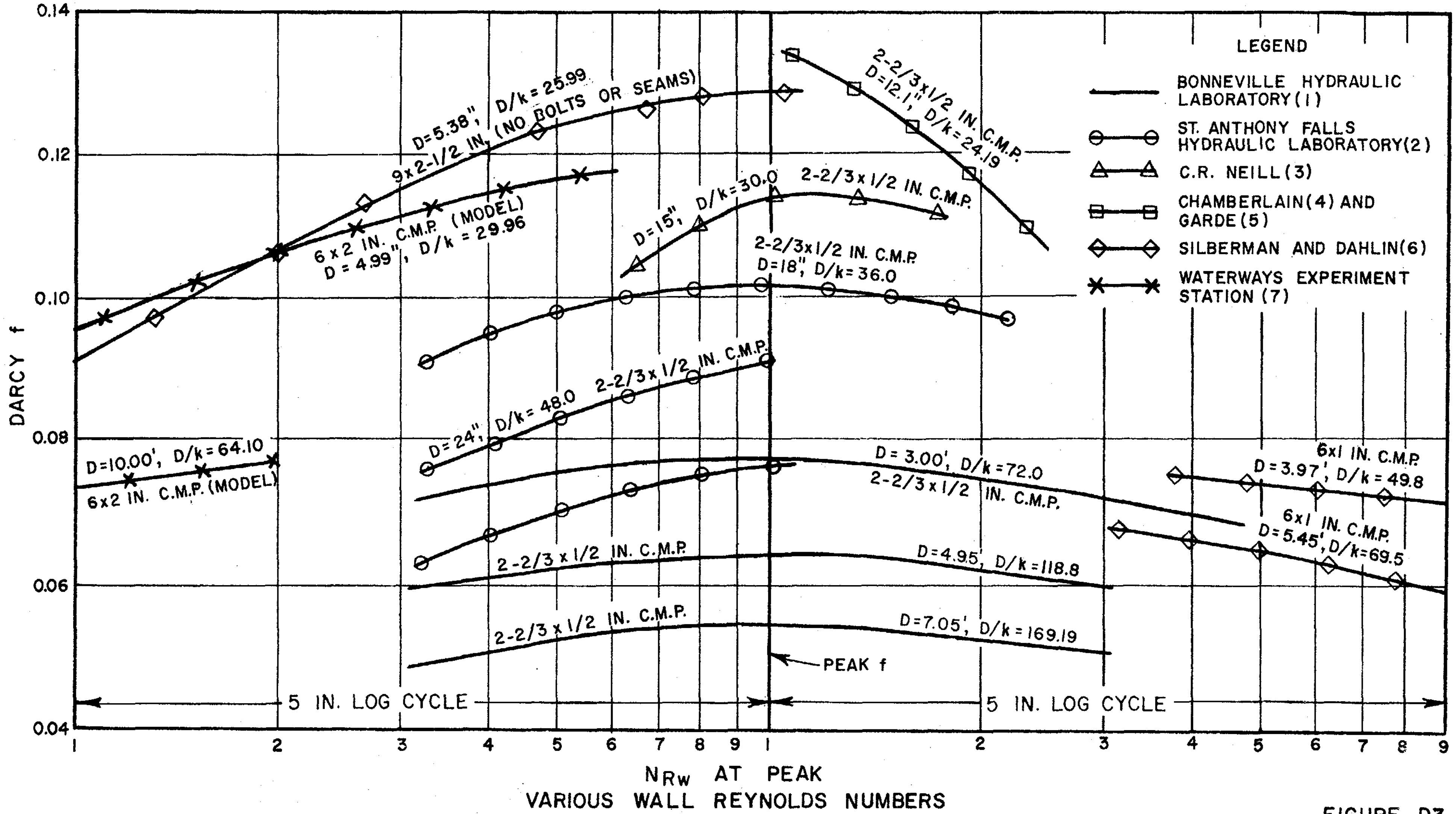


FIGURE D3

D3 Darcy f Versus N_{Rw} for Annular Corrugated Metal Conduits. All Curves Located to Place Peak of f Values at a Common N_{Rw} Value, Arbitrarily Selected as 1 this exercise. It is seen that a common trend exists, consisting of (1) increasing f with increasing N_{Rw} (2) a peak f, followed by decreasing f with increasing N_{Rw}. At higher N_{Rw} values, curves in that range seem to exhibit a declining pattern, thus tending to refute the constant f value after peak suggested in the WES report (7). Therefore, it was decided to assume that all corrugated pipes exhibit an increasing f with increasing N_{Rw}, followed by a peak and a decrease in f with further increases in N_{Rw}. The curves of Figure D3 were later used to define the shapes of N_{Rw} vs. f curves for all annular C.M.P.

From Figure D3, it is also seen that the curves for the smaller D/k values are more peaked in shape than those for the lower Darcy f values. This phenomenon is incorporated into the later development of the design N_{Rw} versus f curves.

In order to further systematize the available data, peak f values (f_p) versus relative roughness (using D/k to eliminate small decimal numbers) were examined for all existing C.M.P. data. Since the most complete data over a range of relative roughnesses are for the 2-2/3 by 1/2 inch (6.8 by 1.3 cm) corrugations, this corrugation was used as a basis to define the slope of the f_p vs. D/k curves. Then, other estimated peak f values for 6 by 1 inch (15.2 by 2.5 cm), 6 by 2 inch (15.2 by 5.1 cm), and 9 by 2-1/2 inch (22.9 by 6.4 cm) C.M.P. were used to develop the spread between Darcy f for various corrugation shapes, and the f_p vs. D/k curves for other shapes.

To define the shape of a corrugation, at least three dimensions are necessary: the pitch (c), the depth (k), and the radius of the inside corrugation crest (r_p). (It is not judged that the radius of the corrugation valley is as important.) To determine which factors were most important in defining peak f values, multiple variate correlation analyses were performed. These analyses, in conjuction with graphical studies by hand, resulted in the conclusion that the ratio c/r_p gives the best estimate of the incremental f (Δf) value at the peak for different corrugation shapes.

As a result of these analyses of all available C.M.P. data on peak Darcy f values, it was determined that the equation:

$$f_p = 0.2788\ (D/k)^{-0.4021}\ (c/r_p)^{0.356} \text{ - - - - - - - - - - - - - - } (D2)$$

represents all the peak f data well from D/k = 36.0 upward.

Below D/k = 36.0, the data appear to curve upward with decreasing D/k, so in the range from D/k = 24.0 to D/k = 36.0, the f_p vs. D/k curves were adjusted based on the data for 2-2/3 by 1/2 inch C.M.P., and the f_p values from Equation D2.

The results of these analyses are depicted in Figure D4, which is plotted on a log-log scale. While the lines appear to be parallel, they actually converge with increasing values of D/k. Note that the f_p values of Figure D4 exclude bolt and seam resistance.

Development of N_{Rw} Versus f Curves for Various Corrugation Shapes

In order to develop standardized f vs. N_{Rw} curves for the corrugations of interest, Figures D2, D3, and D4 were utilized. First, the N_{Rw} corresponding to the peak f for the given corrugation shape is obtained from Figure D2, based on the ratio of c/k.

Second, peak f values are obtained for the various pipe sizes of interest from Figure D4, using the calculated D/k values. (If no curve is given on Figure D4 for the corrugation of interest, utilize Equation (D2) to develop a new curve.)

Next, using a semi-logarithmic graph paper with 5 inch cycles, plot the peak f values at the N_{Rw} value obtained from Figure D2. Be sure to use a vertical scale of 1 inch = 0.02 (Δf) so that the curve shapes can be sketched to approximate the curves of Figure D3.

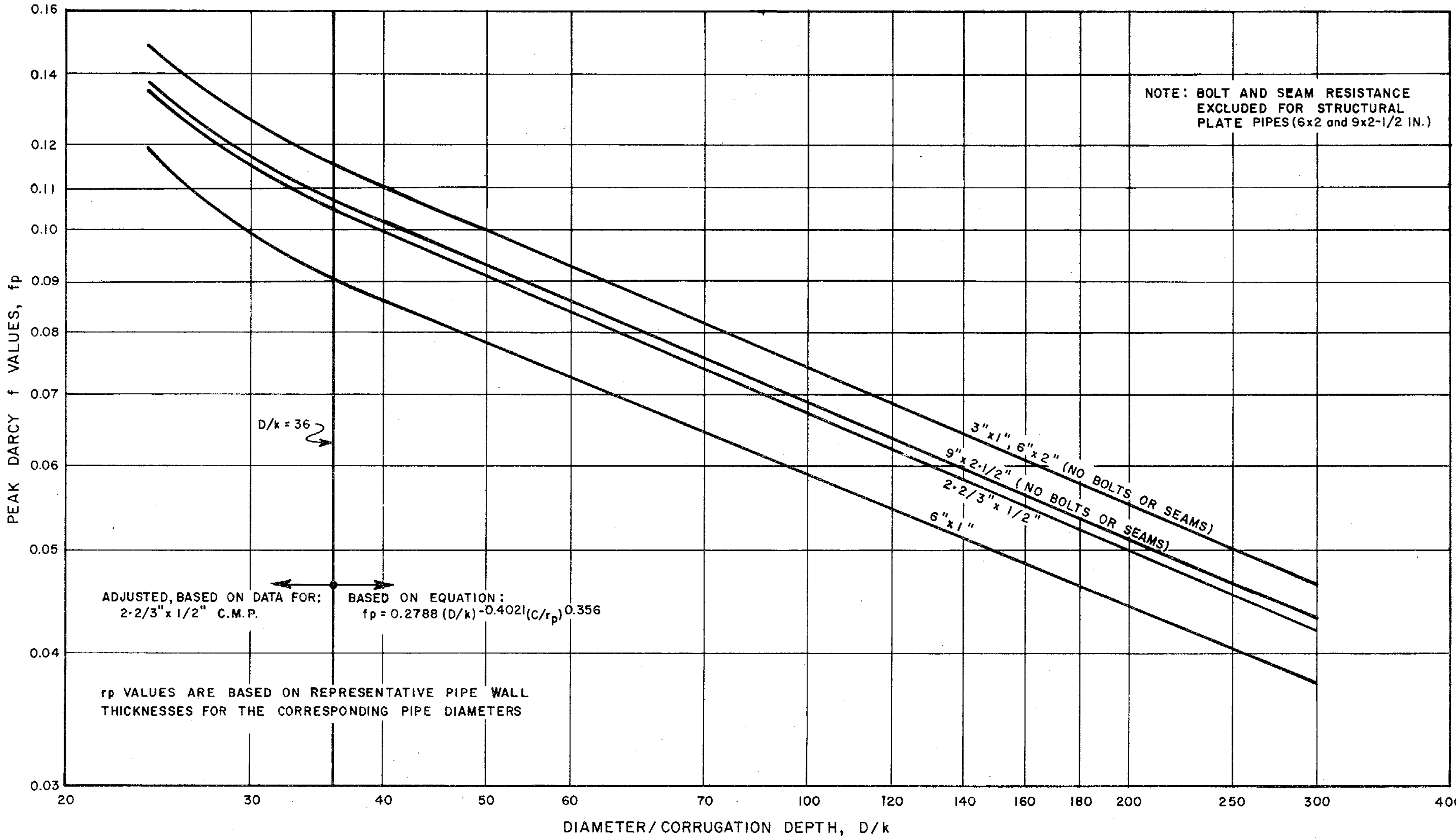


FIGURE D4

D4 Estimated Peak Darcy f Values - Annular Corrugated Metal Pipes

Then, sketch in the f vs N_{Rw} curves using Figure D3 as a guide for shape. Use curves for corrugations with a shape similar to the corrugations of interest. It is suggested that the c/k and c/r_p parameters be used as the basis of comparison between corrugation shapes.

The above steps have been performed for the following corrugations:

Corrugation Shape Pitch by Depth, inches	Figure
2-2/3 by 1/2 inch	D5
6 by 1 inch	D6
3 by 1 inch	D7
6 by 2 inch	D8
9 by 2-1/2 inch	D9

The partly full flow curves of Figures D5-D9 were derived by using the effective diameter,

$$D_e = 4R$$

when R is the hydraulic radius of the partly full flow prism. A relative depth (d/D) of 0.75 was used to develop the partly full flow curves of Figures D5-D9 because the corresponding hydraulic radius represents the range of depths from d/D = 0.7 to d/D = 0.9 very well. Then, the peak f value is obtained from Figure D2, using $D/k = D_e/k = 4R/k$.

<u>Derivation of Darcy f Design Curves</u>

Figures 2 through 5 of the main text were obtained from Figures D5 through D9 of this Appendix, using the following relationship for N_{Rw}:

$$N_{Rw} = \frac{(f)^{0.5} \ (Q/D^{2.5}) \ (D)^{0.5} \ (k)}{2.828 \ (A/D^2) \ \nu} \quad \text{--------} \quad \text{(D3)}$$

Equation D3 was derived from Equation D1, as follows:

$$N_{Rw} = \frac{V^*k}{\nu} = \frac{(R \ S_f \ g)^{1/2}}{\nu} \quad \text{---------------} \quad \text{(D1)}$$

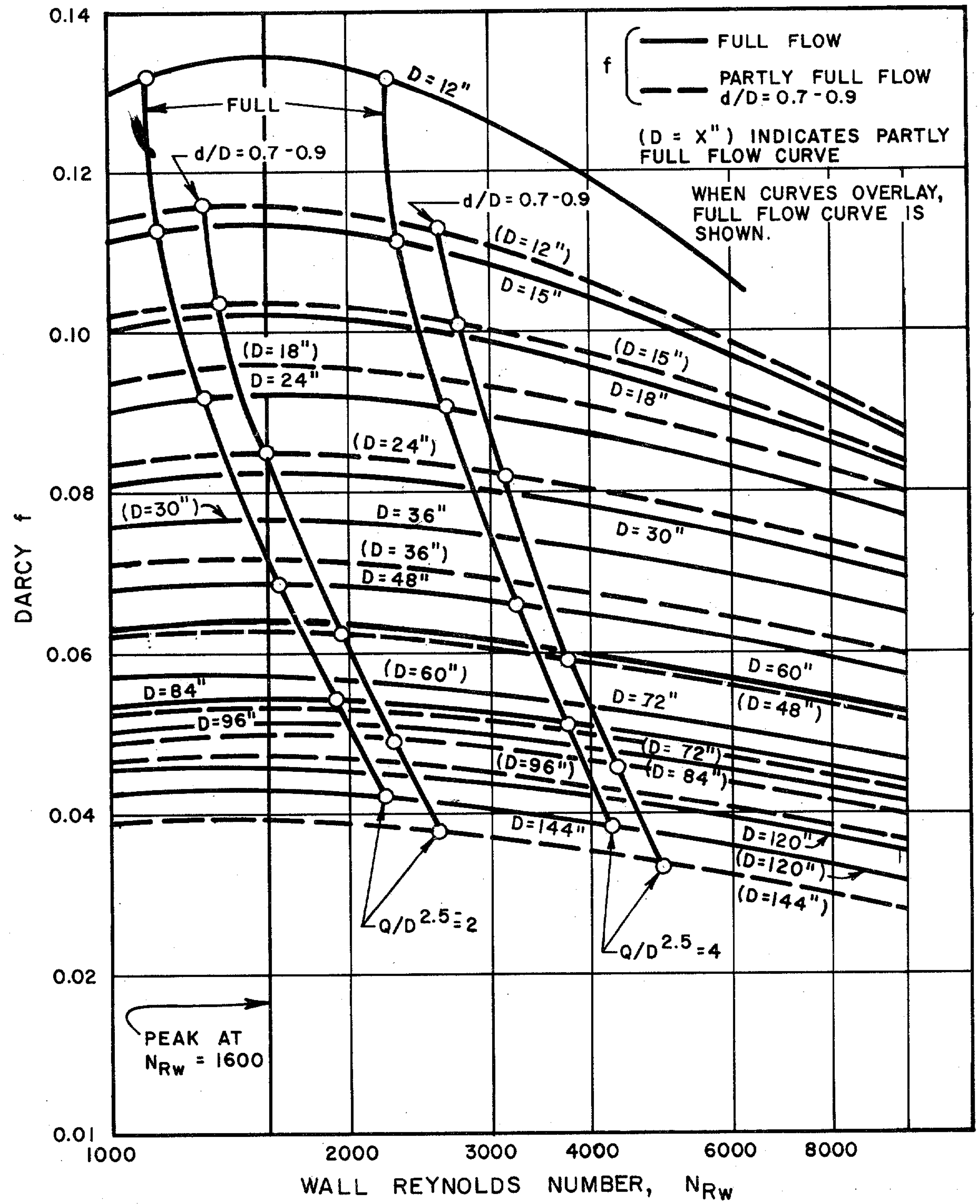


FIGURE D5

D5 Darcy f Versus N_{Rw} for 2-2/3- by 1/2-inch Annular Corrugated Metal Pipe

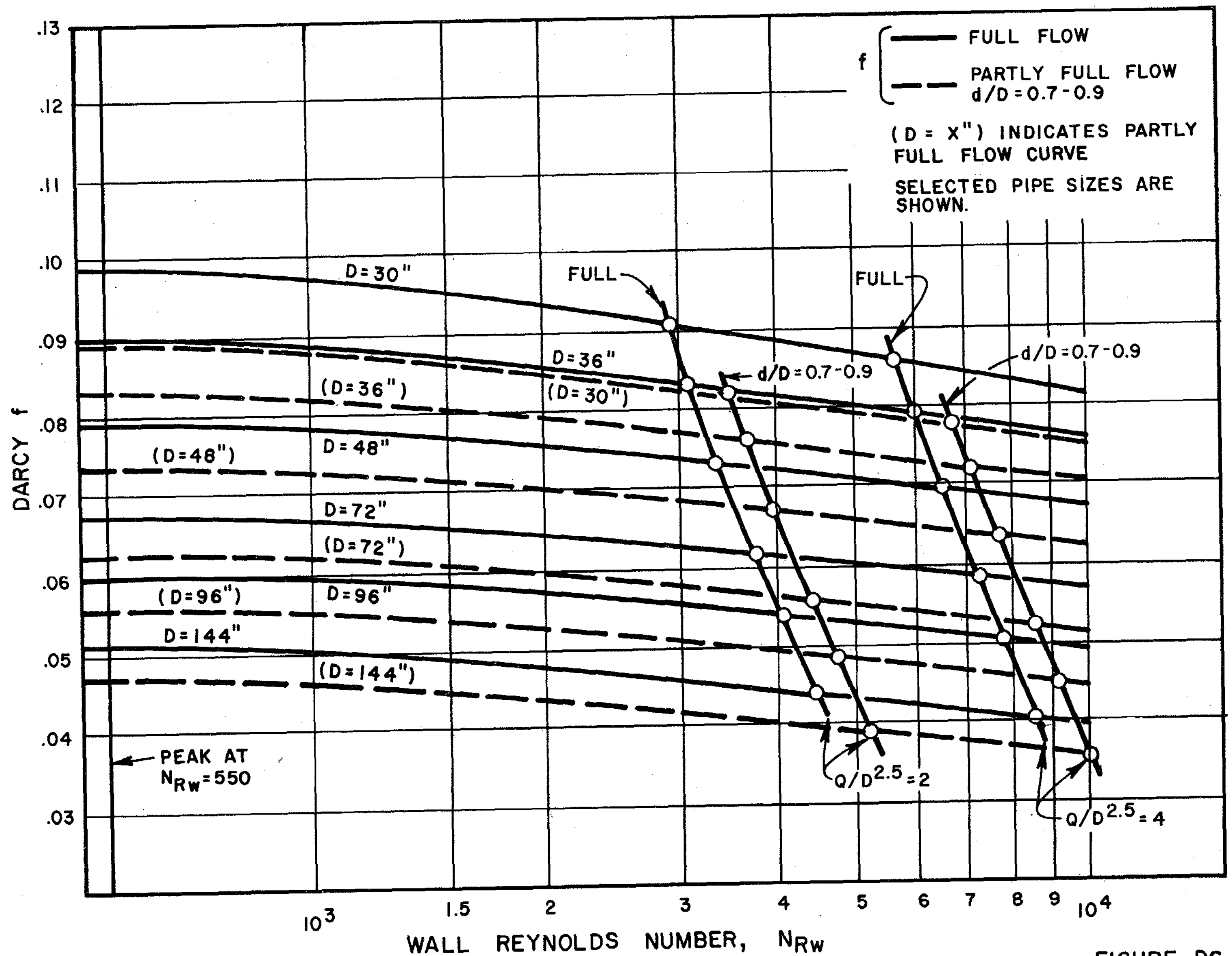


FIGURE D6

D6 Darcy f Versus N_{Rw} for 6- by 1-inch Annular Corrugated Metal Pipe

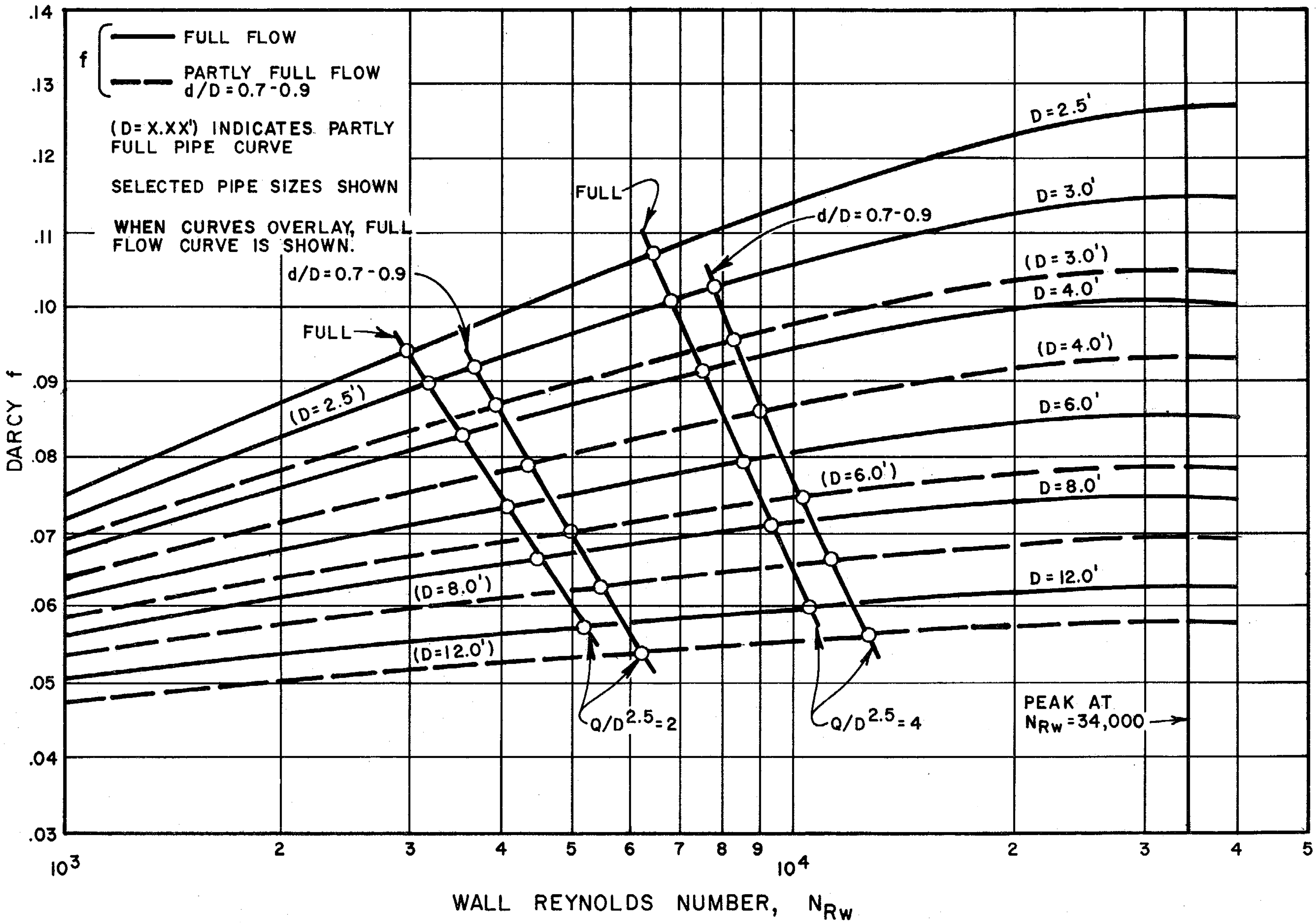


FIGURE D7

D7 Darcy f Versus N_{Rw} for 3- by 1-inch Annular Corrugated Metal Pipe

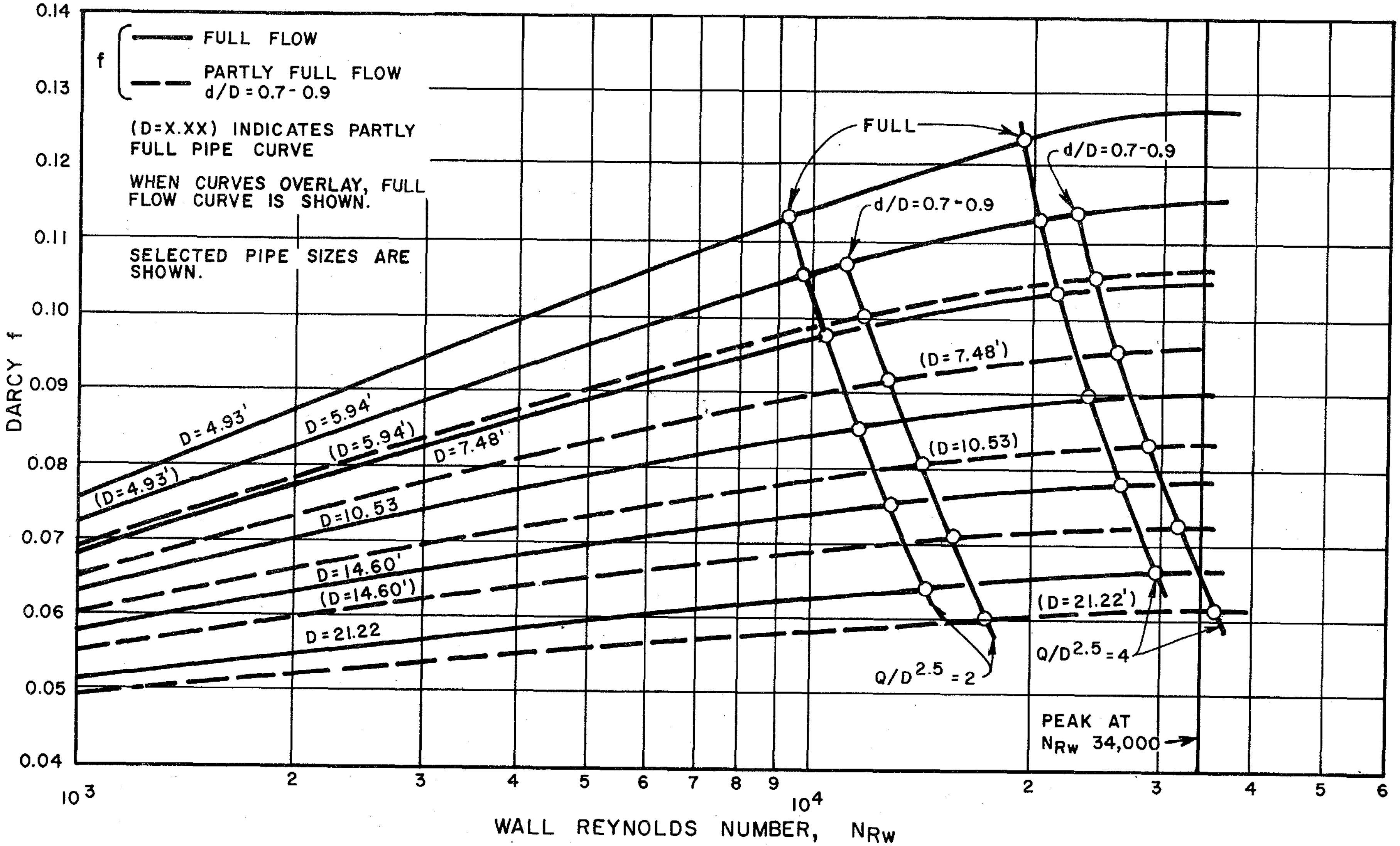


FIGURE D8

D8 Darcy f Versus N_{Rw} for 6- by 2-inch Annular Structural Plate Corrugated Metal Pipe (No Bolt or Seam Resistance Included)

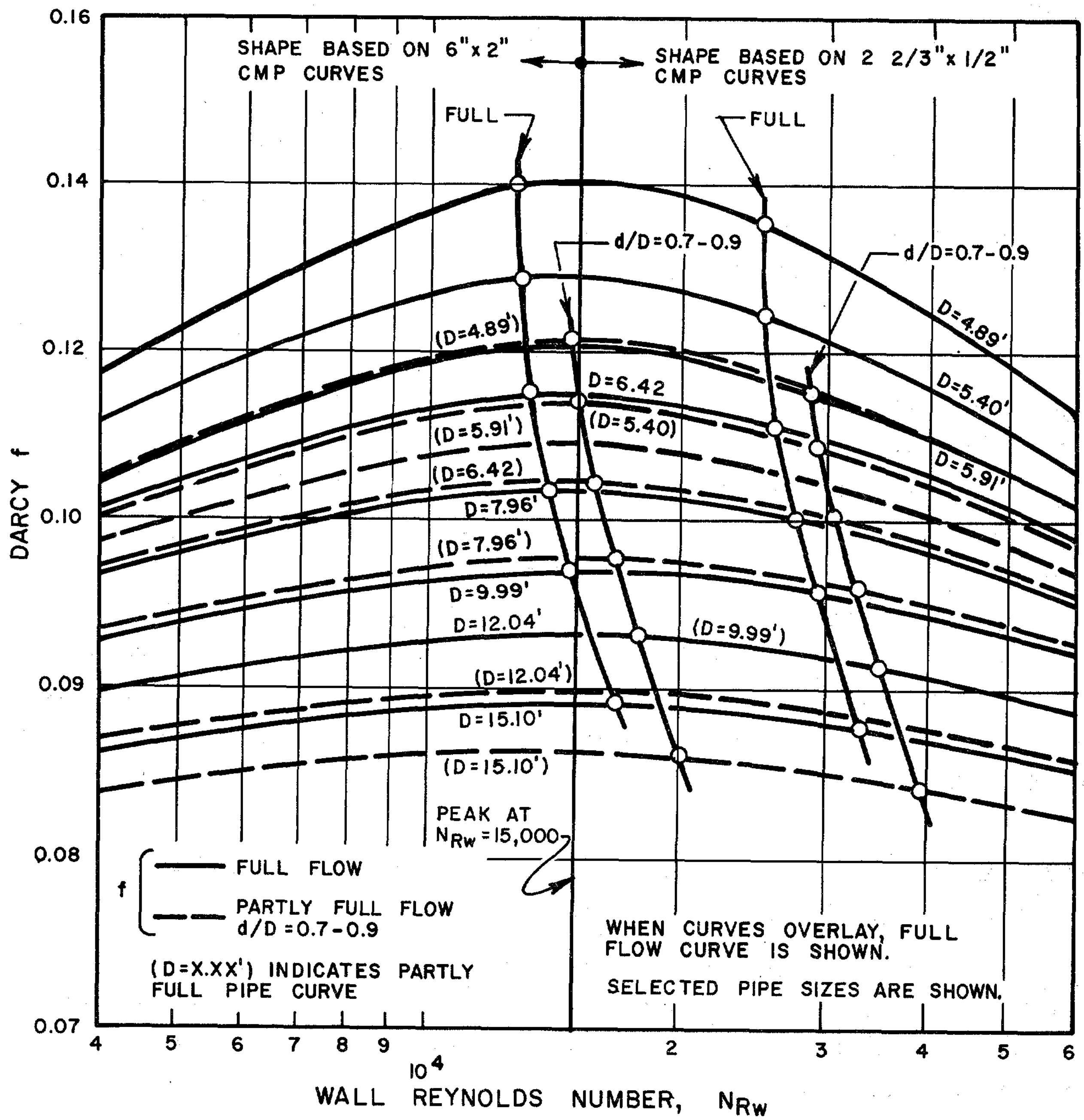


FIGURE D9

D9 Darcy f Versus N_{Rw} for 9- by 2-1/2-inch Annular Structural Plate Corrugated Metal Pipe (No Bolt or Seam Resistance Included)

From the Darcy equation, $S_f = \frac{h_f}{L} = \frac{f}{4R}\ \frac{V^2}{2g}$ if D is replaced by the equivalent diameter, 4R. Substituting into Equation D1,

$$N_{Rw} = \frac{f^{0.5}\ V\ k}{2.828\ \nu} = \frac{f^{0.5}\ Q\ k}{2.828\ A\nu} \quad \text{- - - - - - - - - - - - -} \quad \text{(D4)}$$

Using dimensionless terms, Equation D4 is transformed into Equation D3. The above terms are defined in Appendix B.

From the f vs N_{Rw} curves of Figures D5-D9, the values of f for various pipe diameters flowing full and partly full at $Q/D^{2.5}$ values of 2.0 and 4.0 can be determined using Equation D3. A trial and error procedure is required, where N_{Rw} is estimated, f is computed, and the resultant f is compared with the N_{Rw} curve for the particular diameter. The steps are then repeated until the desired accuracy is obtained. The values obtained by this process are connected by the steeply sloped lines, labeled $Q/D^{2.5}$ = 2 and 4, Full and Partly Full, in Figures D5-D9. The intercepts of the two curves for flow and diameter are the source of the f versus diameter curves of Figures 2 through 5, after bolt and seam resistance estimates are added. Note that Figures D5-D9 do not include bolt or seam effects.

Bolt Resistance in Annular Structural Plate Corrugated Metal Pipes

The resistance of bolt heads or nuts on the inside crests of corrugations must be considered for the structural plate pipes having 6- by 2 inch and 9- by 2-1/2 inch corrugations. It was assumed that bolt heads or nuts in corrugation troughs do not affect resistance. The methods presented by Bossy in Appendix A of the WES report (7) were used in computing the Darcy resistance increment, Δf, caused by these isolated roughness elements, which must be added to the wall resistance to obtain the total f value. Bossy evaluates the resistance increment by the formula:

$$\Delta f = \frac{C_D\ N\ a \left(\frac{v}{V}\right)^2}{\frac{L}{D}\quad A} \qquad \text{(Full flow) - - - - - - - -} \quad \text{(D5a)}$$

$$= \frac{C_D\ N\ a \left(\frac{v}{V}\right)^2}{\frac{L}{4R}\quad A} \qquad \text{(Partly full flow) - - - -} \quad \text{(D5b)}$$

Where,

Δf is the incremental Darcy resistance factor.

C_D is the coefficient of drag, estimated to equal 1.1 for hexagonal nuts or bolt heads.

N is the average number of bolts per length L.

a is the projected area of one nut normal to flow.

v is the velocity near the wall at mid-height of a nut located on the crest of a corrugation.

L is the length of pipe being considered.

R is the hydraulic radius.

A is the flow area.

V is the mean flow velocity.

(Lengths are in feet (m), areas in square feet (m^2), and time is in seconds.)

In the main text of the WES report (7), page 14, it is shown that for 6-by 2-inch annular structural plate corrugated pipes, the local velocity remains nearly constant inward from the crests for a distance of 0.7 times the corrugation depth (which is much greater than the height of a bolt head or nut) and follows the relationship:

$$v = 5.5\, v^* \qquad \text{(D6)}$$

Where,

v is the local velocity, and

v^* is the shear velocity.

Also, as the resistance factors for structural plate corrugated pipes without bolts have already been estimated, the following relationship can be used:

$$\frac{V}{v^*} = \frac{8}{f} \qquad \text{(D7)}$$

Where V is the mean flow velocity.

These two equations permit derivation of the following relationship between the local velocity at the projecting nut and the mean velocity based on f (without bolts):

$$\left(\frac{v}{V}\right)^2 = 3.78f \qquad \text{(D8)}$$

For lack of better information, it was assumed that equation (D6), and therefore equation (D8), applies to the local velocity in 9- by 2-1/2 inch annular structural plate C.M.P., as well as to 6- by 2 inch structural plate C.M.P. Although this is probably not exactly true, it should be close enough for estimation of bolt resistance effects.

$$\Delta f = \frac{C_{D}\, N\, a\, (3.78f)}{\frac{L}{4R}\, A} \qquad \text{(D9a)}$$

$$= \frac{15.12\, C_D N\, a\, (R/D) f}{(A/D^2)\, D\, L} \qquad \text{(D9b)}$$

For the 6- by 2 inch structural plate corrugated pipes with nuts on the inside crests of both longitudinal and circumferential seams, the average number of crest bolts in a length, L, equal to the diameter, D, was computed. The average number of bolts in a length equal to D was determined from the total number at the inside crests in a length of 102 feet made up of twelve 8-foot plates and one 6-foot plate, producing a total of 13 circumferential joints.

For partly full flow, it was necessary to determine the number of bolt heads or nuts on corrugation crests that were actually submerged by the flow depth, d=0.75D, used here to represent a usual range of partly full flow depths (d/D = 0.7 to 0.9). At points where one of the longitudinal seams might or might not be submerged, depending on the orientation of the pipe, an average was used, which resulted in a fractional number of seams. This analysis was based on an equal spacing of longitudinal joints, which occurs in the optimum pipe sections with maximum area per number of circumferential plates.

In Figure 4 of the main text, the f versus D curves are shown for the 6- by 2-inch structural plate C.M.P. The discontinuities in the curves for pipes with bolts indicate changes in the number of plates used to fabricate the particular pipe, which results in an abrupt change in the number of bolts used in fabrication.

The procedure used to determine bolt resistance for the 9- by 2-1/2 inch structural plate C.M.P. was slightly different due to assembly differences between this pipe and the 6- by 2 inch structural plate C.M.P. First, the 9-by 2-1/2 inch structural plate C.M.P. has its circumferential seam bolts in the inside corrugation troughs, so these bolts are neglected. Also, each longitudinal seam has two bolts on each inside crest, instead of the single bolt used in the 6- by 2 inch structural plate C.M.P. Either aluminum or steel bolts and nuts can be used. The steel bolts are the same size as those used in the 6- by 2-inch structural plate C.M.P., but the aluminum nuts are shorter than the steel nuts, 11/16-inch (1.74 cm) compared to 13/16-inch (2.06 cm). The dimensions of the aluminum fasteners were used in the computation of the Δf for Figure 5; the bolt Δf should be increased by a small amount of about 0.0005 for steel nuts.

The curve discontinuities in Figure 9 for 9- by 2-1/2 inch structural plate C.M.P. are also due to changes in the number of plates used to construct the particular size pipe. One minor exception was made for partly full flow in the 14.59 (4.45 cm) and 15.10 foot (4.60 m) (true diameter) pipes. The 14.59 foot pipe has four joints submerged at d=0.75D whereas the 15.10 foot pipe has only two joints submerged. Rather than plot individual points for each of these pipes, an average number of bolts was used for both, resulting in the smooth curve designated 5 in Figure 5.

Seam Resistance in Structural Plate Corrugated Metal Pipes

In the structural plate C.M.P., the circumferential pipe seams normal to the flow direction create some resistance to flow. This resistance is a function of the thickness of the metal plates used to fabricate the conduit. The longitudinal seams should have little influence on resistance, and thus are neglected.

A modification of Equation (D9b) can be used to predict circumferential seam resistance, as follows:

$$\Delta f = \frac{15.12\ C_D\ N\ a\ (R/D)\ f}{(A/D^2)\ D \cdot L} \quad \text{-----------------} \quad (D9b)$$

Let N be the number of joints per length L,

a be the projected area of one seam normal to the flow, and

L be the distance between circumferential seams.

Since N is equal to 1.0, and a is equal to (p/D) (D) (t), where p is the wetted perimeter of the conduit, D is the diameter, and t is the thickness of the metal plate, in feet (meters). For a circular conduit, p/D = 3.1416 for full flow, and p/D = 2.0944 when d/D = 0.75.

Then, the Δf for seams is equal to:

$$\Delta f_{seams} = \frac{15.12\ C_D\ (p/D)\ t\ (R/D)\ f}{(A/D^2)\ L} \quad \text{-----------} \quad (D10)$$

For 6 by 2 inch (15.2 x 5.1 cm) structural plate C.M.P., L equals 7.85 feet (2.39 m) (based on 102 feet (31 m) of conduit made of twelve 8-foot (2.44 m) plates and one 6-foot (1.82 m) plate). For 9 by 2-1/2 inch (22.9 x 6.4 cm) structural plate C.M.P., L equals 4.79 feet (1.46 m).

The above development assumes that all circumferential joints are exposed to the local velocity; that is, they are not protected within corrugation valleys. Also, it is assumed that C_D equals 1.0 and that longitudinal seams do not contribute to hydraulic resistance.

Derivation of Manning n Design Curves

The Manning n curves of Figures 6 through 9 were derived by applying the following equation to the f values, including bolt and seam resistance, of Figures 2 through 5.

$$n = 0.0926\ (R)^{1/6}\ (f)^{1/2} \quad \text{- - - - - - - - - - - - - - - - -} \quad (D11)$$

This same equation is listed as Equation (5) in the main text. In this case, R is the hydraulic radius of the flow prism.

Summary of Procedure to Derive Design Curves for New or Untested Corrugation Types

1. Determine the N_{Rw} at peak f from Figure D2, using c/k for the corrugation of interest.

2. Determine the effective diameter, D_e, of the conduit in feet (m). For full circular pipes, this is the true diameter. For partly full circular pipes or for pipe-arches, D_e equals four times the hydraulic radius of the flow prism.

3. Determine the inverse of the relative roughness, D_e/k, where k is the corrugation depth in feet.

4. Enter figure D4 with the D_e/k ratio and read f from the curve for the appropriate corrugation type. This is the peak f value, which is the total f for riveted or welded C.M.P., and the wall f, excluding bolt and seam resistance, for structural plate C.M.P.

   Note: If a curve for the corrugations of interest is not included in Figure D4, compute the curve using Equation D2, and adjust the curvature below D/k = 36.0 based on the other curves.

$$f_p = 0.2788\ (D_e/k)^{-0.4021}\ (c/r_p)^{0.356} \quad \text{- - - - - - - - -} \quad (D2)$$

5. On a sheet of semi-logarithmic graph paper with 5 inch cycles, plot the peak f values at the appropriate N_{Rw} value.

6. Using Figure D3 as a guide, draw N_{Rw} vs. f curves through the points plotted in step 5. Use corrugations with a similar shape, based on c/k and c/r_p.

7. Based on Equation (D3), determine the relationships between N_{Rw} and f. (Q, conduit size, relative depth, A, and ν are either known or have been estimated).

8. By a trial and error procedure, using the relationship derived in step 7, determine the f and N_{Rw} values that intersect on the appropriate relative depth curve constructed in step 6. This is the desired Darcy f value for the specific corrugation type, conduit shape, flow rate, and depth of flow.

9. Determine the bolt resistance, Δf, for the structural plate pipe or pipe-arch, based on the number of crest bolts (do not include bolt heads or nuts in inside valleys of corrugations) submerged by the particular relative depth, using Equation (D9b).

10. Determine seam resistance using Equation (D10), based on the spacing of circumferential seams and the metal plate thickness.

11. Determine the total Darcy f by adding the wall resistance from step 8, the bolt resistance from step 9, and the seam resistance from step 10. Steps 9 and 10 apply only to structural plate conduits.

12. Convert the Darcy f to the Manning n by use of Equation (D11), if desired.

Examples of Use of Appendix D Curves

Example D1 - Use of N_{Rw} vs. f curves:

Given: A 14 foot (4.27 m) (nominal diameter) circular annular structural plate C.M.P. with 6 by 2 inch (15.2 by 5.1 cm) corrugations. Flow rates are 338 cfs (9.57 m^3/s) and 540 cfs (15.3 m^3/s).

Required: Determine the Darcy f values, including bolt and seam resistance, for this pipe at the above flow rates.

True diameter = 14.06 feet (4.29 m) from field test data.

From Equation (D2):

$$N_{Rw} = \frac{f^{0.5} \quad (Q)(k)}{2.828 \quad (A)(\nu)}$$

k = 2 inches = 0.1667 feet (5.1 cm)

$A = A/D^2 \ (D)^2 = 0.7854 \ (14.06)^2 = 155.3 \ ft^2 \ (14.43 \ m^2)$

$\nu = 1.215 \times 10^{-5} \ ft^2/sec. \ (1.131 \times 10^{-6} \ m^2/sec.)$

For Q = 338 cfs (9.57 m^3/s):

$$N_{Rw} = \frac{f^{0.5} \quad (338)(.1667)}{2.828 \ (155.3)(1.217 \times 10^{-5})}$$

$$= 10{,}542 \ (f)^{0.5}$$

For Q = 540 cfs (15.3 m^3/sec.):

$$N_{Rw} = 16{,}842 \ (f)^{0.5}$$

Using Figure D8 for 6 by 2 inch (15.3 by 5.1 cm) annular structural plate C.M.P., and interpolating between full flow curves for D = 10.53 feet (3.21 m) and D = 14.60 feet (4.45 m), sketch in a curve for D = 14.06 feet (4.29 m).

Then, using a trial and error procedure, determine the N_{Rw} and f intercepts on the curve constructed for D = 14.06 feet.

The results are as follows:

D,ft.	Q,cfs	N_{Rw}	f*
14.06	338	2718	0.0665
"	450	4456	0.0700

*No bolts or seams.

To estimate bolt effects, use Equation (D9a):

$$\Delta f = \frac{C_D\ N\ a\ (3.78\ f)}{\frac{L}{4R} \cdot A} \qquad \text{(D9a)}$$

where:
C_D = 1.1
N = 2256 bolts per 102 ft. (31.1 m) length of conduit
a = 0.0070 ft^2 (.00065 m^2) = area of one bolt head, normal to flow
L = 102 feet (31.1 m)
4R = D = 14.06 feet (4.28 m)
A = 155.3 ft^2 (14.42 m^2)

$$\Delta f_{bolts} = \frac{(1.1)(2256)(.0070)(3.78\ f)}{\left(\frac{102}{14.06}\right) 155.3}$$

$$= 0.0583\ f$$

Therefore, bolt resistance amounts to about 6 percent of the wall resistance for this structural plate conduit.

To estimate seam effects, use Equation (D10):

$$\Delta f_{seams} = \frac{15.12\ C_D\ (p/D)\ t\ (R/D)\ f}{(A/D^2)\ (L)}$$

Where, C_D = 1.0
p/D = 3.1416 for full flow
t = 0.0182 ft. (0.0055 m) (assumed)
R/D = 0.25 for full flow (Table C-2)
A/D^2 = 0.7854 for full flow (Table C-2)
L = 7.85 feet (2.39 m)

$$\Delta f_{seams} = \frac{(15.12)(1.0)(3.1416)(0.0182)(0.25)(f)}{(0.7854)\ (7.85)}$$

$$= 0.0351\ f$$

Seam resistance is about 3.5 percent of the wall resistance for this conduit, and the total bolt and seam resistance amounts to almost 10 percent of the wall resistance.

The total f values are:

D,ft.	Q,cfs	N_{Rw}	f	Δf_{bolts}	Δf_{seams}	f_{total}
14.06	338	2718	0.0665	0.0039	0.0023	0.0727
"	450	4456	0.0700	0.0041	0.0025	0.0766

These total f values are higher than those obtained by Bauer Engineering (9) for a pipe of the same size (0.0675 for Q = 338 cfs and 0.0650 for Q = 450 cfs, as interpreted by the BPR staff), but the difference is thought to be within an acceptable range of accuracy for comparisons between field measurements and independently developed design curves. Also, some of the factors used in the above development of losses are estimates of parameters not contained in the test data. The differences in pipe capacity due to using the calculated resistance versus the measured resistance would be 3.8 percent and 8.6 percent, respectively.

Example D2 - Derivation of Design Curves for an Untested Corrugation Type

Assume that 2 by 1/2 inch (5.1 by 1.3 cm) corrugated metal is used to fabricate annular C.M.P. as well as helical C.M.P. This corrugation shape has never been tested in annular C.M.P. The corrugations have the following dimensions:

c = 2 inches (5.1 cm)
k = 0.5 inch (1.3 cm)
r_v = 0.375 inch (0.95 cm)
t = 0.030 inch - 0.109 inch (0.076 - 0.277 cm)

The pipe will be fabricated in sizes from D = 1.0 ft (.305 m) to D = 8.0 ft. (2.44 m). Check the following specific sizes:

D, ft.	D, m.	t, in.	$r_p = r_v + t$, in.	D/k	c/k	c/r_p
1.0	.305	0.052	0.427	24	4.0	4.68
2.0	.61	0.064	.439	48	"	4.56
4.0	1.22	0.079	.454	96	"	4.40
8.0	2.44	0.109	.484	192	"	4.13

Note the r_p tends to increase with diameter due to increases in wall thickness.

Follow steps 1-12, at the beginning of this section:

1. Determine N_{RW} at peak f from Figure D2, using c/k for the corrugations of interest.

$$c/k = 4.0$$

From Figure D2, for c/k = 4.0, N_{Rw} at peak f = 9×10^3.

2. Determine the effective diameter, D_e, of the conduit.

For these conduits, assume that the nominal diameter equals the true diameter. Therefore, for full flow, $D_e = D$.

For partly full flow, use the hydraulic radius at d/D = 0.75 to represent the range from d/D = 0.7 to d/D = 0.9. From Table C-2, for d/D = 0.75, R/D = 0.3017. Therefore, R = 0.3017 D, and D_e = 4R (see table following step 4).

3. Determine D_e/k for each flow prism of interest (see table following step 4).

4. Enter Figure D4 with the D_e/k ratios and read f_p values, or compute f_p using Equation D2, $f_p = 0.2788\ (D_e/k)^{-.4021}\ (c/r_p)^{0.356}$.

   Since there is no curve for 2 by 1/2 inch corrugations, peak f values must be computed.

Full Flow				Partly Full Flow				
D,ft.	D_e/k	c/r_p	f_p	R,ft.	D_e,ft.	D_e/k	c/r_p	f_p
1.0	24	4.68	0.1480*	0.302	1.21	29.0	4.68	0.1285*
2.0	48	4.56	.1009	.603	2.41	57.8	4.56	.0936
4.0	96	4.40	.0754	1.21	4.84	116.2	4.40	.0698
8.0	192	4.13	.0558	2.41	9.64	231.4	4.13	.0517

5. On a sheet of semi-logarithmic graph paper with a 5 inch log cycle, plot peak f values at the appropriate N_{Rw} value.

   At f_p, N_{Rw} = 9,000, from step 1 (see following graph).

6. Using Figure D3 as a guide, draw N_{Rw} vs. f curves through the peak f points plotted in step 5.

   The 6 x 2 inch corrugates have a similar c/r_p ratio, and their c/k is approximately the same. Therefore, Figure D8 for 6 x 2 inch corrugations is also used as a guide for this step (see the following graph).

7. Based on Equation (D3), determine the relationship between N_{Rw} and f.

$$N_{Rw} = \frac{(f)^{0.5}(Q/D^{2.5})(D)^{0.5}(k)}{2.828\ (A/D^2)\ \nu} \quad \text{(D3)}$$

For example, determine f for $Q/D^{2.5} = 2.0$, full flow ($A/D^2 = .7854$) and partly full flow ($A/D^2 = 0.6318$), with $\nu = 1.217 \times 10^{-5}$ ft^2/sec ($T = 60^{o}F$), and k = 0.5 inch = 0.0417 ft.

For full flow:

$$N_{Rw} = \frac{(f)^{0.5}(2.0)(D)^{0.5}(0.0417)}{2.828\ (0.7854)(1.212 \times 10^{-5})}$$

$$= 3{,}085\ (f)^{0.5}(D)^{0.5}$$

For partly full flow (d/D = 0.75):

$$N_{Rw} = \frac{(f)^{0.5}(2.0)(D)^{0.5}(.0417)}{2.828\ (0.6318)(1.217 \times 10^{-5})}$$

$$= 3{,}835\ (f)^{0.5}(D)^{0.5}$$

8. Using a trial and error procedure, with the relationships from step 7, determine the f and N_{Rw} values that intersect on the appropriate curve from step 6. For example, for the 1 foot pipe flowing full:

Trial	N_{Rw}	Estimated f	Computed N_{Rw}	Corresponding f
1	$3085\ (f)^{0.5}$	0.1180	1059	0.1075
2	"	.1075	1011	.1062
3	"	.1062	1005	.1060
4	"	.1060	1004	.1060

By a similar process, the following N_{Rw} and f values were determined and plotted on the following graph, all for $Q/D^{2.5} = 2.0$.

D,ft.	d/D	N_{Rw}	Darcy f	R,ft.*	$R^{1/6}$*	Manning n*
1.0	1.0	1004	0.1060	0.250	0.794	0.0239
1.0	0.75	1215	.1005	.3017	.819	.0240
2.0	1.0	1271	.0850	.500	.891	.0241
2.0	0.75	1557	.0825	.603	.919	.0244
4.0	1.0	1610	.0682	1.0	1.0	.0242
4.0	0.75	1954	.0650	1.207	1.032	.0244
8.0	1.0	2020	.0537	2.0	1.122	.0241
8.0	0.75	2419	.0498	2.414	1.158	.0239

*See step 12.

9. Determine bolt resistance, using Equation (D9b).

   Not applicable, no bolts in this conduit.

10. Determine seam resistance, using Equation (D10).

    Not applicable, seams are negligible in riveted or welded C.M.P.

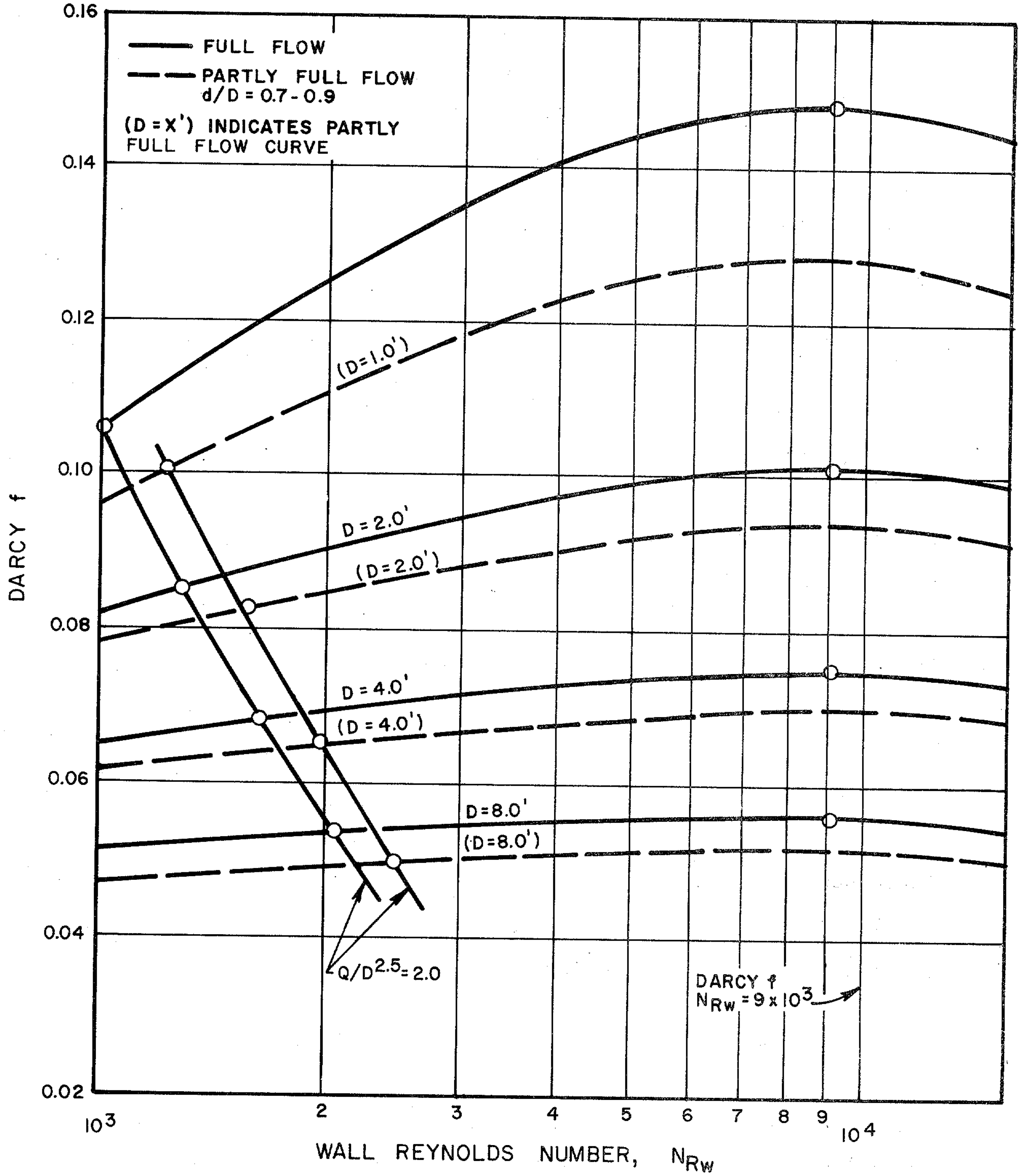
11. Determine the total Darcy f by adding the results from steps 8, 9, and 10.

    Since steps 9 and 10 are not applicable, step 8 yields the total Darcy f value.

12. Convert the Darcy f to the Manning n by use of Equation (D11):

$$n = 0.926\ (R)^{1/6}\ (f)^{1/2} \quad \text{- - - - - - - - - - - - - - - - -} \quad (D11)$$

For the results, see the table in step 8. That table contains the Darcy f and Manning n resistance coefficients for this hypothetical C.M.P., at $Q/D^{5/2} = 2.0$. Values for other flow rates can be developed in a similar fashion. Then, the f and n values can be plotted versus diameter as in Figures 2 through 9 of the main text.



EXAMPLE D2

DARCY f VERSUS N_{Rw} FOR 2 BY 1/2 INCH ANNULAR CORRUGATED METAL PIPE

HELICALLY CORRUGATED METAL PIPES

Background Information

The handbook of the American Iron and Steel Institute (AISI) (18) presents a range of f values for different pipe diameters that were obtained from flow tests in which air was used as the fluid. However, the reason for the range of values is not explained and no indication of the Reynolds numbers of the tests is presented. Chamberlain (4) tested 12-inch (0.305 m) helically corrugated metal pipe with 2- by 1/2-inch (5.1 by 1.3 cm) corrugations in conjunction with his sediment transport studies. No systematic variation with Reynolds number changes was detected, and the mean f value was determined to be 0.040. Rice (9) conducted flow tests on 8-inch (0.203 m) and 12-inch (0.305 m) helically corrugated metal pipe with 1-1/2- by 1/4-inch (3.8 by 0.64 cm) and 2- by 1/2-inch (5.1 by 1.3 cm) corrugations respectively, and a decline in f with increasing Reynolds number was detected in the 8-inch pipe.

Silberman and Dahlin conducted the following tests on helically corrugated metal pipes at the University of Minnesota, St. Anthony Falls Hydraulic Laboratory:

Pipe Size, Nominal, (in.)	(cm)	Corrugation Shape Pitch by Depth (inches)	(cm)	Strip Width (inches)	(cm)	Reference
12	30.5	2 x 7/16	5.0 x 1.1	20	51	10
18	45.7	2 x 7/16	5.0 x 1.1	20	51	10
24	61.0	2 x 1/2	5.0 x 1.3	20	51	10
48	121.9	2 x 1/2	5.0 x 1.3	20	51	6
12	30.5	2-2/3 x 7/16	6.8 x 1.1	24	61	6
48	121.9	2-2/3 x 1/2	6.8 x 1.3	24	61	6
12*	30.5*	2-2/3 x 7/16	6.8 x 1.1	24	61	11
24*	61.0*	2-2/3 x 1/2	6.8 x 1.3	24	61	11

*Re-corrugated annular rings on pipe ends.

The last two tests served to verify the earlier results, and the principal finding was that the re-corrugated end sections cause an increase of 10.5 percent in Darcy f and an increase of 6 percent in the Manning n value. The results from Reference 11 are not discussed further here.

Figure D10 contains plots of Darcy f versus Reynolds number for the pipe sizes and corrugations tested. It will be seen that the f value tends to decrease and then reach a constant value with increasing Reynolds Numbers.

Derivation of Darcy f Design Curves

To develop Figure 10 of the main text, Reynolds number values were computed for each pipe for $Q/D^{2.5}$ values of 2 and 4, and the f values read from the curves of Figure D10. In the plots of Figure 10, some curve smoothing was performed. For example, the results for the 24 inch (0.61 m) pipe with 2-2/3 by 1/2 inch (6.8 by 1.3 cm) corrugations were disregarded, since they seem out of line when compared with all other results. The potential error is not serious, on the order of seven percent, should the test results for the 24-inch pipe actually be correct.

Derivation of Manning n Design Curves

Figure 11 of the main text was developed by converting the Darcy f values to Manning n values, using Equation (D11).

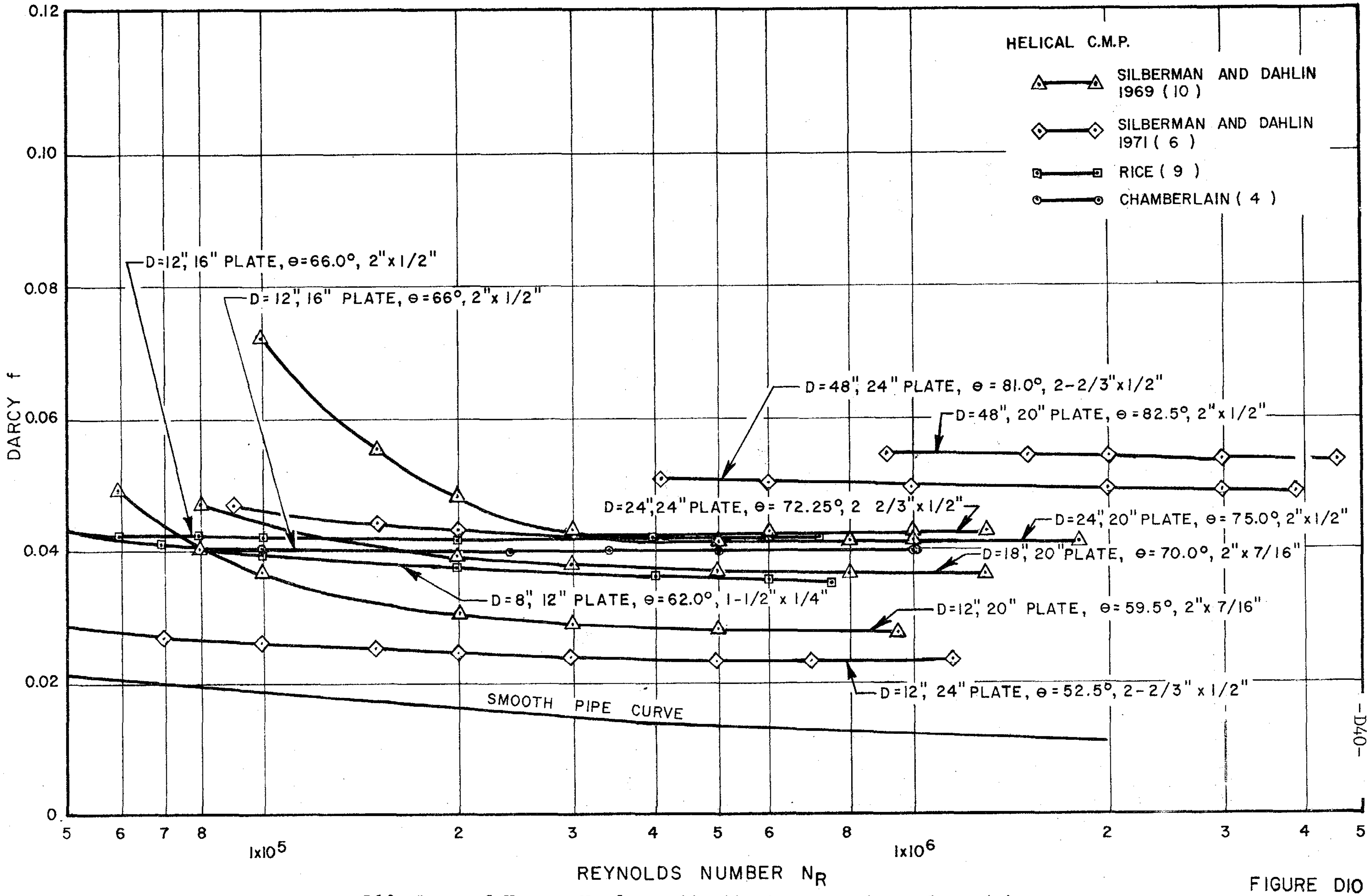


FIGURE D10

D10 Darcy f Versus N_R for Helically Corrugated Metal Conduits

APPENDIX E - CONVERSION FACTORS - ENGLISH UNITS TO SI UNITS

To Convert From	To	Multiply By
Degree	Radian	0.017453
Foot	Meter	0.3048
$Foot^{1.5}$	$Meter^{1.5}$	0.168276
$Foot^{2}$	$Meter^{2}$	0.092903
$Foot^{2.5}$	$Meter^{2.5}$	0.05129
Foot/Second	Meter/Second	0.3048
$Foot^{3}$/Second	$Meter^{3}$/Second	0.02831685
Inch	Centimeter	2.540
$Inch^{2}$	$Centimeter^{2}$	6.4500
Pound	Kilogram	0.453592
$Pound/Foot^{3}$	$Kilogram/Meter^{3}$	16.01846
$Q/D^{2.5}$ (English)	$Q/D^{2.5}$ (SI)	0.552093

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