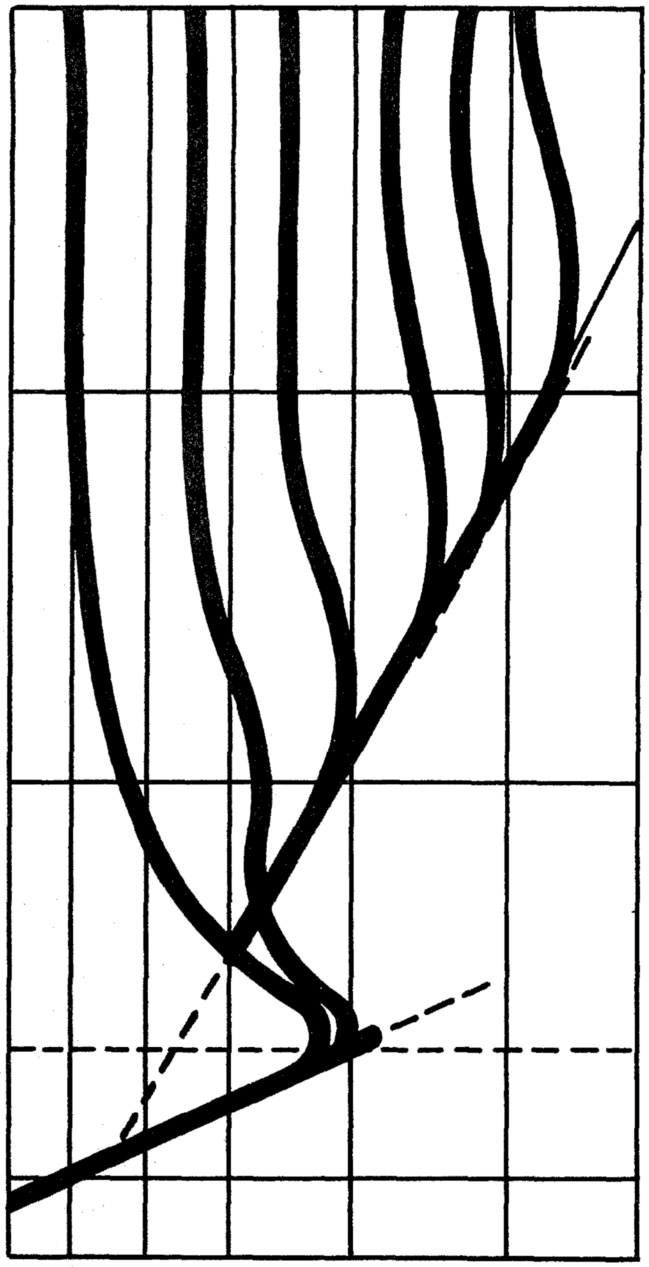
A WATER RESOURCES TECHNICAL PUBLICATION

ENGINEERING MONOGRAPH No. 7



Friction Factors for Large Conduits Flowing Full

UNITED STATES DEPARTMENT
OF THE INTERIOR
BUREAU OF RECLAMATION

A WATER RESOURCES TECHNICAL PUBLICATION

Engineering Monograph No. 7

Friction Factors for Large Conduits Flowing Full

Engineering and Research Center
Denver, Colorado

United States Department of the Interior

BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

ENGINEERING MONOGRAPHS are published in limited editions for the technical staff of the Bureau of Reclamation and interested technical circles in government and private agencies. Their purpose is to record developments, innovations, and progress in the engineering and scientific techniques and practices that are employed in the planning, design, construction, and operation of Reclamation structures and equipment. Copies may be obtained from the Bureau of Reclamation, Denver Federal Center, Denver, Colo., and Washington, D.C.

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Preface

THIS ENGINEERING MONOGRAPH, prepared in the Hydraulics Branch of the Bureau of Reclamation's Division of Research in Denver, Colo., was first issued in 1951 under the authorship of J. N. Bradley and L. R. Thompson. Copies were prepared in limited editions by the Office of the Bureau's Chief Engineer in Denver.

Subsequent to the first issuance of the monograph, new data from outside sources were obtained and included in a revised edition issued by the Office of Chief Engineer in 1962. C. W. Thomas and R. B. Dexter obtained some of the new data through the cooperation of the Bureau's Design and Construction Divisions. J. C. Schuster made the revisions under the supervision of A. J. Peterka and direction of H. M. Martin, Chief of the Hydraulics Branch.

Because of the continuing interest in the monograph, it is being printed in the present format for wider distribution.

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Introduction

THIS MONOGRAPH is intended to furnish the engineer up-to-date, practical information for accurately estimating the friction losses in large concrete, steel, and wood-stave pipes running full under steady flow conditions. It summarizes experimental information obtained through field measurements and large-scale laboratory experiments which the Bureau of Reclamation has compiled from worldwide sources over a period of years.[1] Charts are presented for obtaining friction factors for concrete pipe, continuous-interior, full-riveted and spiral-riveted steel pipe, and wood-stave pipe. These will assist the designer in predicting the behavior of a particular conduit.

The method presented, although not new so far as laboratory practice is concerned, introduces the *relative* roughness factor for use in large pipeline computations and enables the designer to evaluate the coefficient of friction much more closely than is possible with ordinary methods. A few feet of hydraulic head saved through more accurate determination of friction losses may often save many thousands of dollars in construction costs through reduction in pipe size thus permitted. The present study applies not only to water but to all types of fluids flowing in pipes 12 inches or more in diameter. As an abundance of information on friction in small pipes, including the effects of relative roughness, already exists in published literature, these will not be considered here.

Typical examples are presented illustrating the method of estimating pipe friction using relative roughness. Included also are sufficient information and examples to guide the designer in the computation of pressure drop in long air ducts and lifts, which frequently are made integral with conduits in dams and involve extremely high velocities. In addition, information requisite to laboratory testing of hydraulic machinery models with air rather than water is included, and support is given to the practice of using air as a medium for hydraulic model testing. A brief review of recent developments on closed-channel flow is presented as a background for the method which follows.

[1] Much potential data on pipe friction lie in the irrigation pipes and power penstocks of Reclamation projects in the West, but, to date, comparatively little information has been obtained from these sources.

Review of Developments

Developments by Osborne Reynolds

ENGINEERS HAD long used the theory of similitude in studying solid structures by means of models, but it was not until the latter part of the 19th century that they began to extend the theory to flowing water as well. About this time, Osborne Reynolds,[2] in studying flow through pipes, derived the expression $VD\rho/\mu$ and called attention to its significance. Here, V is velocity of flow, D the diameter of the conduit, ρ the density of the fluid, and μ the absolute coefficient of viscosity (the kinematic viscosity ν is equal to μ/ρ). The expression is dimensionless and is known as the Reynolds number, which will be referred to as R_n. The Reynolds criterion led to a more rational basis for establishing dynamic similarity of fluid motion in closed conduits, as it made possible the correlation of the flow of gases and highly viscous liquids, such as oils and sirups, along with the more common fluid, water.

When laminar flow occurs in a smooth straight pipe, the resistance to that flow is produced by viscous shear of the particles of fluid moving in parallel paths with different velocities. In addition, particles moving along the pipe walls are subjected to viscous shear from other particles which adhere to the walls. The motion of each particle is translatory only and it is distinctive by the absence of eddies. Experiment indicates that with laminar flow the frictional resistance varies as the first power of the velocity, the second power of the pipe diameter, and directly as the length.

With turbulent flow, the velocity variation across the pipe is not a result of viscous shear alone but also depends on the degree and intensity of turbulence. The particles follow irregular paths which cross and recross one another, thus producing large and small vortices and eddies which are formed, destroyed, then re-formed and destroyed, the process being repeated ad infinitum. Experiments show that frictional resistance for turbulent flow varies with approximately the second power of the velocity, the first power of the diameter, and directly as the length.

The Reynolds criterion or number serves to type these two modes of flow for which the characteristics are entirely different. Line A (see fig. 1)

[2] Gibson, A. H., *Hydraulics and Its Applications*, fourth edition, p. 45, D. Van Nostrand, publisher.

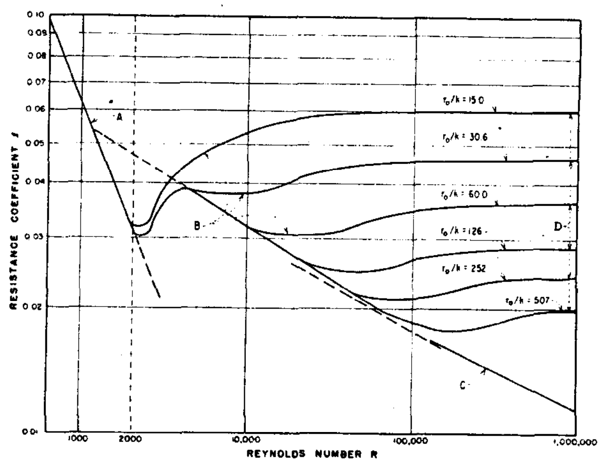


FIGURE 1.—*Variation of the resistance coefficient with the Reynolds number for artificially roughened pipes (Nikuradse experiments).*

represents laminar flow which, generally speaking, occurs when R_n is less than 2,000. Turbulent flow is evidenced by line C (for smooth pipes) and line D (for rough pipes) on the same figure. There is a rather extensive transition zone between laminar and fully developed turbulent flow in which the resistance varies between the first and second power of both the velocity and the diameter. This accounts for the various exponential formulas for pipe friction now in use. The importance of the contribution by Osborne Reynolds is borne out in the following pages.

The Darcy Contribution

In 1857, Darcy [3] proposed an empirical formula for frictional resistance in pipes which, as modified since by Weisbach and others, reads:

$$h_f = f\frac{L}{D}\frac{V^2}{2g} \qquad (1)$$

where h_f is total friction loss, f is a coefficient denoting surface roughness, L is length of the conduit, D is diameter of the conduit, and V is velocity of flow.

Many empirical formulas for flow in pipes have been proposed by others, such as Bazin, Rehbock, Williams and Hazen, Weston, etc., some of which are still popular; but the Darcy expression appears to have best withstood the test of time. Upon inspection of expression (1), the reasons are quite obvious. The friction factor f is dimensionless, and no fractional powers are involved. Also, upon subjecting expression (1) to dimensional analysis, Russell [4] shows that the friction factor can be expressed as

$$f = 2CR_n^{(n-2)}$$

where C is a constant of proportionality, R_n is the Reynolds number, and the exponent n is merely a number. Since ρ and μ appear in the Reynolds number and also in the friction factor f, the Darcy expression holds for the flow of any liquid or gas. Moreover, nothing in the derivation stipulates the type of flow, so the formula applies equally well for both laminar and turbulent flow. The value C contains a measure of the relative roughness of the conduit and a constant which is dependent on the system of units employed. The friction factor f is thus a function of the Reynolds number and the relative roughness k/D, where k represents the average nonuniform roughness of the conduit and D is the diameter.

The Nikuradse Experiments

In 1932 and 1933 Nikuradse,[5,6] working under the direction of Drs. Prandtl and von Karman, published the results of his now famous experiments on artificially roughened pipe. Rather small, smooth pipes of different diameters were coated with uniform sand grains and subjected to a wide range of velocities. The resistance to flow represented by the friction factor f was plotted with respect to the Reynolds number for various values of the relative roughness r_o/k, where r_o represents the radius of the pipe and k the absolute uniform roughness or diameter of sand grains. (See fig. 1.)

Nikuradse used the criterion r_o/k in an attempt to type roughness. For example, for a given velocity and diameter, a rough pipe will produce more turbulence and consequently offer a greater resistance to the flow per unit length for a particular fluid than a smooth one. On the other hand, should the velocity, the surface roughness, and the fluid remain the same but the diameter of the two pipes be different, the resistance offered

[3] Darcy, Henri, *Recherches Experimentales Relatives au Mouvement de l'Eau dans les Tuyaux*, Paris, 1857.

[4] Russell, G. E., *Hydraulics*, fifth edition, p. 181, Henry Holt, publishers.

[5] Nikuradse, J., "Gestzmassigkeiten der turbulenten Stromung in Glatten Rohren," *Forschungsheft*, 1932, p. 356.

[6] Nikuradse, J., "Stromungsgesetze in rauhen Rohren," *Forschungsheft*, No. 361, 1933, p. 18.

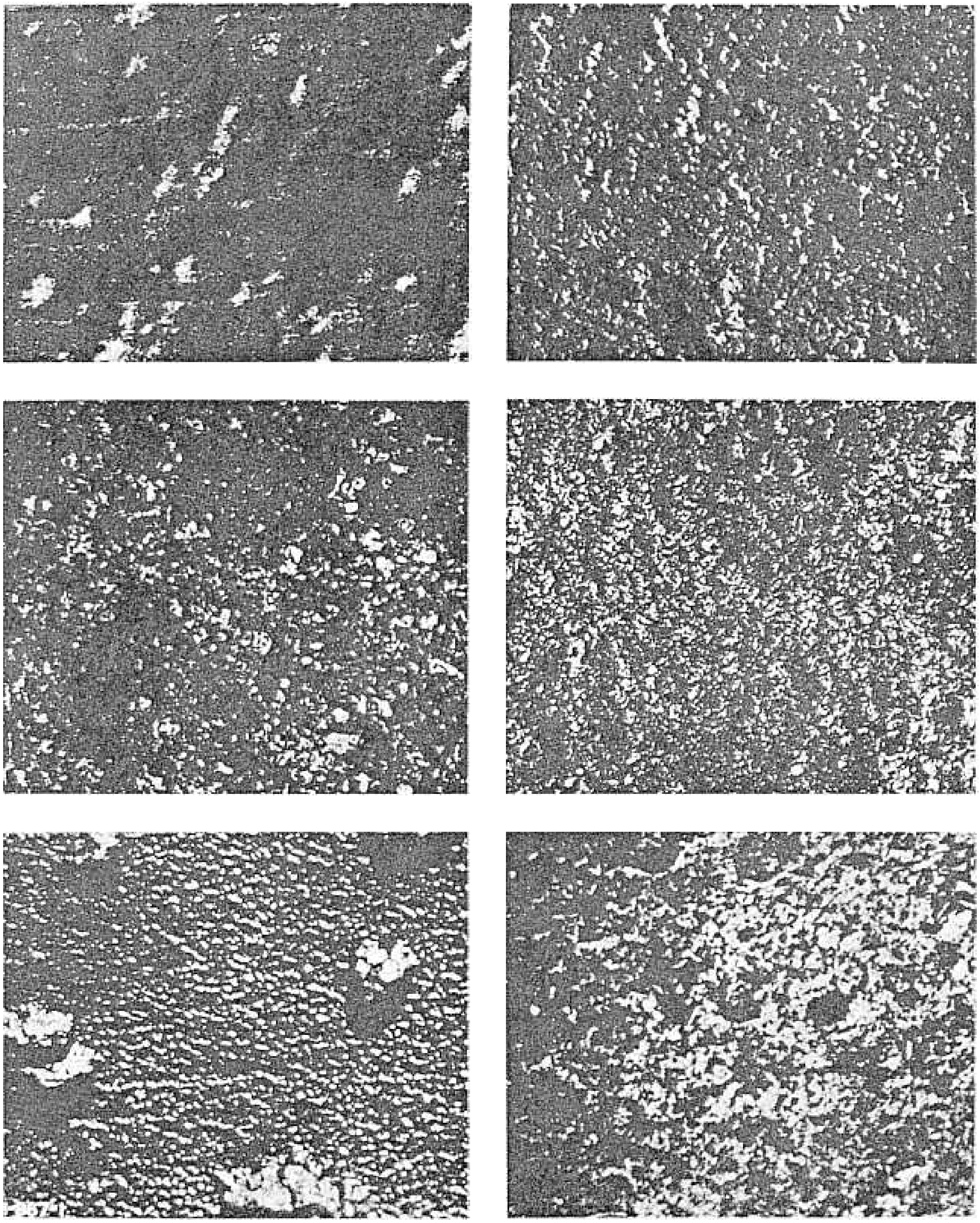


FIGURE 2. -*Pipe surfaces may vary in roughness from smooth to very rough, with combinations such as that at the lower left possible.*

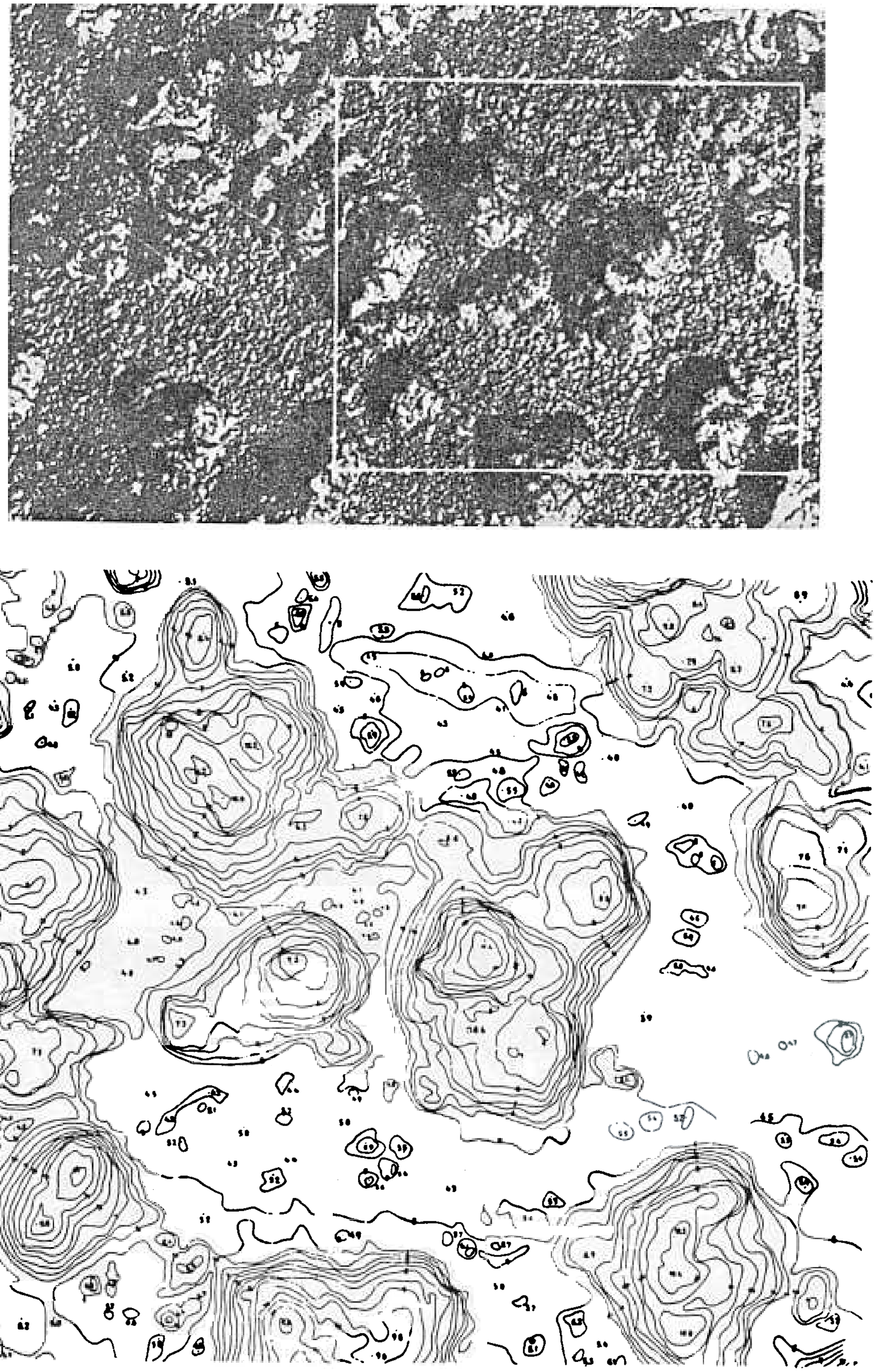


Figure 3. -*A hypsographic chart of a portion of the pipe surface may be constructed as a means of evaluating the surface roughness.*

to the flow would decrease with an increase in pipe diameter. The criterion r_0/k thus offers a means of grouping pipes having similar absolute uniform roughness for partially and fully developed turbulent flow. The straight line A on figure 1 represents laminar flow where $f=64/R_n$ for values of R_n less than 2,000. Line C represents the results obtained for turbulent flow in smooth brass pipe. The lines denoted as D are for turbulent flow in pipes coated with uniform sand grains. The size of pipe and diameter of sand grain coating were varied in the experiments, and the results are plotted in terms of the relative roughness r_0/k.

Von Karman and Prandtl Equations

Concurrently with the Nikuradse experiments, von Karman and Prandtl developed a theoretical analysis for pipe flow with suitable formulas for smooth and rough pipe. Smooth pipes are defined as those having small irregularities when compared with the thickness of the boundary layer. Rough pipes are significant in that the irregularities of the walls are sufficient to break up the laminar boundary layer, with the result that completely turbulent flow is developed. The von Karman-Prandtl resistance equation for turbulent flow in smooth pipe is

$$\frac{1}{\sqrt{f}}=2\log_{10} R_n\sqrt{f}-0.8$$

which would correspond to line C in figure 1. This constitutes merely one of a number of expressions developed for smooth pipe flow. Other well-known investigators are Blasius,[7] Ombeek, and Schiller and Herman. The results from all of these sources are in good agreement.

The von Karman-Prandtl equation for turbulent flow in rough pipes is

$$\frac{1}{\sqrt{f}}=2\log_{10}\frac{r_0}{k}+1.74.$$

Investigators von Mises, Lebeau, Hanocq, and others also developed formulas for rough pipe flow, although the agreement is not as satisfactory as for the former case.

The curves of Nikuradse consistently show a sharp drop followed by a reverse curve in the transition zone, B, between smooth and rough pipe flow. (See fig. 1.) The theoretical analysis of von Karman and Prandtl, based on the Nikuradse experiments with artificially roughened pipe, was not satisfactory over the entirety of the curves but showed disagreement in the transition zone with similar diagrams prepared by Piggott and others for commercial pipes.[8] This disagreement went unexplained until 1939, when Colebrook and White developed a practical form of transition to bridge the gap.[9]

The Colebrook and White Contribution

Colebrook and White showed that the deviation of experimental results stemmed from the fact that resistance to flow for uniform sand roughness is different from that for equivalent nonuniform roughness such as exists in commercial pipes. This was demonstrated by experimenting with nonuniform sand grains in artificially roughened pipes. It was found that the coarsest irregularities of the nonuniform boundary disturbed the laminar sublayer considerably before the smaller irregularities became effective. A semiempirical formula proposed by Colebrook and White follows the trend of experimental results and is asymptotic to both the smooth pipe and rough pipe equations of Prandtl and von Karman. This formula is

$$\frac{1}{\sqrt{f}}-2\log_{10}\frac{r_0}{k}=1.74-2\log_{10}\left(1+18.7\,\frac{r_0/k}{R_n\sqrt{f}}\right).$$

As the above expression is rather complex for practical use, Rouse[10] has plotted a chart utilizing this information. The factor f appears in both main coordinates, while values of R_n are represented by curved coordinates.

Moody[11] later constructed a chart of rectangular coordinates based on the Prandtl-von Karman experiments, the Colebrook and White function, and experiments on commercial pipes, which is included as figure 4. As the Moody chart is preferable from a practical standpoint, it has been superimposed on all of the experimental f versus R curves for large pipes. (See figs. 5 through 10 and tables I through VI.)

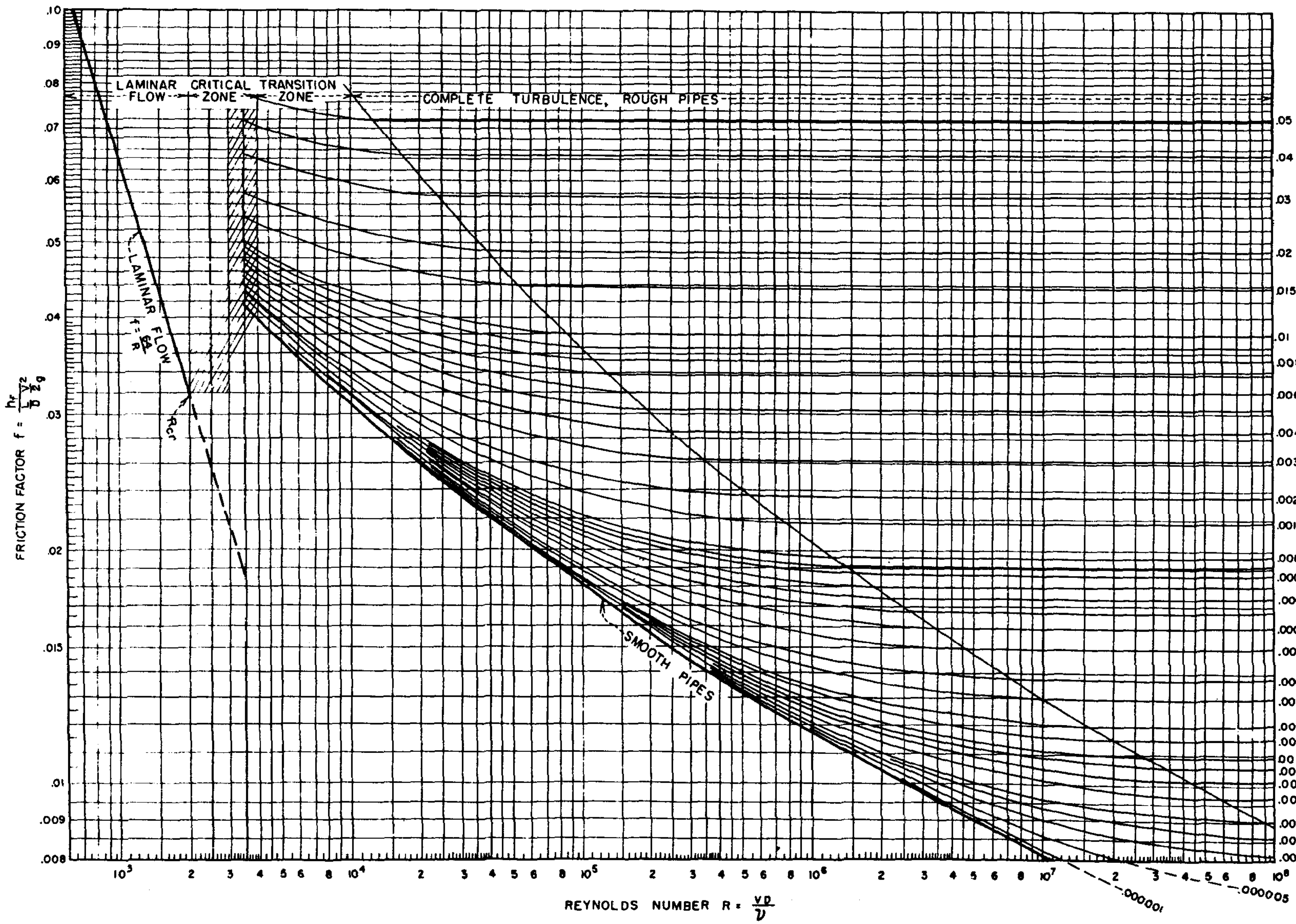
[7] Blasius, H., "Das Aehnlichkeitsgesetz bei Reibungsvorgangen in Flussigkeiten," *Forschung Ing Wes*, no. 131, 1913.

[8] Piggott, R. J. S., "The Flow of Fluids in Closed Conduits," *Mechanical Engineering*, August 1933.

[9] Colebrook, C. F., and White, C. M., Institute of Civil Engineers, Vol. II, February to April 1939, p. 133.

[10] Rouse, Hunter, *Elementary Mechanics of Fluids*, p. 211, John Wiley.

[11] Moody, L. F., "Friction Factors for Pipe Flow," *Transactions*, ASME, November 1944.



MOODY DIAGRAM FOR FRICTION IN PIPES

FIGURE 4.—*The Moody diagram for friction in pipes is based on the Prandtl-von Karman experiments, the Colebrook and White function, and experiments on commercial pipes.*

FIGURE 5.—*Friction factors for concrete pipe (refer also to tables A and G in the appendix).* 101-D-634

TABLE I.—*Friction factors for concrete pipe*

(Curves shown on fig. 5 represent data derived from these sources)

Friction factors for large conduits flowing full

Curve	Name and location	Age, years	Diameter, feet	Velocity, feet per second	Length	
					Feet	Diameters
1	Powerplant, Castelleto, Italy	10	7.94	2.61 – 4.19	5,062	636
2	Chelan station, State of Washington	New	14.0	1.25 –14.8	9,227	659
3	Deer Flat, Boise project, Idaho	6	3.0	5.45 – 9.06	7,282	2,427
4	Water conduit No. 10, Denver, Colo	4	4.5	2.58 – 3.50	18,598	4,130
		1	4.5	2.58 – 3.50	13,902	3,089
5	Dijon, France	New	2.625	3.01 – 6.59	262.5	100
6	Englewood Dam, Ohio	1–4	10.84	17.6 –42.2	712	66
7	Germantown Dam, Ohio	1–4	9.72	20.2 –36.5	546	56
8	Reported by E. Kemler, Pennsylvania		0.009–0.438			1,500–2,000
9	Powerplant, Livenza, Italy	2	12.46	2.76 –10.17	13,850	1,111
10	Powerplant, Melones, California		12	7.60 –13.49	4,469	372
11	Reported by J. Nikuradse, Germany		0.033–0.328			
12	Tunnel, Ontario Power Co., Niagara Falls, Canada.	8	18.0	4.0 – 2.00	6,500	361
13	Powerplant, Partidor, Italy	18	10	2.2 – 6.8	2,985	298
14	Powerplant, Piavi-Ansiel, Italy	1	8.2	3.28 – 9.31	6,150	749
15	Powerplant, Pit Dam No. 1, California.	New	13.68	4.7 – 8.2	10,160	743
16	Prosser pressure pipe, Yakima, Wash	4	2.54	4.9 – 5.8	2,276	896
17	Rondout siphon, Catskill Aqueduct, New York.	New	14.5	1.6 – 4.8	9,102	628
18	Reported by E. W. Spies, Germany					
19	Water pipeline, Spavinaw Aqueduct, Tulsa, Okla.	New	5	2.25	34,788	6,958
			5	2.25	60,998	16,180
			4.5	2.63	21,047	4,680
20	Umatilla Dam siphon, Umatilla project, Oregon.	New	2.5	3.4 – 3.6	5,026	2,011
21	Umatilla River siphon, Umatilla project, Oregon.	5	3.83	1.4 – 3.2	9,774	2,550
		2	3.83	4.0 – 4.2	9,831	2,565
22	Hose-formed conduit, Colorado	New	.086	1.9 – 7.2	36.5	424
			.108	2.1 – 7.2	36.5	336
23	Aqueduct, Victoria, British Columbia, Canada.	2	3.5	1.0 – 2.9	1,336	382
24	Waggitaler, Germany		11.35			
25	Wallkill siphon, Catskill Aqueduct, New York.	New	14.5	1.6 – 4.8	14,300	986
26	Apalachia Tunnel, TVA, Tennessee	New	18	4.2 –12.6	21,380	1,185
27	L'Ecole Polytechnique, Grenoble, France.	New	2.65	2.5 – 6.4	495	187
28	do	New	2.61	2.6 – 6.4	484	185
29	Perlmoos Cement Works, Austria	New	7.22	1.4 – 4.1	4,200	582
30	Winchester siphon, San Diego Aqueduct.	New	6	1.2 – 3.5	7,376.5	1,229
31	Rainbow siphon, San Diego Aqueduct.	New	4.5	1.2 – 6.2	8,371.64	1,860
32	Escondido siphon, San Diego Aqueduct.	New	4	1.5 – 7.9	54,973	13,720
33	San Diego Aqueduct	New	6	3.3 – 3.5	3,748.9	625
34	Winchester siphon, San Diego Aqueduct.	New	6	3.30 – 3.59	7,376	1,229
35	Santa Gertrudis siphon, San Diego Aqueduct.	New	4.5	3.13 – 6.38	23,280	5,173
36	Temecula siphon, San Diego Aqueduct	New	4	3.96 – 8.03	10,852	2,713

TABLE I.—*Friction factors for concrete pipe*—Continued

(Curves shown on fig. 5 represent data derived from these sources)

Friction factors for large conduits flowing full

Curve	Name and location	Age, years	Diameter, feet	Velocity, feet per second	Length	
					Feet	Diameters
37	Rainbow siphon, San Diego Aqueduct	New	4.5	1.86 – 6.37	8,371	1,860
38	San Luis Rey siphon, San Diego Aqueduct.	New	4	2.35 – 8.09	18,549	4,627
39	Escondido siphon, San Diego Aqueduct.	New	4	2.35 – 8.10	54,973	13,743
40	Poway Valley siphon, San Diego Aqueduct.	New	4	2.35 – 8.08	11,297	2,824
41	Eklutna Tunnel, Alaska	5	9.04	.686– 9.271	22,805	2,523
42	Neversink Tunnel, New York Water Board.	2	8	6.450–15.373	1,360	170
43	do	3	8	6.129–15.198	1,360	170
44	do	2	10	4.133– 9.839	24,850	2,485
45	do	3	10	3.923– 9.927	24,850	2,485
46	East Delaware Tunnel, New York Water Board.	New	11.33	2.516–10.562	102,224	11,585
47	Weber-Coulee siphon	3	14.67	3.943– 7.37	5,641	385
48	Inverted siphon, San Diego Aqueduct	New	4	2.344– 8.238	4,476	1,119
49	do	New	5	1.502– 5.229	6,293	1,259
50	do	New	5	1.501– 5.278	8,003	1,601
51	do	New	5	1.502– 5.278	30,754	6,151
52	Winchester siphon, San Diego Aqueduct.	8	6	3.140– 3.350	7,376	1,229
53	Inverted siphon, San Diego Aqueduct	8	4.5	5.698– 5.868	18,510	4,113
54	do	8	4.5	5.698– 5.868	15,767	3,504
55	Bersimis No. 1 Development, North Quebec.	New	31	6.3 –14.42	39,201	1,265
56	Tunnel No. 1, Niagara Water Supply	New	45	8.39 –15.12	11,044	245
57	Experimental pipe, St. Anthony Falls Hydraulic Laboratory.	New	3	.453–21.181		
58	do	New	3	.413– 7.856		
59	do	New	2	1.048– 8.778		
60	Salt Lake Aqueduct, Utah	15	5.75	7.12	103,000	17,900

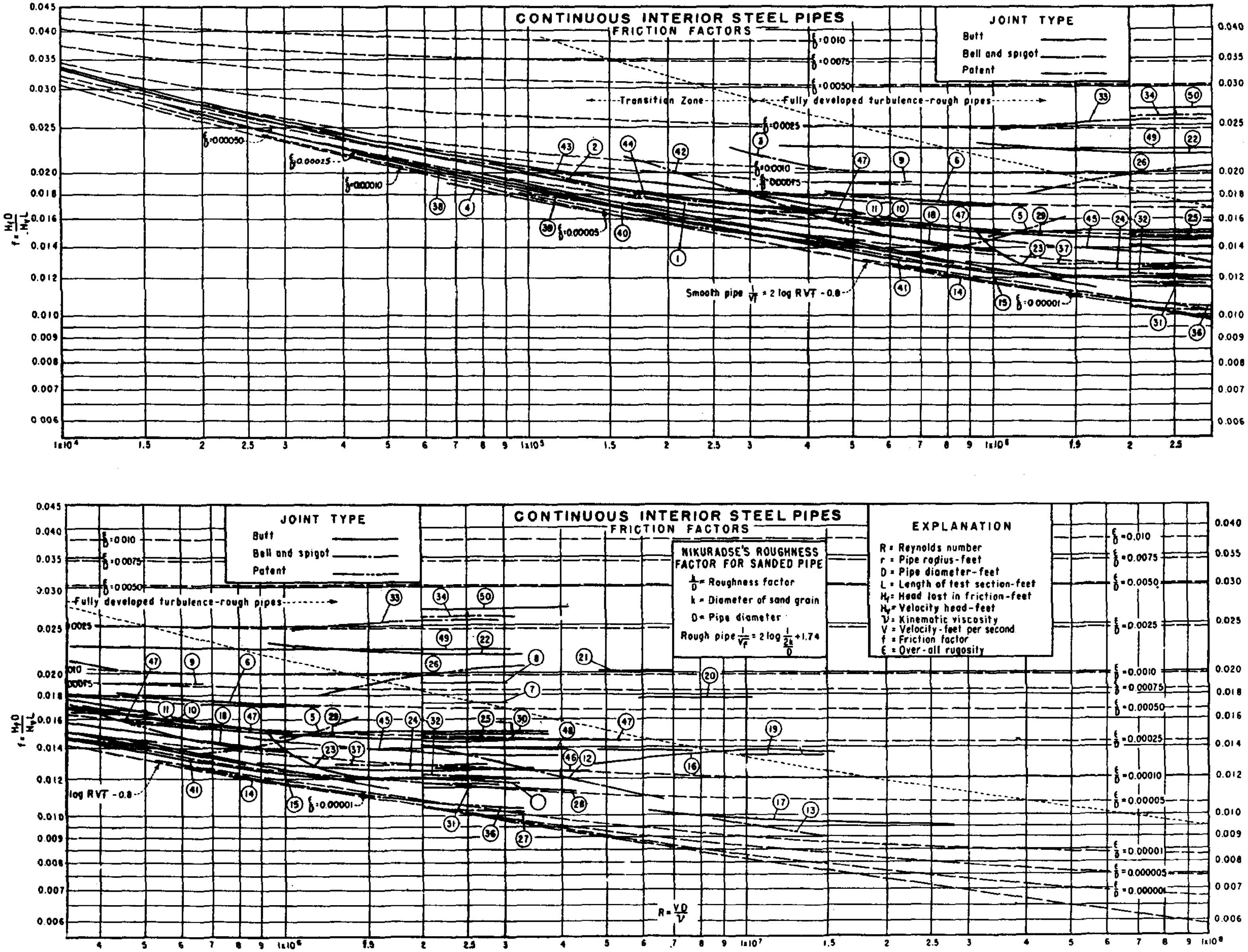


FIGURE 6.—*Friction factors for continuous-interior steel pipe (refer also to tables B and H in the appendix).*

TABLE II.—*Friction factors for continuous-interior pipe (steel and cast-iron)*

(Curves shown on fig. 6 represent data derived from these sources)

Curve	Name and location	Age, years	Diameter	Velocity, feet per second	Length	
					Feet	Diameters
1	Experimental pipe, Versailles, Pa	1	3.628 in	2. 5 –11. 7	1, 000	3, 310
2	do	1	5.72 in	1. 1 –10. 0	1, 000	2, 100
3	Lateral 21, Chatsworth High Line, Los Angeles, Calif.	3	7.69 in	4. 5 – 6. 5	586	914
4	Experimental pipe, Versailles, Pa	1	8.00 in	0. 3 – 3. 3	1, 000	1, 500
5	Municipal powerplant, Colorado Springs, Colo.	1.5	19.2 in	3. 0 – 8. 0	12, 528	7, 830
6	Marvin Municipal Water District, California	1	26.0 in	2. 9 – 6. 0	18, 400	8, 500
7	Pacific Mills Penstock No. 2, Lawrence, Mass.	2.3	84.0 in	2. 5 – 3. 5	100	14. 3
8	Pacific Mills Penstock No. 3, Lawrence, Mass.	2.3	84.0 in	2. 7 – 3. 8	100	14. 3
9	Coolgardie Pipeline, Australia	New	30.0 in	1. 9 – 2. 1	12–22 mi.	
10	Gordon Valley Pipe, Vallejo, Calif	New	24 in	1. 73– 2. 66	79, 755	39, 878
11	do	New	22 in	2. 05– 3. 16	35, 260	19, 225
12	Mese, Italy	1	78.8 in		532	81
13	Pit No. 1, Pacific Gas & Electric Co., California.	New	108 in		515	57. 2
14	Experimental cast iron pipe, Grenoble, France.	New	31.23 in	2. 3 – 6. 9	476	183
15	Experimental welded steel pipe, Grenoble, France.	New	31.35 in	2. 3 – 6. 9	486	187
16	Apalachia Tunnel, TVA, Tenn	New	18 ft	3. 8 –12. 6	580	32. 2
17	Bypass conduits, Ross Dam, Wash	New	72 in	0 –73. 0	514	85. 7
18	Experimental pipe, Fort Collins, Colo	New	10 in	0 –16. 5	45	54
19	Outlet pipes at Hoover Dam, Ariz.-Nev	New	30 ft	4. 0 – 5. 6	990	33
20	do	New	13 ft	5. 5 –10. 2	250	19. 2
21	do	New	8.5 ft	7. 1 – 9. 9	125	14. 7
22	D'Ackersoud power penstock, Switzerland.		31.5 ft	3. 3 –19. 7	486	185
23	Barberine power penstock, Switzerland.		3.93 ft	4. 0 –12. 5	275	70
24	do		3.61 ft	5. 2 –15. 1	355	98. 4
25	do		3. 443 ft	5. 6 –15. 7	630	183
26	Cavaglia power penstocks, Switzerland.		3.346 ft	5. 9 –16. 4	314	94
27	do		3.346 ft	5. 2 –17. 4	314	94
28	Lontsch power penstocks, Switzerland		3.935 ft	5. 9 –14. 1	141	35. 8
29	do		3.68 ft	5. 9 –16. 1	586	159
30	do		3.45 ft	3. 3 –18. 4	580	168
31	Palu power penstocks, Switzerland		3. 69 ft	5. 2 –12. 5	432	117
32	do		3.525 ft	6. 2 –14. 1	354	100
33	Cavaglia power penstocks, Switzerland		3.935 ft	3. 9 –12. 5	612	155
34	do		3.77 ft	4. 3 –13. 1	543	144
35	do		3.935 ft	2. 6 –10. 0	612	155
36	do		3. 77 ft	4. 5 –13. 8	667	177
37	Palu power penstocks, Switzerland		3.935 ft	5. 2 –10. 8	1, 060	270
38	Hydraulic Laboratory at Polytechnic Institute of Milan, Milan, Italy.	New	3.94 in	0. 9 –17. 0	78 and 135	238 and 411
39	do	New	5.90 in	1. 3 –13. 6	118	240
40	do	New	9. 84 in	1. 4 –19. 1	79 and 98	96 and 120
41	do	New	13.78 in	1. 8 –12. 6	118	103
42	Panther Water Co., Tamaqua, Pa	New	30 in	0. 7 – 3. 8	101, 400	40, 500

TABLE II.—*Friction factors for continuous-interior pipe (steel and cast-iron)*—Continued

(Curves shown on fig. 6 represent data derived from these sources)

Curve	Name and location	Age, years	Diameter	Velocity, feet per second	Length	
					Feet	Diameters
43	Laboratory test pipe	New	6 and 8 in			
44	do	New	8 in			
45	Portillon, France	New	2.785 ft	5 –25	1, 550	556
46	Portillon, Lac Bleu, France	2	2.785 ft	12 –29	1, 550	556
47	Teillet-Argenty, France	34	6.56 ft	1 –12	1, 325	202
48	do	34	9.84 ft	2 –11	1, 405	143
49	do	34	8.20 ft	0. 5–5	1, 356	165
50	do	34	8.20 ft	2 –7	1, 320	161

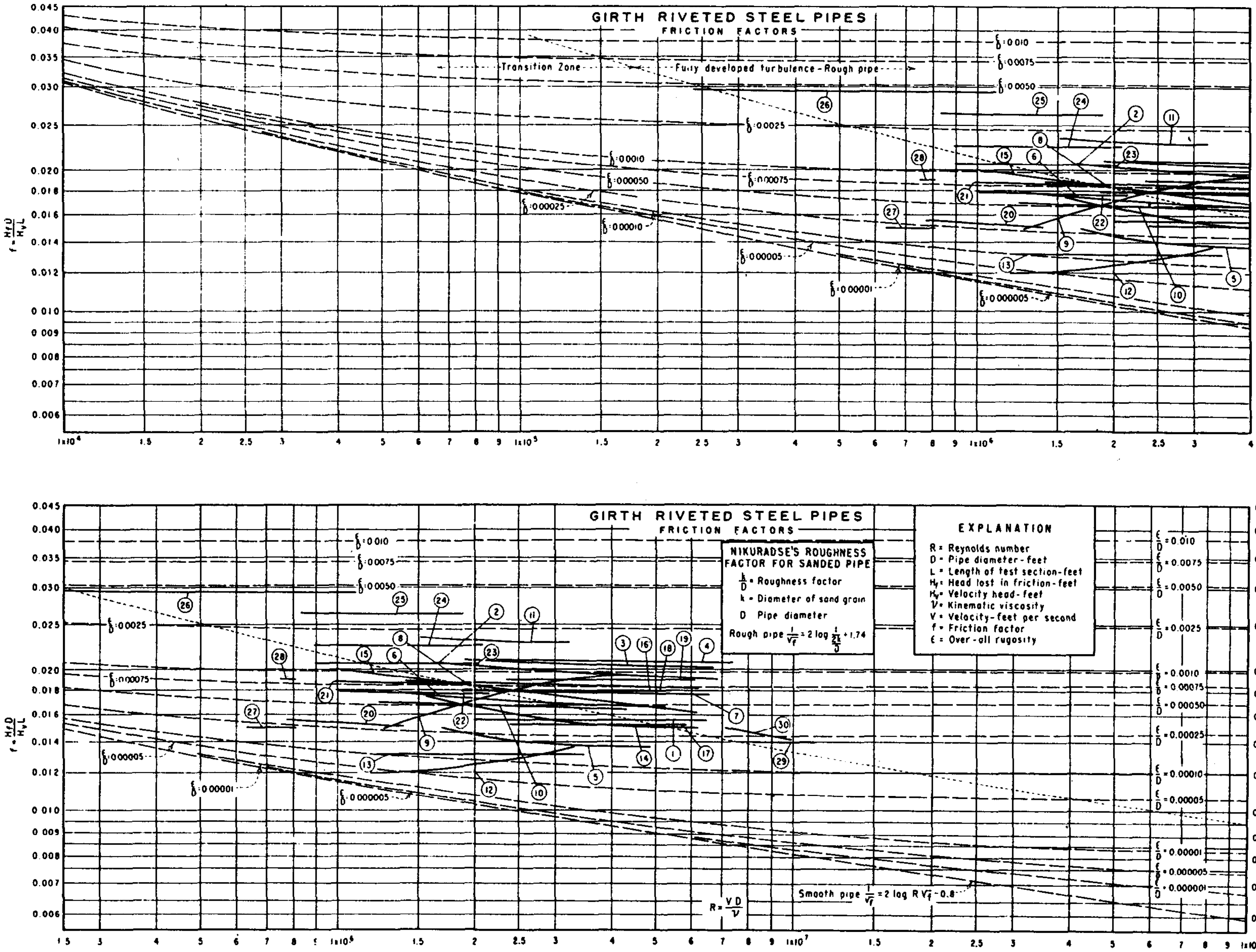


FIGURE 7.—*Friction factors for girth-riveted steel pipe (refer also to tables C and J in the appendix).*

TABLE III.—*Friction factors for girth-riveted steel pipe*

(Curves shown on fig. 7 represent data derived from these sources)

Curve	Name and location	Age, years	Diameter, feet	Velocity, feet per second	Length	
					Feet	Diameters
1	Cogolo, Italy	3	3. 215	6. 2–15. 3	507. 57	157. 87
2	Temu, Italy		2. 953	4. 7–19. 8	395. 18	133. 82
3	do		3. 609	4. 7–15. 1	508. 88	141. 00
4	do		3. 281	5. 7–18. 6	395. 33	120. 49
5	Di Ponte, Italy	1	4. 921	3. 3– 8. 4	812. 01	165. 00
6	do	1	4. 593	2. 4– 9. 7	464. 23	101. 07
7	do	1	4. 265	2. 7–11. 2	847. 91	198. 80
8	do	1	3. 871	3. 3–13. 6	503. 89	130. 17
9	Barbellino, Italy	2	4. 265	2. 5– 8. 8	363. 73	85. 28
10	do	2	4. 101	2. 7– 9. 5	413. 08	100. 72
11	do	2	1. 804	7. 6–14. 9	413. 08	228. 98
12	Barberine, Switzerland		3. 61		354	98. 1
13	do		3. 44		650	189
14	Rempen, Switzerland		7. 22		469	65
15	do		6. 92		322	46. 5
16	Laval De Cere, France	15	5. 74	7–14	764	133
17	do	15	5. 74	7–14	797	139
18	do	15	5. 74	7–14	833	145
19	do	15	5. 74	7–14	870	151
20	Esterre, France	15	4. 27	3–6	813	190
21	Luz-St-San Veur, France	19	5. 26	3–6	772	147
22	do	19	4. 59	4–8	850	185
23	Lamativie, France	19	5. 08	3–6	1, 148	226
24	do	19	5. 08	3–6	1, 148	226
25	do	19	5. 08	3–5	1, 148	226
26	Rattlesnake Siphon Spring-Brook Water Supply, Wilkes-Barre, Pa.	4	3	1. 2– 4. 6	1, 273	425
27	Montreal Water & Power Co	4	3	3. 0– 3. 7	36, 000	12, 000
28	Springfield, Mass	17	3. 5	4. 1	39, 053	11, 160
29	Penstock No. 1, Calif	New	8	14–20	240	30
30	do	New	9	11–16	515	57

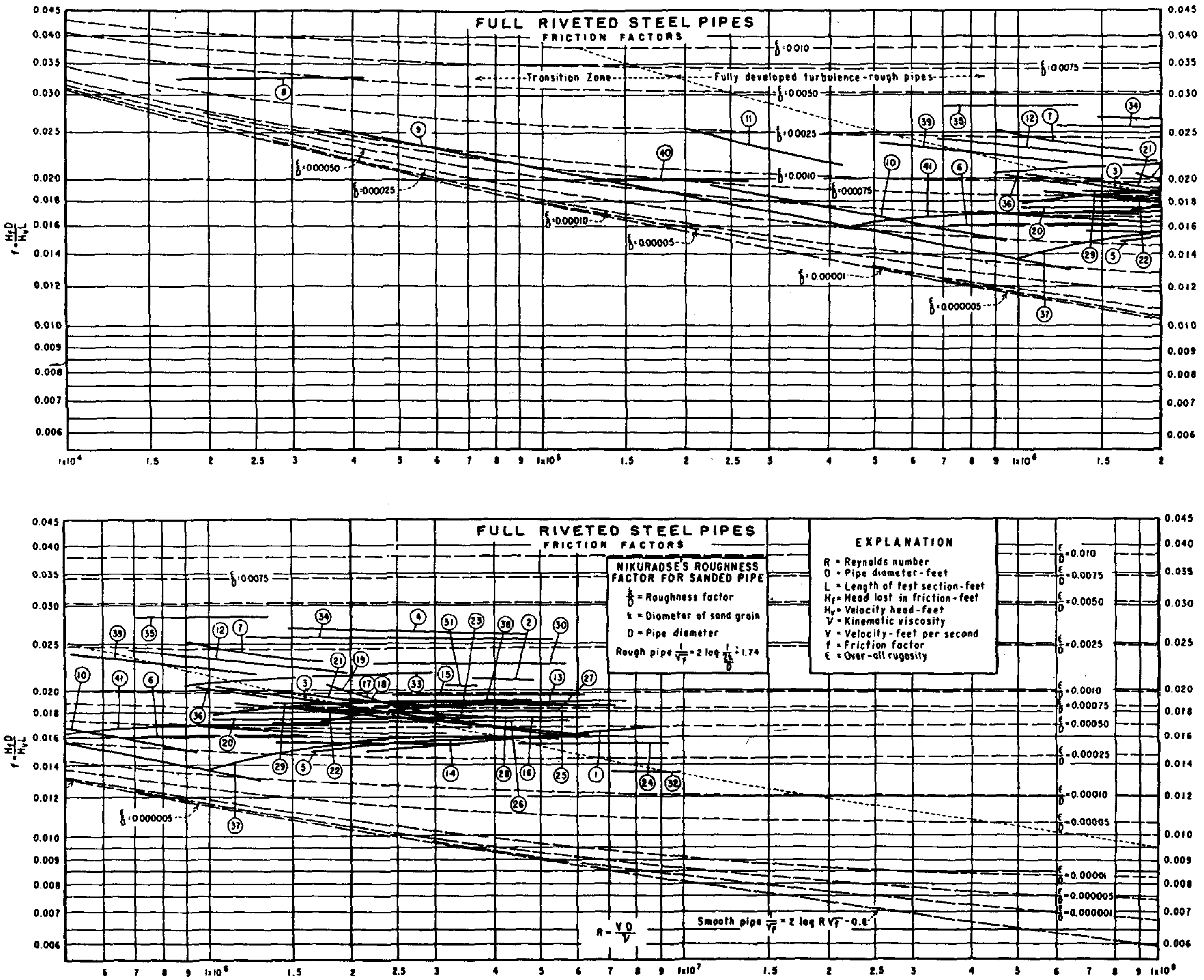


FIGURE 8.—*Friction factors for full-riveted steel pipe (refer also to tables D and K in the appendix).*

TABLE IV.—*Friction factors for full-riveted steel pipe*

(Curves shown on fig. 8 represent data derived from these sources)

Curve	Name and location	Age, years	Diameter, feet	Velocity, feet per second	Length	
					Feet	Diameters
1	Farneta, Italy	1	5. 58	5. 2 –16. 3	433. 91	77. 76
2	do		4. 26	10. 4 –13. 9	644. 72	151. 34
3	Cogolo, Italy	3	3. 97	2. 4 –10. 0	407. 17	102. 56
4	Temu, Italy		3. 12	4. 2 –17. 8	508. 60	163. 01
5	Barbellino, Italy	2	4. 27	2. 5 – 8. 8	570. 89	133. 69
6	do		2. 62	3. 6 – 7. 1	570. 89	217. 89
7	do		2. 13	5. 4 –10. 7	363. 173	170. 50
8	Okanogan project, Washington	2	. 323	0. 6 – 1. 3	494. 5	1, 530. 9
9		New	. 642	0. 6 –19. 7	365. 3	568. 5
10		New	. 935	1. 3 –10. 5	365. 5	390. 90
11	Rochester, N.Y., conduit No. 2 from overflow No. 1 to Mount Hope Reservoir.	2.0	3. 167	0. 6 – 1. 3	46, 339	14, 632
12	East Jersey Water Co., New Jersey	New	3. 5	2. 1 – 5. 0	81, 139. 0	23, 182. 5
13	Pacific Gas & Electric Co. penstock, Calif	New	6	2. 3 –11. 7	319. 9	53. 32
14	do	New	6	2. 3 –11. 7	583. 4	97. 23
15	Penstock, Pacific Gas & Electric Co., Wise powerhouse, California.	New	7	3. 4 – 8. 3	744. 7	106. 38
16	do	New	7	3. 4 – 8. 3	768. 0	109. 71
17	do	New	7	3. 4 – 8. 3	1, 070. 6	152. 85
18	Combined reaches of 15, 16, and 17	New	7	3. 4 – 8. 3	2, 683. 3	383. 32
19	Oak Grove No. 3 penstock, Portland Electric Power Co., Portland, Oreg.	0. 8	9. 0	1. 99– 6. 97	33, 920	3, 769
20	Barberine, Switzerland		3. 94		275	69. 8
21	Vernayaz, Switzerland		4. 94		142	28. 7
22	do		4. 78		600	125. 5
23	do		4. 64		197	42. 5
24	Champ S Drac, France	1	9. 19	2. 0 –14. 0	8, 140	885
25	Ventavon, France	33	7. 55	2. 5 –10. 0	1, 305	173
26	do	33	7. 55	2. 5 –10. 0	1, 295	172
27	do	33	7. 55	2. 5 –10. 0	1, 283	170
28	do	33	7. 55	2. 5 –10. 0	1, 246	165
29	do	33	7. 55	2. 5 –10. 0	1, 234	164
30	Bancairon, France	14	5. 74	7. 0 –17. 0	952	166
31	Deadman siphon, Los Angeles, Calif	7	11. 00	3. 2 – 3. 5	3, 324	302
32	Pit No. 1 penstock, California	New	10. 75	8. 0 –11. 0	231	21
33	Holyoke, Mass	5	8. 61	0. 5 – 5. 4	153	18
34	Wise penstock, Pacific Gas & Electric Co	2	7. 00	2. 0 – 8. 0	3, 696	528
35	Munroe penstock No. 2, Lawrence, Mass	22	6. 45	1. 2 – 3. 3	150	23
36	Penstock, drum powerhouse, Pacific Gas & Electric Co., California.	New	6. 00	2. 1 – 3. 0	424	71
37	Penstock, Halsey powerhouse, California	New	6. 00	2. 3 –11. 7	584	97
38	do	New	6. 00	2. 3 –11. 7	320	533
39	Kearney Ext., New Jersey	New	3. 50	2. 0 – 5. 0	81, 139	23, 200
40	Conduit No. 2, Rochester, N.Y	3	3. 165	0. 6 – 1. 2	46, 399	15, 450
41	Pump lift, Lindsay-Strathmore, Calif	2	3. 00	1. 6 – 6. 1	896	299

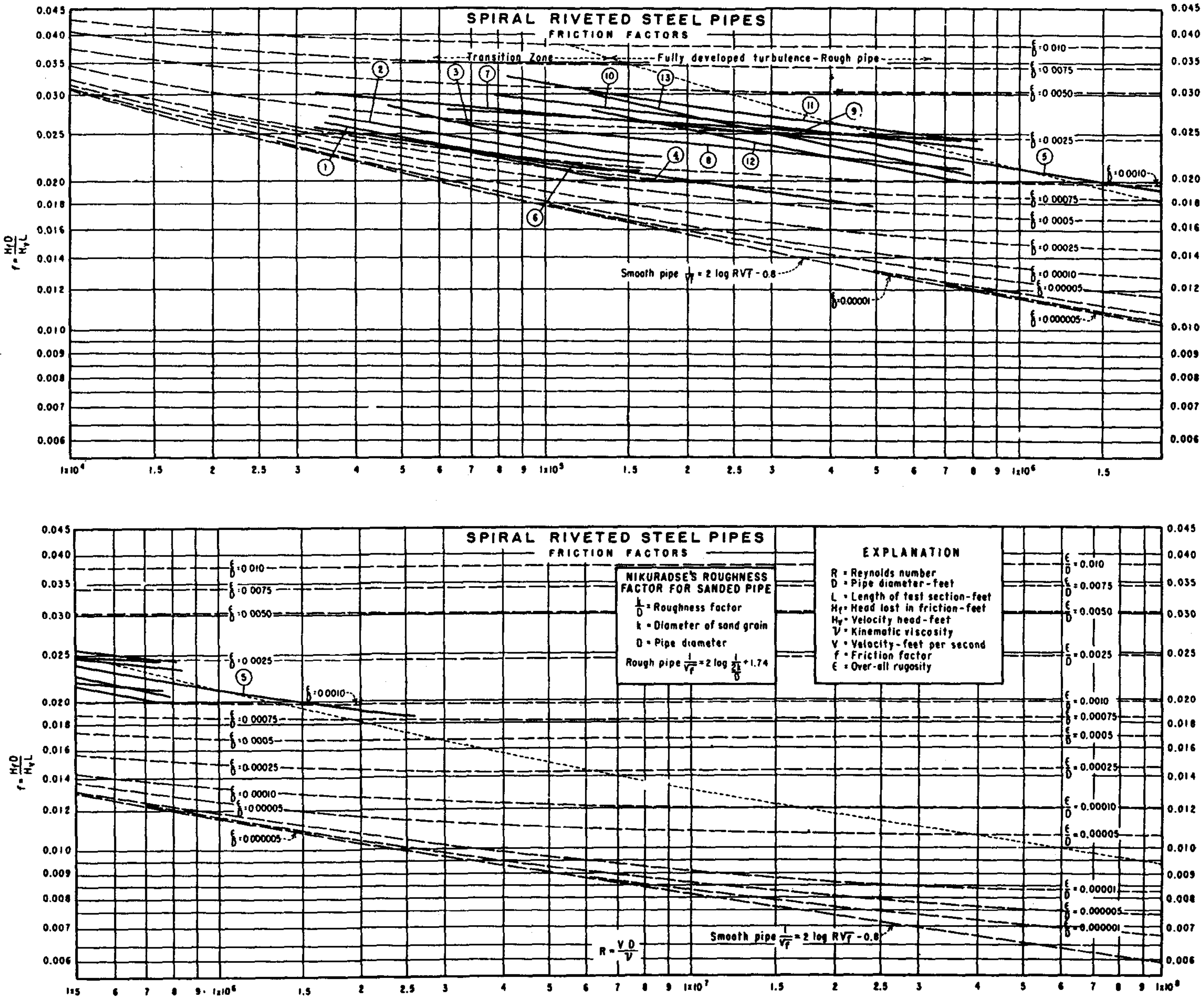


FIGURE 9.—*Friction factors for spiral-riveted steel pipe (refer also to tables E and L in the appendix).*

TABLE V.—*Friction factors for spiral-riveted steel pipe*

(Curves shown on fig. 9 represent data derived from these sources)

Curve	Name and location	Age, years	Diameter, feet	Velocity, feet per second	Length	
					Feet	Diameters
1	Experimental pipe, Cornell University	New	0. 340	1. 9 – 7. 8	80. 06.	235. 47
2	do	1	. 340	1. 5 – 7. 0	60. 01	176. 50
3	do	1	. 495	2. 3 – 7. 4	80. 1	161. 8
4	Experimental pipe	New	. 495	2. 6 – 6. 5	60. 16	121. 54
5	do	New	. 495	2. 0 – 6. 7	60. 16	121. 54
6	Experimental pipe, Purdue Engineering Experiment Station.	New	. 333	1 –15	60	180
7	do	New	. 333	1 –15	60	180
8	do	New	. 500	1. 25–15	40	80
9	do	New	. 500	1. 25–15	40	80
10	do	New	. 667	1. 25–15	40	60
11	do	New	. 667	1. 25–15	40	60
12	do	New	. 833	1. 5 – 9. 0	40	48
13	do	New	. 833	1. 5 – 9. 0	40	48

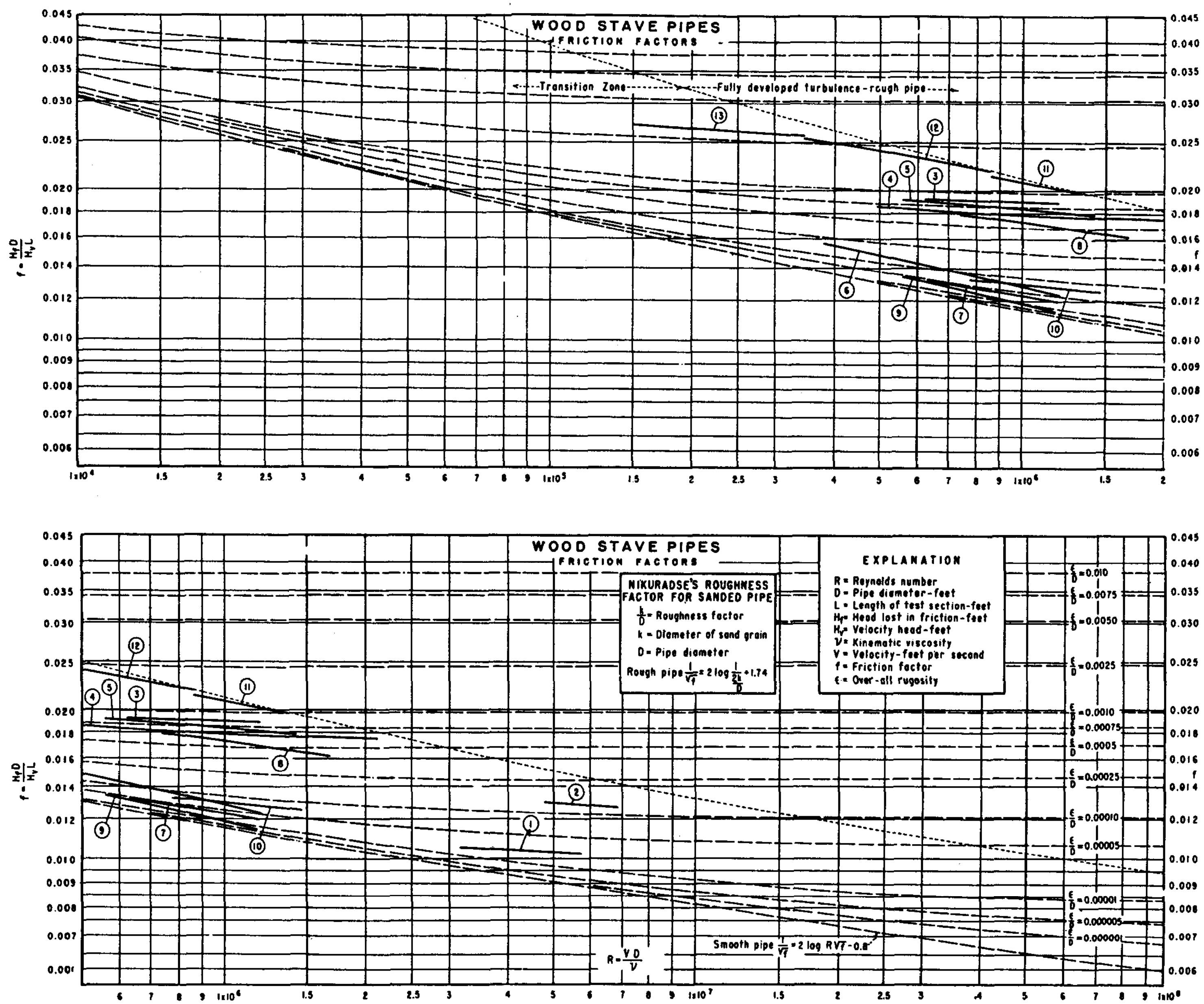


FIGURE 10.—*Friction factors for wood-stave pipe (refer also to tables F and M in the appendix).*

TABLE VI.—*Friction factors for wood-stave pipe*

(Curves shown on fig. 10 represent data derived from these sources)

Curve	Name and location	Age, years	Diameter, feet	Velocity, feet per second	Length	
					Feet	Diameters
1	Northwestern Electric Co., Washington	1	13. 5	3. 5–6. 1	2, 379	176
2	Salmon River Power Co., New York	1	12. 0	5. 9–8. 2	2, 169	181
3	Mohawk Hydro Electric Co., New York	5	6. 5	0. 9–2. 6	2, 650	407
4	Pioneer Electric Power Co., Ogden, Utah	3	6. 04	1. 2–5. 3	22, 672	3, 760
5	do	1	6. 04	0. 5–3. 6	2, 710	448
6	Mabton pressure pipe, Sunnyside project, Washington	1. 5	4. 65	1. 2–3. 9	2, 848	613
7	do	. 5	4. 65	1. 8–3. 1	2, 848	613
8	Seattle Water Works, Washington	1	4. 52	2. 3–4. 7	2, 447	540
9	Mabton pressure pipe, Sunnyside project, Washington	2. 5	4. 06	2. 3–3. 6	1, 341	330
10	Cowiche siphon, Washington	. 5	4. 0	3. 1–4. 8	887	222
11	Seattle Water Works, Washington	1	3. 71	3. 5–4. 8	4, 041	1, 090
12	Sunnyside project, Washington	0	2. 58	2. 2–4. 6	4, 514	1, 750
13	do	0	2. 58	0. 6–4. 1	7, 354	2, 850

Evaluation of Surface Rugosity

All of the foregoing development represented great strides in understanding and correlating the nature of pipe flow resistance. However, a practical and satisfactory method for arriving at the value of the roughness for commercially manufactured pipe is still in the experimental stage. As a means of differentiation between the Nikuradse roughness and that found in commercially manufactured pipes, uniform sand grain roughness will be denoted as k, while nonuniform roughness such as found in commercial pipes will be referred to as rugosity and will be designated as ϵ.

The determination of rugosity is very difficult. The protuberances in pipes vary not only in size but in pattern of spacing, as the illustrations in figure 2 will attest. The surface may be uniformly fine grained, uniformly medium grained, or coarse grained, or it may be a combination of any or all of these types together with irregularly spaced large pits, protuberances, or rivet heads. As the combinations are innumerable, a versatile method is required to obtain even a semblance of uniformity in measurement.

A promising method for the determination of the value of ϵ for large- and medium-sized conduits consists of making a small cast of one or more representative portions of the surface. The cast can be made of a plastic, plaster of paris, portland cement without sand, or other materials. The only equipment required is a small can of the matrix and a few small tools. The mold can be made in a matter of minutes and can be examined later as convenient.

A method of analyzing the surface of the cast, as practiced by a group of Swiss engineers,[12] is partially illustrated in figure 3. The photograph shows the pipe surface and indicates the extent of the cast. The hypsographic chart on the same figure is actually a contour map of the protuberances and their spacing. The exact method for determining the average rugosity of the surface is not clear. The contouring, however, is done by photomicrometry resembling the method employed in aerial mapping.

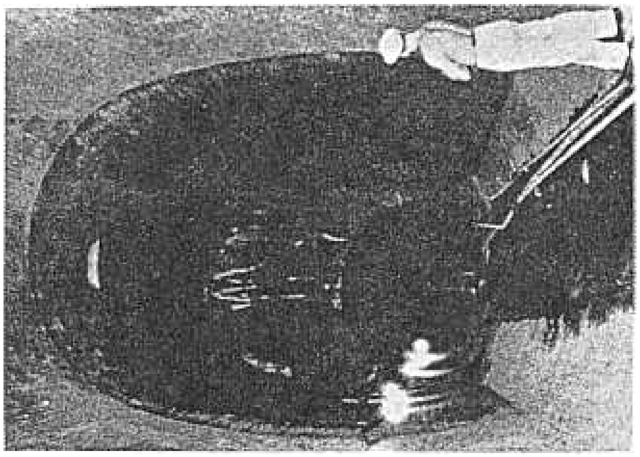
A second method for analyzing the roughness of a pipe surface is being developed in the Hydraulic Laboratory of the University of Liege in Belgium with promising success.[13] This method consists of passing a hollow feeler, or probe, over a repre-

[12] "Pertes de Charge Dans les Conduites Forcees des Grandes Centrales Hydro Electriques," in *Revue Generale de L'Hydraulique*, No. 40, July-August 1947, p. 171.

[13] "Contribution a L'Etude des Pertes de Charge Continues dans les Conduites Circulaires," paper for doctor of science degree by Andre Jorissen, University of Liege, Belgium.

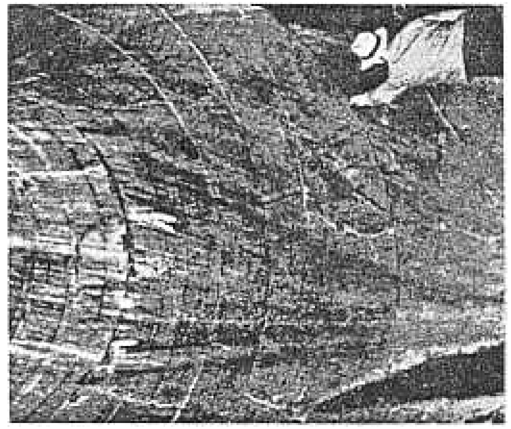
sentative section of the cast, or pipe surface. The probe is connected to a small pressure pump and an air-measuring device by means of a flexible hose. As the probe is firmly passed over the surface of the cast, or pipe, air flows from the pump through the hose and measuring device to the probe and back into the atmosphere through the granular pipe surface. The more granular the surface, the greater will be the flow of air for a given length of time. Thus, by maintaining a constant pressure on the measuring device, airflow volume is calibrated against the overall rugosity ϵ. It has been announced that the experiments on small commercial smooth pipe using this method have been completed successfully. However, a great amount of experimentation and improvement in techniques will be necessary before a satisfactory method is devised for measuring directly the overall rugosity factors of rough pipes in general. Until that time, it will remain necessary to describe roughness of commercial and field-constructed pipe in words rather than by a numerical system and estimate the rugosity factors on the basis of charts such as those herein presented. (See figs. 14 through 18.)

A—Unusually smooth pipe (steel forms)



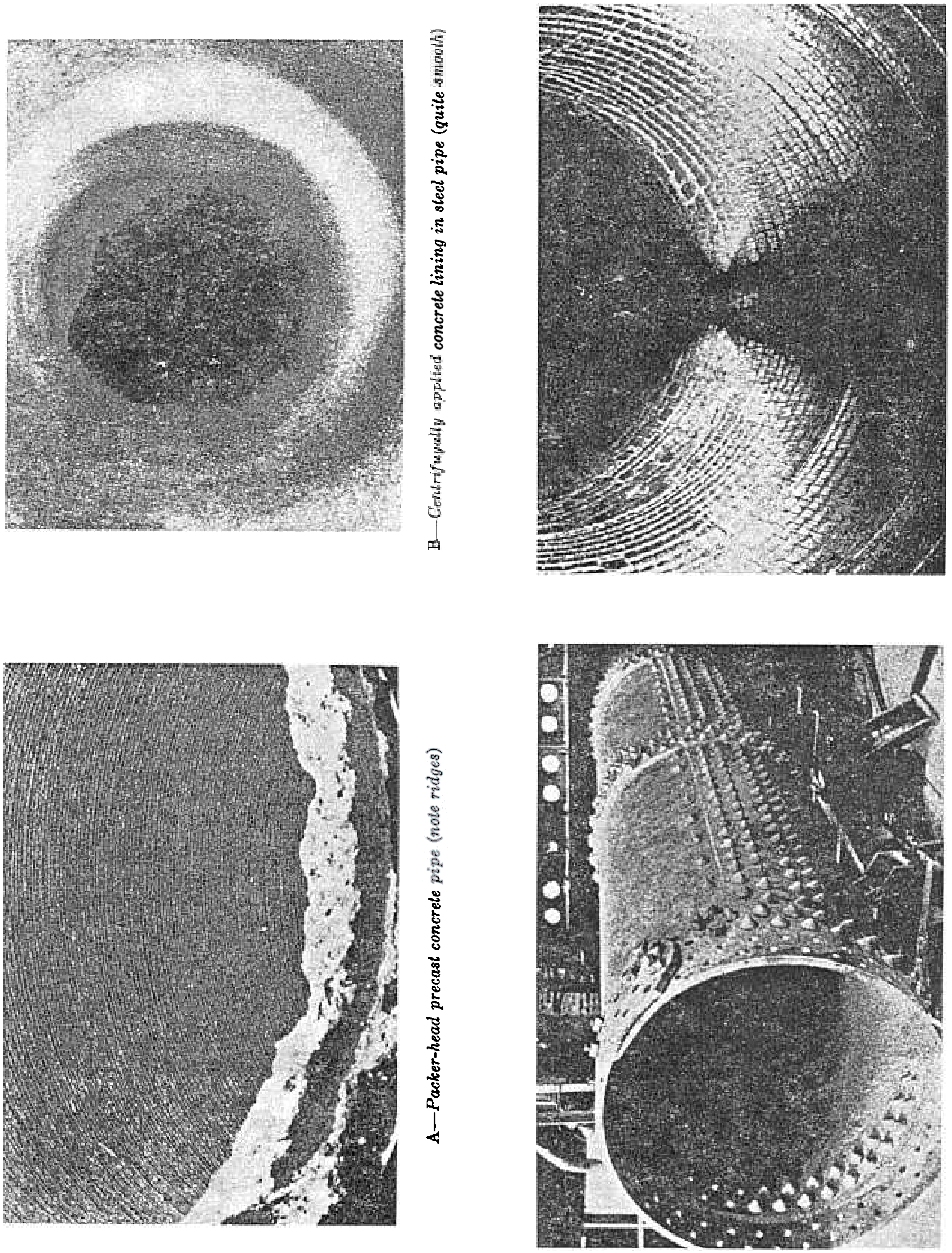
B—Reasonably smooth pipe (steel forms)

C—Regular precast pipe



D—Rough pipe (eroded areas and marks from wooden forms)

FIGURE 11.—*Concrete surfaces in pipe and tunnels. Variation shown is from the unusually smooth to the rough.*



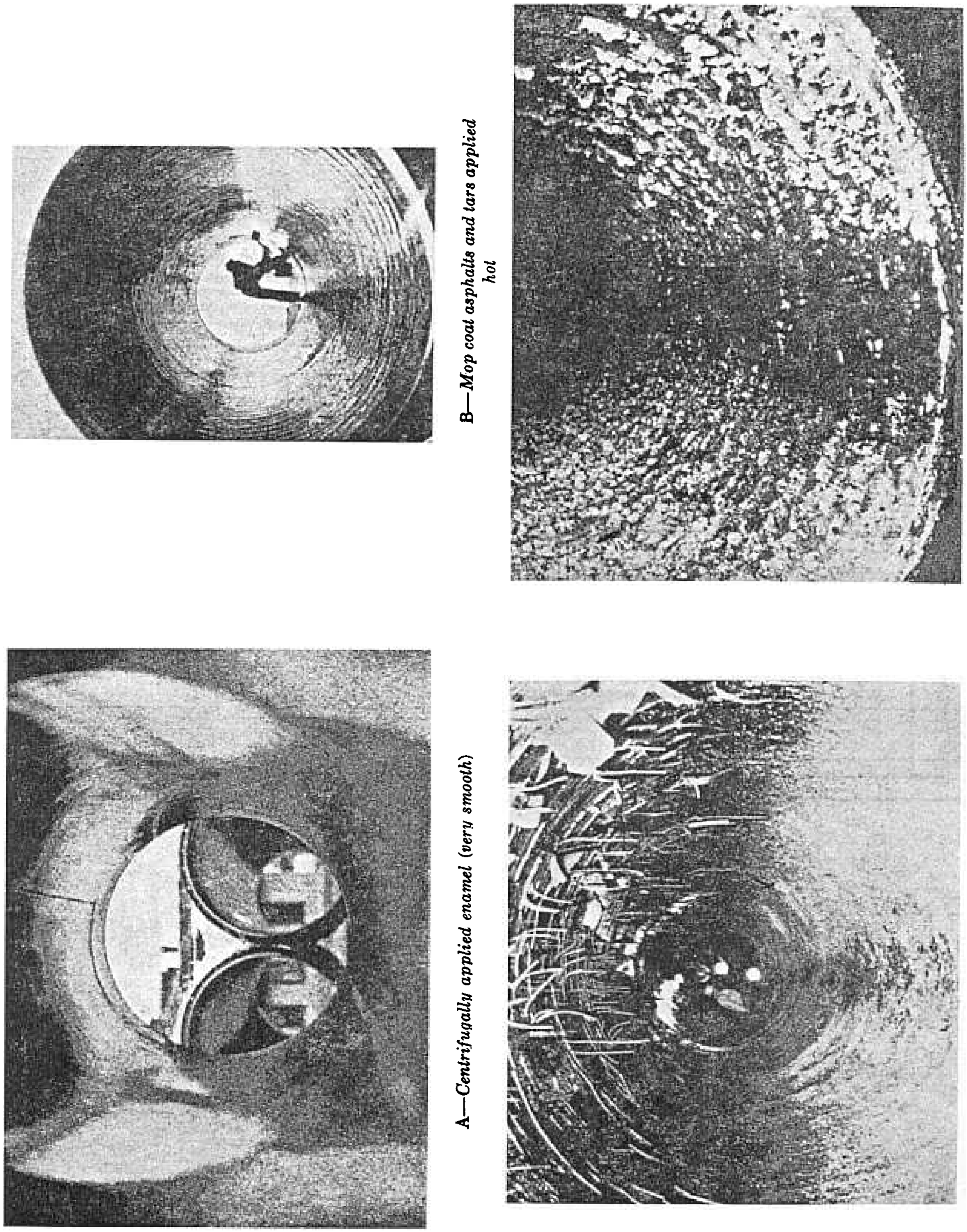
A—*Packer-head precast concrete pipe (note ridges)*

B—*Centrifugally applied concrete lining in steel pipe (quite smooth)*

C—*Fully double-riveted steel pipe (involves four rows of rivets per joint)*

D—*Hand-daubed coal-tar enamel applied hot*

FIGURE 12.—*Smooth concrete surfaces and new steel pipe surfaces show variations in roughness.*



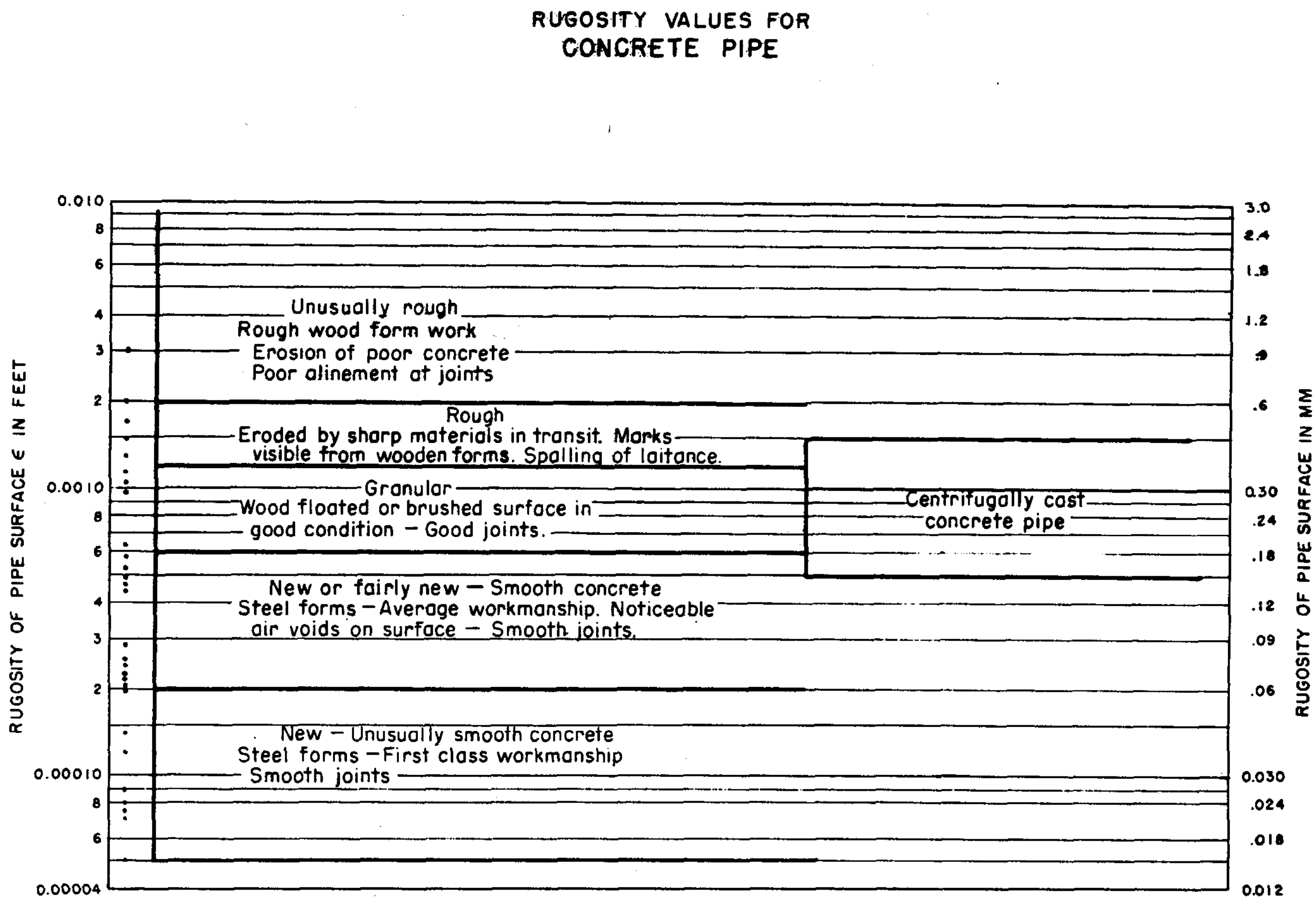
A—*Centrifugally applied enamel (very smooth)*

B—*Mop coat asphalts and tars applied hot*

C—*Brush coat asphalt in process of peeling*

D—*Severe tuberculation in steel pipe*

FIGURE 13.—*Steel pipe surfaces of continuous-interior pipe may exhibit considerable variation in roughness.*



NOTE: FOR PRECAST PIPE
SMOOTH JOINTS—NO CORRECTION
AVERAGE JOINTS—INCREASE K BY 0.003 TO 0.005
MISALINED JOINTS—INCREASE K BY 0.006 TO 0.009

FIGURE 14.—*Rugosity values for concrete pipe vary from 0.00005 to 0.0013 foot.*

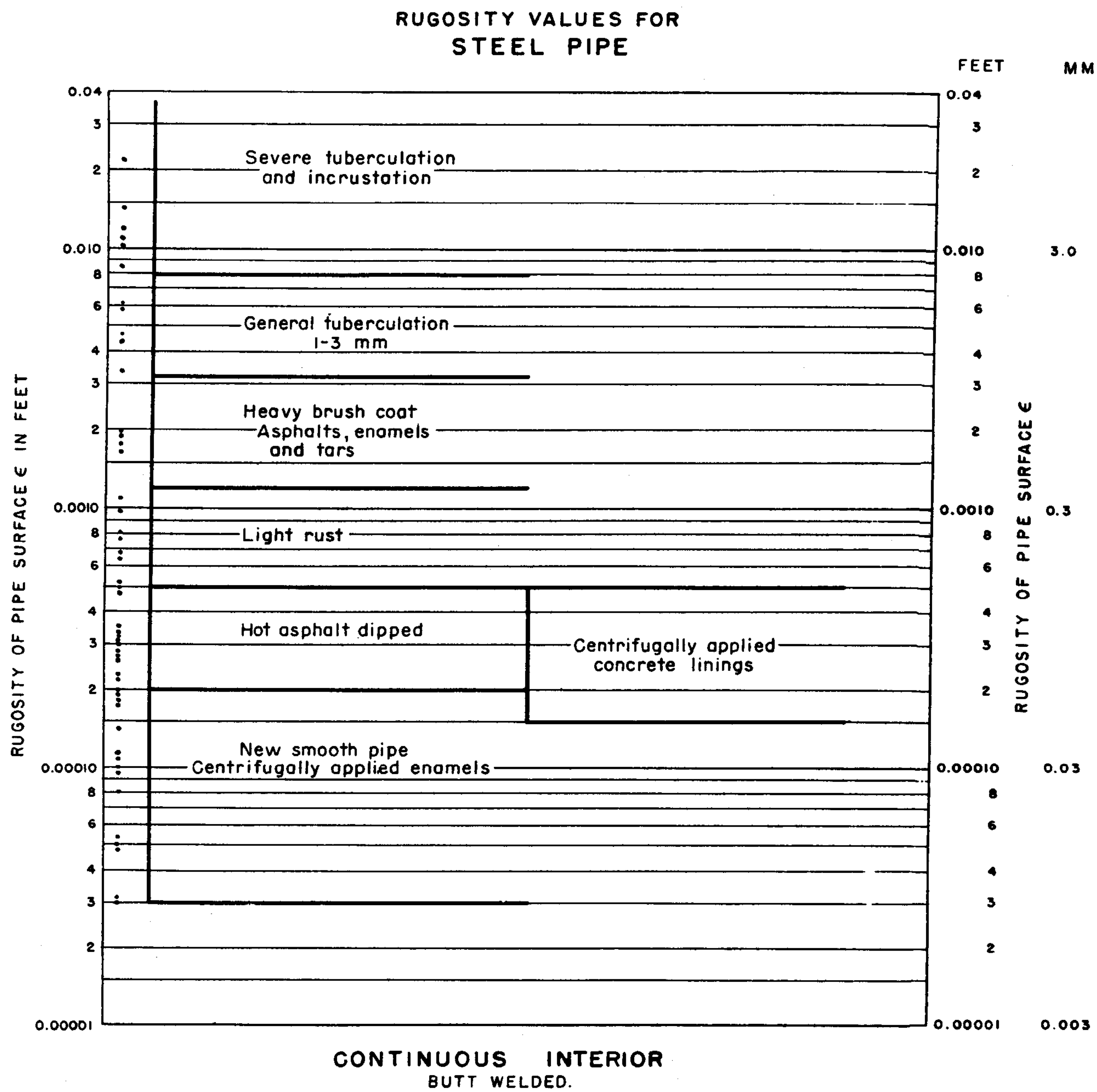


FIGURE 15.—*Rugosity values for continuous-interior, butt-welded steel pipe vary from 0.00003 to 0.02 foot.*

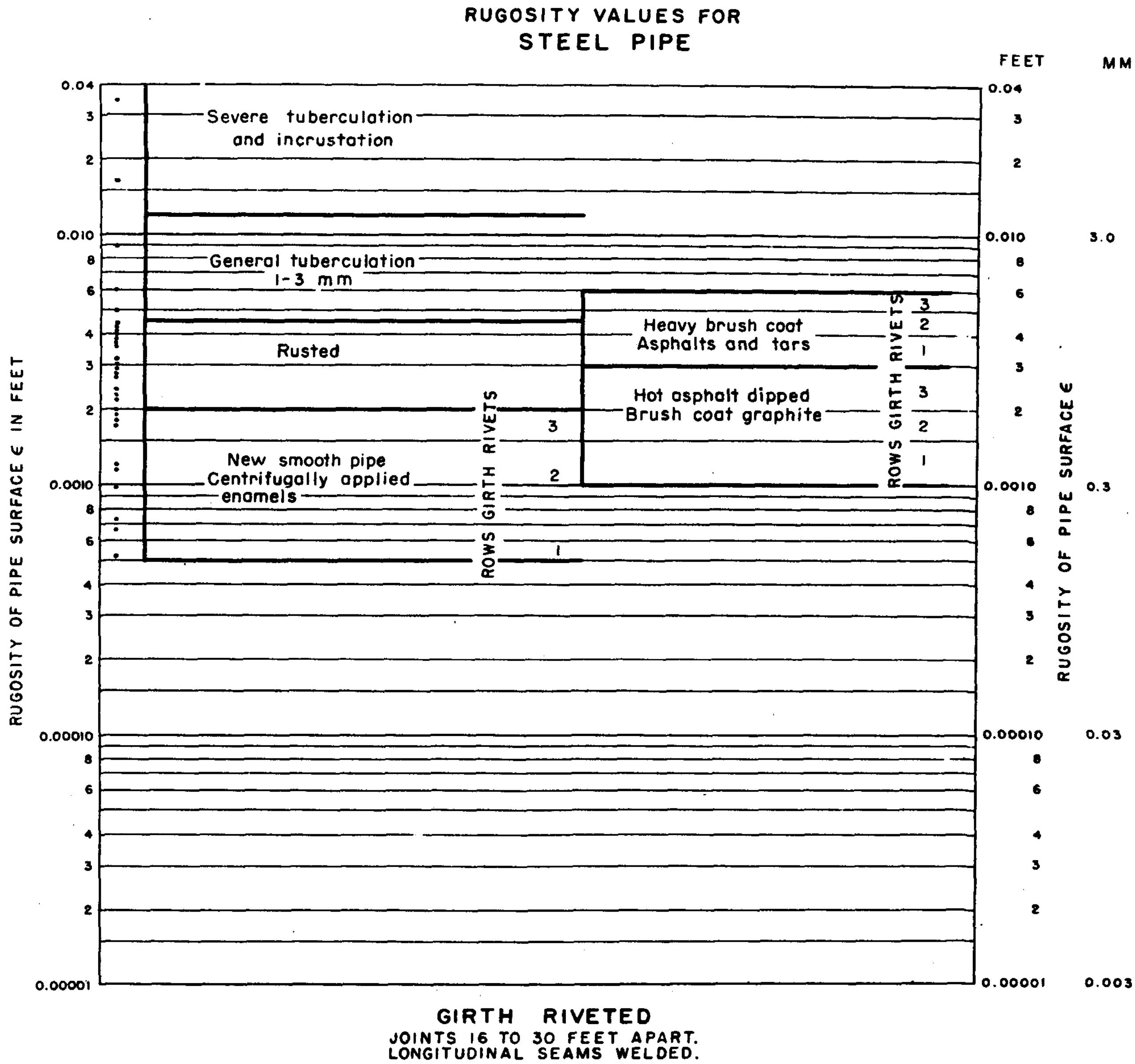


FIGURE 16.—*Rugosity values for girth-riveted steel pipe vary from 0.0005 to 0.035 foot.*

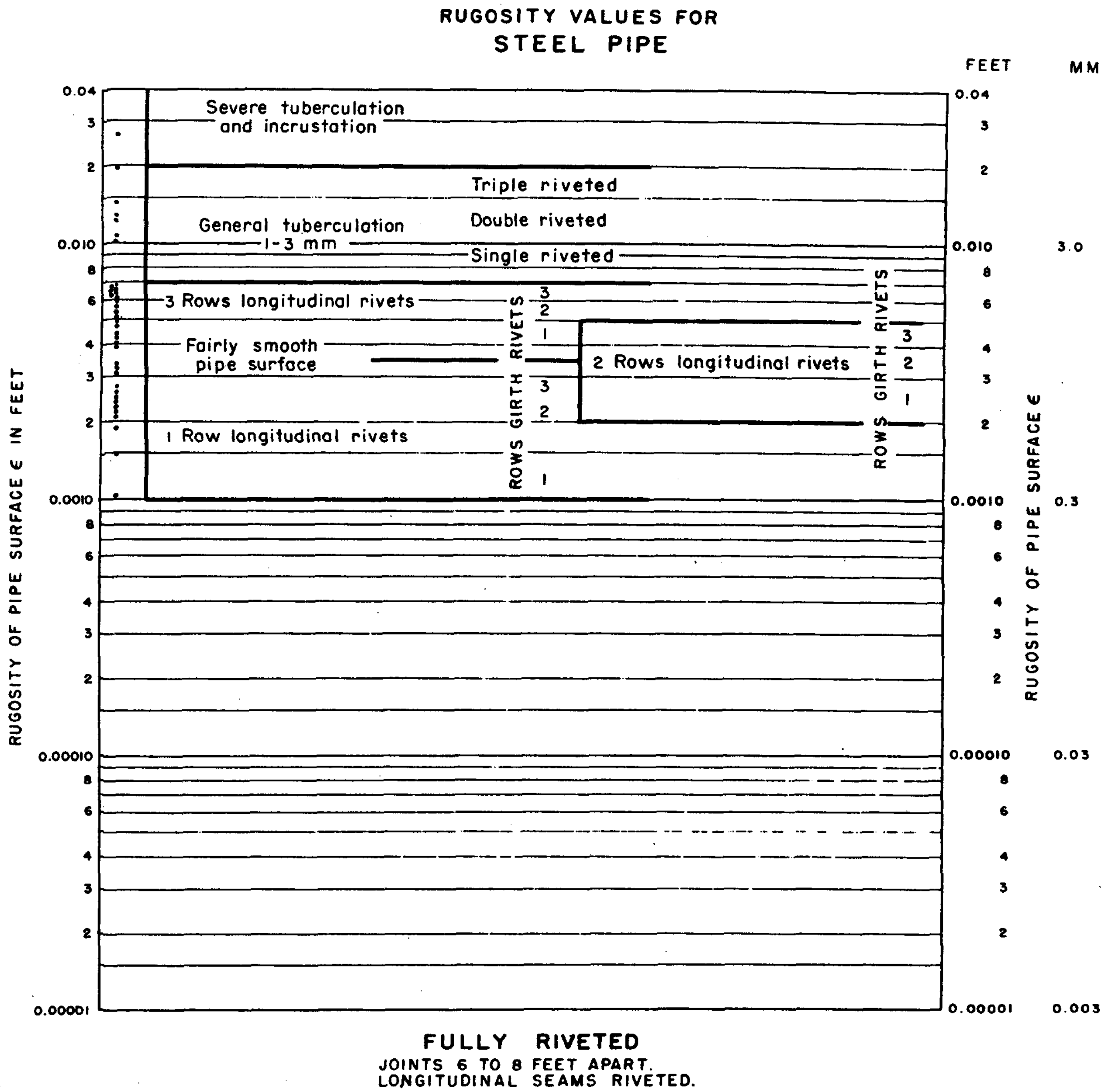


FIGURE 17.—*Rugosity values for full-riveted steel pipe vary from 0.001 to 0.03 foot.*

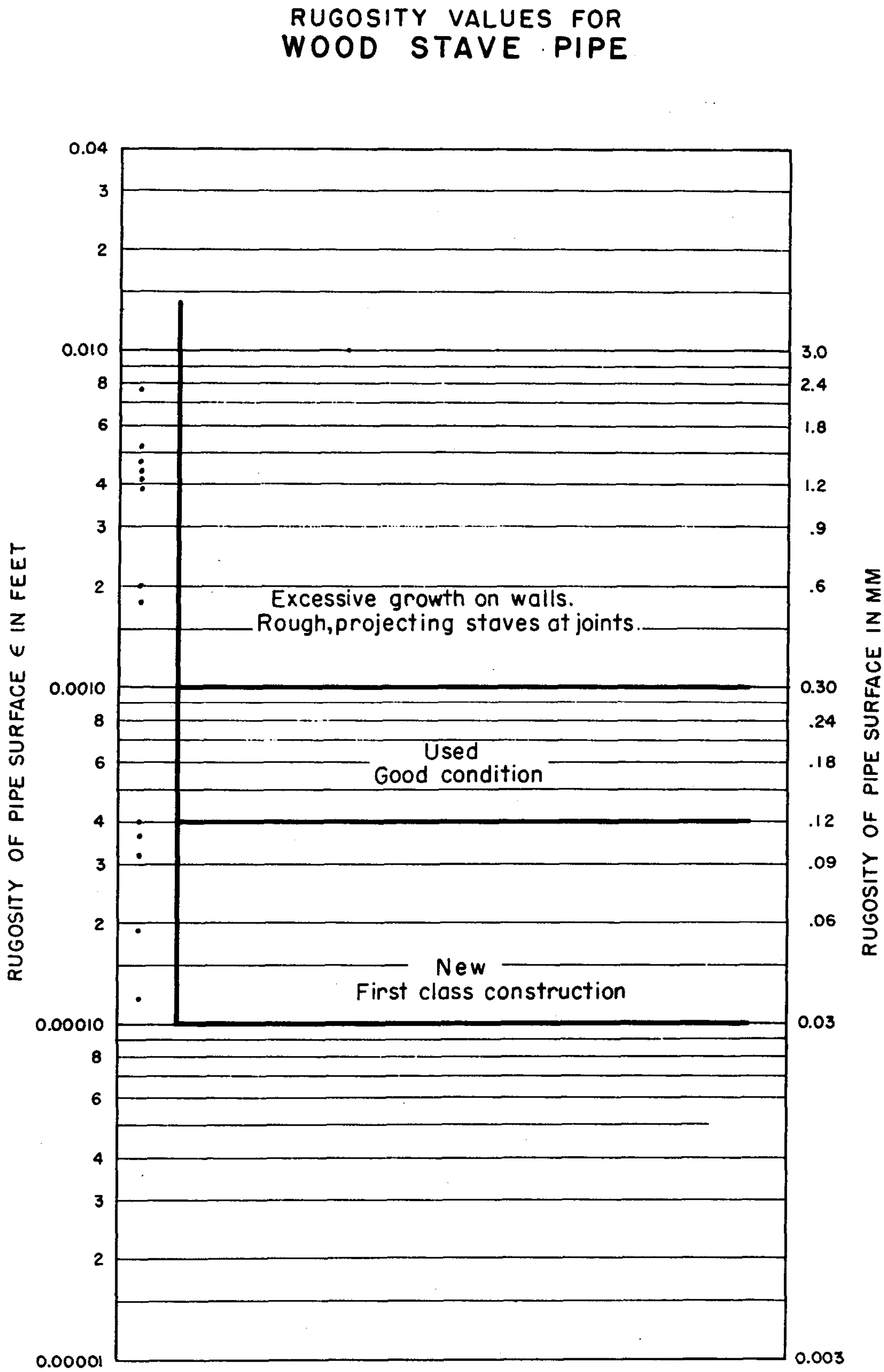


FIGURE 18.—*Rugosity values for wood-stave pipe vary from 0.00012 to 0.008 foot.*

Friction Factors for Design

Experimental Information

The pipes for which charts of friction factors are presented include concrete pipe (fig. 5); continuous-interior steel pipe, which may be butt-welded throughout or have bell-and-spigot or patented joints (fig. 6); girth-riveted steel pipe, which implies that the transverse joints are riveted and the longitudinal seams are welded (fig. 7); full-riveted steel pipe in which both girth and longitudinal joints are riveted (fig. 8); spiral-riveted pipe (fig. 9); and wood-stave pipe (fig. 10). The friction factor f in the Darcy formula has been plotted against the Reynolds number R_n to produce the curves in the above figures.

Each curve in figures 5 through 10 is designated by a number. By referring to data in tables I through VI by curve number, information can be obtained as to location of the tests and the age, diameter, velocity, and length of the pipe in question. Additional information as to joints, seams, condition of the surface, paint, method of testing, and evaluation of the results with references to published papers and bulletins on the original work, is included for the various types of conduits in tables A through F of the appendix. Where information on a test was plentiful, all that pertained to the condition of the pipe was included. Information on some of the tests was, however, meager.

For the sake of clarity, the actual test points were omitted from figures 5 through 10; thus, the curves shown thereon represent average values. In the majority of cases, the points did not fall directly on the curve as drawn but fell to both sides with considerable variation. As a great deal of time was involved in the collection and compilation of the test data which were obtained from many sources and found in various forms, a permanent record of this material was desirable. For those who may wish to investigate or experiment with these data, a complete record of the test points is included for each type of pipe tested in tables G through M of the appendix.

Limitation of Study

The study was made principally on large pipelines in which turbulent flow was well developed, with the values of Reynolds number ranging from approximately 1 million upwards. It can be observed from figures 5 through 10 that the greater portion of the test data collected falls within or approaches fully developed turbulent flow, for which the friction factor f approximates a constant value.

Previous compilers of pipe friction data have, in general, limited their investigations to smaller pipes in which turbulence was not fully developed; thus, their compilations fall principally in the transition zone. This can probably be explained by the fact that, until recently, there has not been available a sufficient amount of reliable experimental data on large pipelines to warrant a compilation. Incidentally, more data are required for large pipes than small ones, as the experimental error appears to increase with pipe size.

The curves in figures 5 through 10 contain practically all experimental information available on large pipes, but they are difficult to use in this form as they represent many types of surface conditions and the accuracy of some of the data is questionable. Thus, it was advisable to devise a method for sorting out the questionable material and combining the remainder.

Method of Evaluating Results

Superimposed on figures 5 through 10 is the Moody diagram, the construction of which was described in the introduction. The diagram consists of curves indicated by dash lines, which represent constant values of the relative roughness or rugosity ϵ/D. By means of the Moody diagram, it was possible to read off values of ϵ/D from the various experimental curves of figures 5 through 10. An average value of ϵ was obtained for each curve by multiplying the ϵ/D value by its respective pipe diameter. Values of ϵ obtained in this manner were then plotted for concrete pipe in figure 14; steel pipe in figures 15, 16, and 17; and wood-stave pipe in figure 18, with as detailed a word description of the pipe surface as it was possible to make from the available information. Each dot to the left of these charts represents one experiment. The photographs in figures 11, 12, and 13 were included to supplement the word description applied to the pipe surfaces throughout the text.

A comparison of figure 14 and figures 15, 16, and 17 indicates that continuous-interior steel pipe can be both smoother and rougher than concrete pipe. The practice of tabulating friction coefficients with respect to the age of a pipe, such as is done with small commercial pipes, means nothing in the case of larger pipe where maintenance is possible. The friction factor for large pipes varies with the condition of the pipe surface, which may change from year to year, depending upon whether the surface is repainted or allowed to deteriorate. For example, the friction factor f for steel penstocks 34 years old was found to be comparable to that of new pipe.

In well-constructed concrete pipe, it was found that the friction factor f remained very much the same regardless of age, unless the water flowing through it carried appreciable amounts of abrasive material. In some cases, algae growth was reported to have little effect on the carrying capacity of concrete pipe, providing it was not sufficient in amount to reduce the cross-sectional area of the conduit. In other instances such as the San Diego Aqueduct, a thin film of algae produced a 10-percent decrease in the carrying capacity of the conduit during the summer months. The water in this case carried fine sand which lodged in the algae deposits.

Figures 15, 16, and 17 show the progressive increase of the friction factor with increase in the number of rivets. Although the minimum value of ϵ increases with the number of rivets involved, the maximum value of ϵ for full-riveted pipe is shown to be no higher than for poorly maintained and encrusted continuous-interior pipe.

The resistance to flow in the three types of construction differ in these respects: (1) The resistance to flow in new concrete pipe is entirely dependent on the condition of the finished surface and on the frequency and alinement of joints; (2) the resistance to flow in new continuous-interior steel pipe is principally dependent on the type and application of the protective coating employed; (3) for heavy riveted steel pipe in good condition, the obstruction offered to the flow by rivet heads predominates while the protective coating becomes of minor importance.

The values of ϵ for spiral-riveted steel pipe are not shown in figures 15, 16, and 17, as the information available is too meager to allow drawing any general conclusions and the experimental information available was on pipes less than 1 foot in diameter.

Values of ϵ for wood-stave pipe are shown in figure 18. Again the available information is meager, but the pipelines tested were fairly large in diameter. These results are not considered conclusive.

Theoretically, the value of the friction factor f for any conduit lies between the smooth pipe curve and a constant value of approximately 0.054 for entirely rough surfaces. If the irregularities in the walls of the conduit are sufficient to produce noticeable expansion and contraction losses, such as would be the case for unlined rock tunnels, the factor may be even greater than 0.054. For example, Hickox, Peterka, and Elder [14] obtained a value of $f=0.10$ for the unlined portion of the Apalachia Tunnel. It is apparent that the friction factor for all types of rough surfaces tends to approach the values for smooth pipe as the diameter increases.

Special care is necessary in the determination of the pipe diameter, as the reduction in carrying capacity of a conduit due to tuberculation, especially in the smaller sizes, can be as much a function of reduction in diameter as it is a result of an increase in the value of f. The reason that a small change in the diameter can produce a rather large change in the value of f is that f varies inversely as the fifth power of the diameter. Thus, if heavy incrustation is expected in a pipe installation, it may be better to compute the diameter based on $f=0.054$ than to attempt to estimate the ultimate value of f based on the original diameter.

Bend Losses

Although much of the experimental pipe contained bends of various degrees and number, the values of ϵ in figures 14 through 18 have been adjusted, according to the best judgment of the authors, to exclude bend losses. No information of value has been found on bend losses in large pipelines, principally because long reaches of straight pipe must accompany a bend if reliable measurements are to be made.

The best experimental information to date on pipe bends is shown in figure 19A, which was compiled by Beij [15] of the Bureau of Standards. It will be observed that the largest pipe tested in this group was 8 inches in diameter, and the experimental results are at considerable variance with one another. Generally speaking, it appears that the loss coefficient for 90° bends is a minimum when the ratio of the radius of the bend to the diameter is between 3 and 6. As R_b/D (the ratio of the radius of the bend to the pipe diameter) increases, the bend coefficient shows a secondary rise, but then it must gradually fall to zero as the value of R_b/D continues to increase. The reason for the secondary rise is explained quite logically by Anderson and Straub.[16]

Supposedly, the bend loss coefficients in figure 19A constitute only those losses chargeable to the bend, the straight pipe loss having been deducted. The study by Beij demonstrated that the bend coefficient is independent of the Reynolds number when the latter exceeds a value of 200,000. The bend coefficient is influenced, however, by the relative roughness ϵ/D and, in the case of rectangular elbows, by the aspect ratio W/D (ratio of width normal to radius to width in same plane as radius).

Anderson and Straub reduced the data in figure 19A to those for an equivalent smooth bend. The resulting curve, labeled "adjusted curve," is shown by the heavy solid line in the figure. This line supposedly represents the average loss coefficient for 90° bends in circular pipes having smooth surfaces. As the relative roughness need be no greater for a rough pipe of large diameter than for a small smooth pipe, it stands to reason that bend loss coefficients for large conduits are probably no greater than those shown for small smooth pipe by the adjusted curve in the figure.

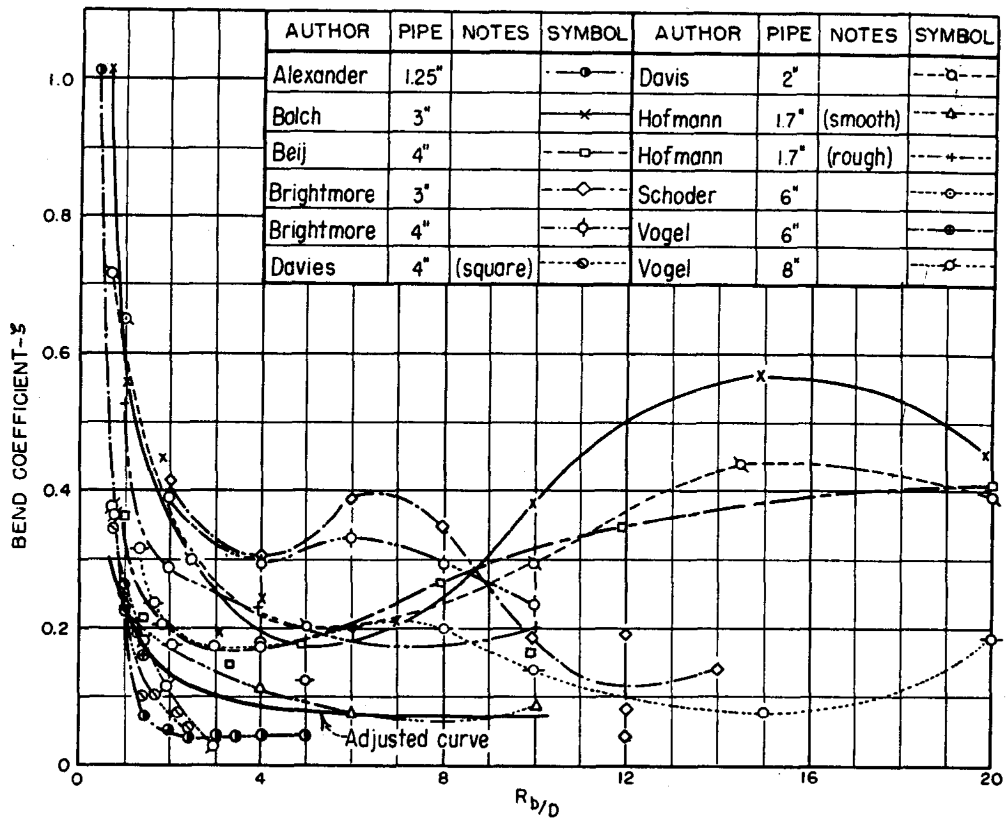
It therefore appears that the engineering profession has been making a practice of overestimating bend loss coefficients for large pipes by from 50 to 100 percent. This was partially verified when an attempt was made to separate bend losses from the experimental results of figures 5 through 10. It was found that, when bend losses were subtracted out using the generally accepted coefficients of $0.15\,\frac{V^2}{2g}$ for a 90° bend and $0.11\,\frac{V^2}{2g}$ for a 45° bend, the remaining straight pipe friction often fell below the values given by the curve for smooth pipe. Although there is much to be desired in the way of confirmation, the authors are convinced that bend loss coefficients for large pipe are being consistently overestimated.

Loss coefficients for other than 90° bends can be obtained by multiplying the 90° bend coefficients in figure 19A by a factor from figure 19B.

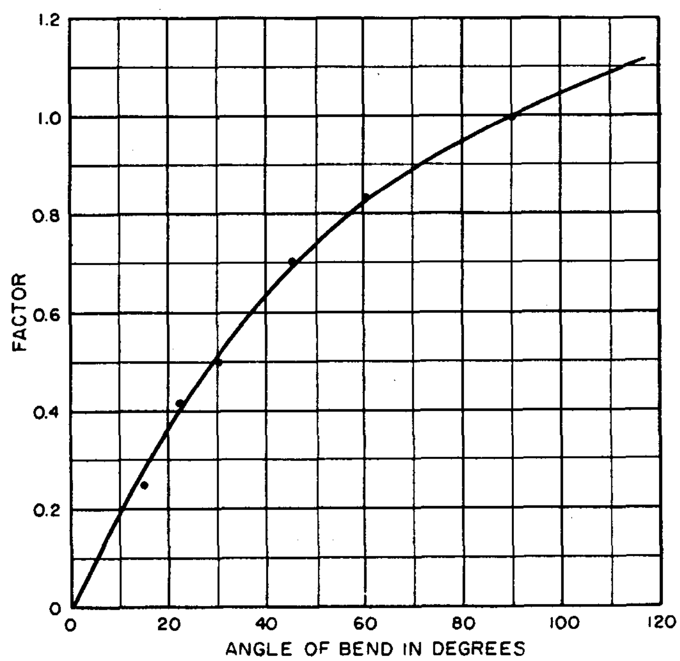
[14] Elder, R. A., "Friction Measurements in Apalachia Tunnel," *Transactions*, ASCE, Vol. 123, 1958, p. 1249.

[15] Beij, K. H., "Pressure Losses for Fluid Flow in 90° Pipe Bends," *Journal of Research*, National Bureau of Standards, Vol. 21, July 1938.

[16] Anderson, A. G., and Straub, L. G., "Hydraulics of Conduit Bends," St. Anthony Falls Hydraulic Laboratory, *Bulletin* No. 1, Minneapolis, Minn., December 1948.



A-VARIATION OF BEND COEFFICIENT WITH RELATIVE RADIUS FOR 90° BENDS OF CIRCULAR CROSS SECTION, AS MEASURED BY VARIOUS INVESTIGATORS



B-FACTORS FOR OTHER THAN 90° BENDS

FIGURE 19.—*Bend loss coefficients as observed are tabulated in A, and a multiplying factor for bends other than 90° can be obtained from B.*

Information for the Designer

Experimental Information

FOR THE designer, the experimental information on straight pipe resistance is condensed in figures 14 through 18. This, together with a chart of the Moody diagram (see fig. 4), is essentially all that is needed for computing frictional resistance in large straight pipelines.

Additional Useful Information

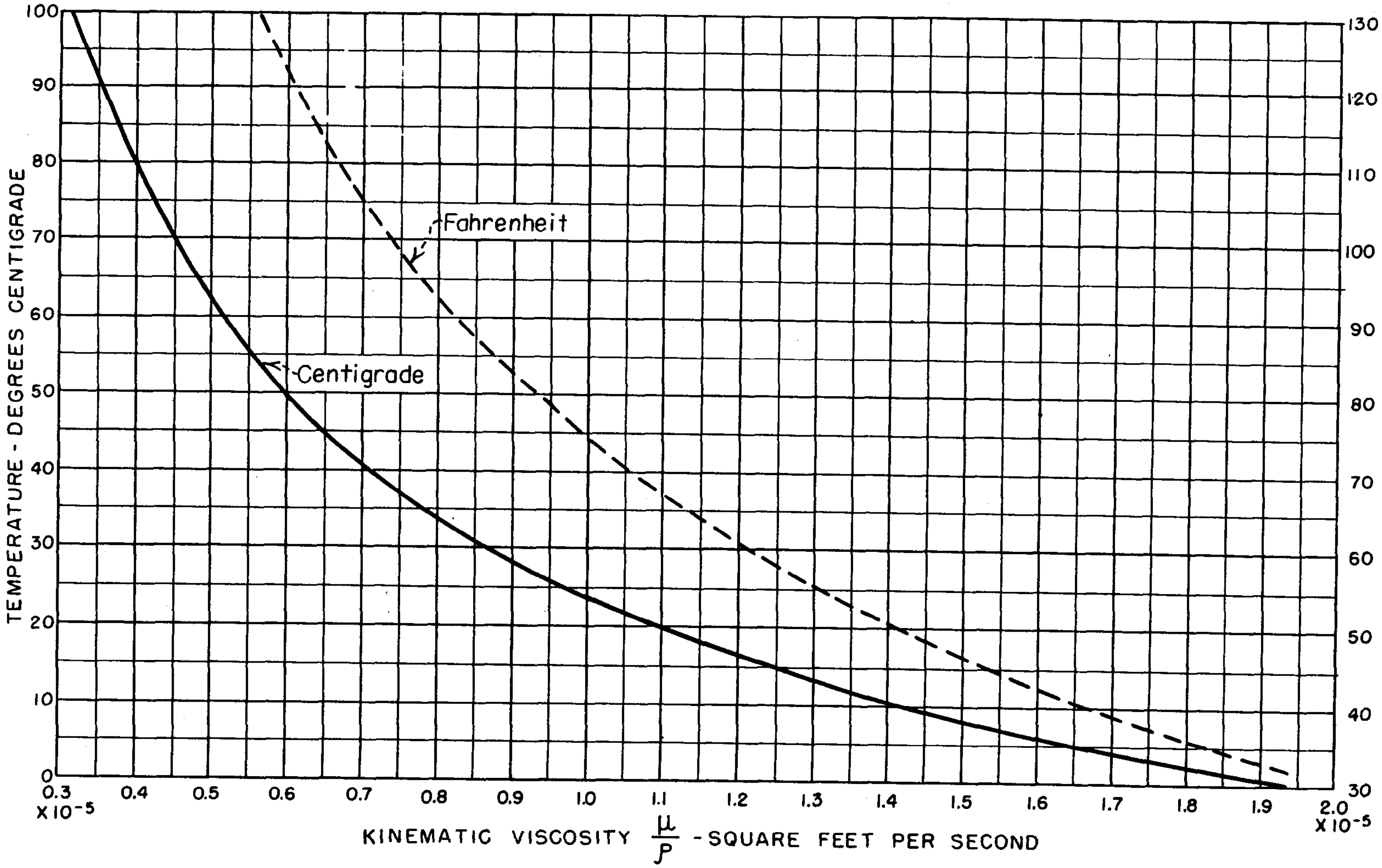
Other tables and graphs are included which will be found useful in the solution of fluid-flow problems, especially the kinematic viscosity tables and charts which are needed for the determination of the Reynolds number. The kinematic viscosity of water, which varies with the temperature, is shown for the Fahrenheit and Centigrade scales in figure 20. The kinematic viscosities of fluids other than water,[17] such as brine, oils, and some gases, are shown in figure 21. It should be remembered that the kinematic viscosity of gases varies with pressure as well as temperature. The values shown in figure 21 are for standard atmospheric conditions. Table VII gives the kinematic viscosity of dry air for various values of temperature and pressure. Table VIII shows the specific weight of dry air for various temperatures and pressures Figure 22 was prepared for conversion of altitude to standard pressure in inches of mercury.

[17] This chart appears in *Fluid Mechanics for Hydraulic Engineers*, by Hunter Rouse, McGraw-Hill, 1938.

Use of Air in Hydraulic Model Testing

When air or gas travels at high velocity through a conduit, a change in density occurs. This change in density affects any pressure reading that might be observed along the conduit. Figure 23 has been included to indicate the change in density and pressure for air at one atmosphere pressure and 20° C. when high velocities are involved. This illustration applies principally to hydraulic model testing where air is employed as the fluid rather than water.

The engineer has been skeptical about the use of air for testing hydraulic machines such as valves, turbines, pumps, etc., as compression of the air caused by high velocity is unavoidable. Figure 23 demonstrates that this distrust toward the use of air for quantitative measurements in models is far from justified. The mechanical properties of air can usually be considered constant in the region of operation up to a velocity of 300 feet per second.



KINEMATIC VISCOSITY OF WATER RELATIVE TO TEMPERATURE

FIGURE 20.—*The ratio of the kinematic viscosity of water to its temperature may be obtained from this chart.*

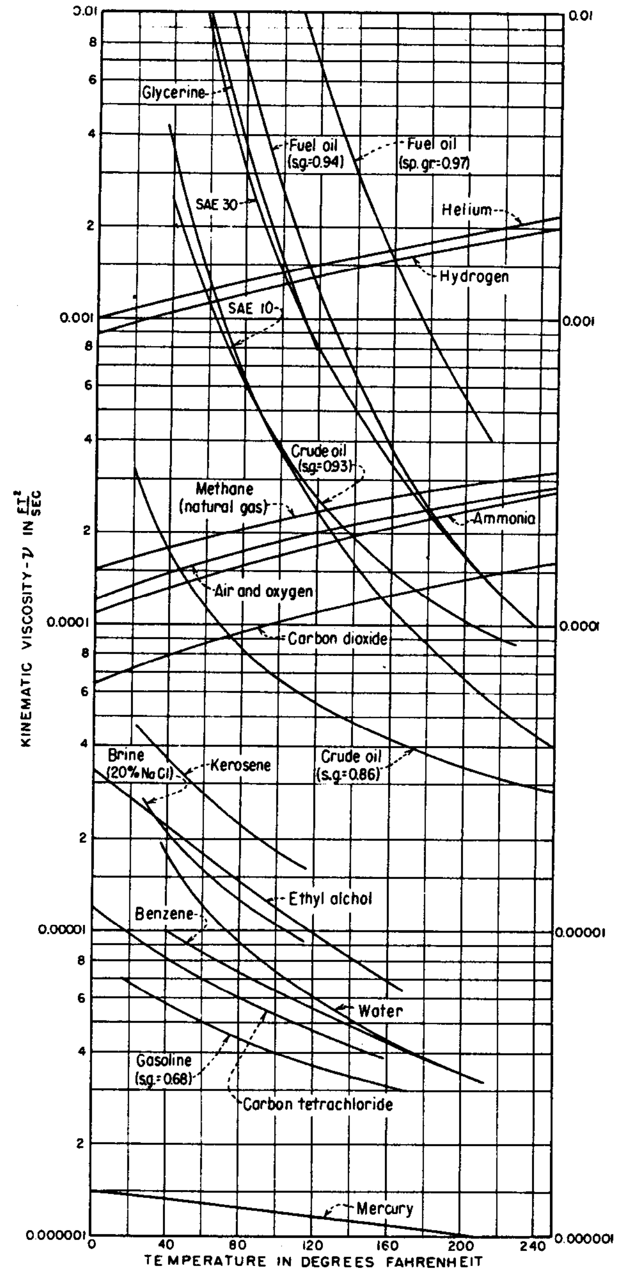


FIGURE 21.—*The ratio of the kinematic viscosity of various fluids to temperature is shown in this figure.*

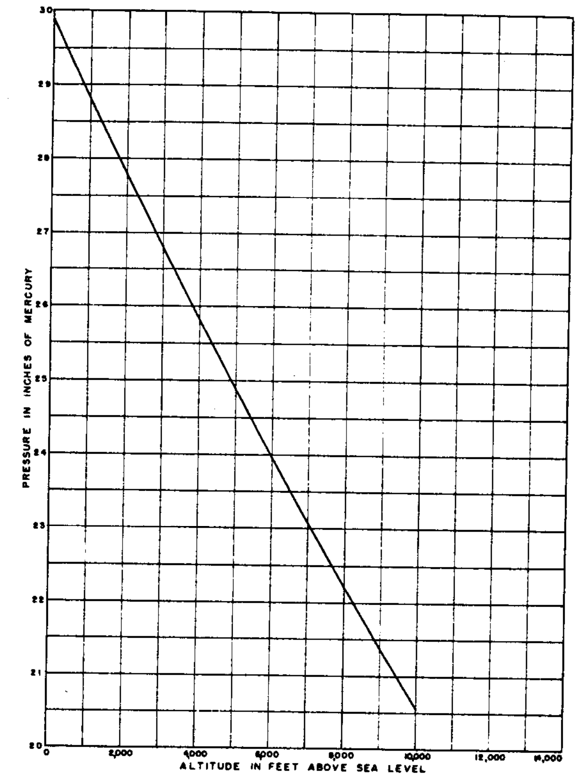


FIGURE 22.—*Atmospheric pressure (in inches) can be ascertained for various altitudes from this chart.*

As the figure shows, the density of air varies approximately 3.5 percent for a velocity of 300 feet per second, and the piezometric pressure measured throughout a model would be no more than 1.8 percent in error for the same velocity. Thus, by restricting air velocity to 300 feet per second, there is no reason to expect the change in density to have any decisive effect on the flow phenomena, on the energy exchange, or on the performance of the model valve or machine. This conclusion has been confirmed by aerodynamic studies during the past few years.[18]

The Reynolds Number

In pipe friction problems, it is often necessary to determine the Reynolds number by trial. To simplify this procedure, a graphical method is presented in figure 24. To obtain the Reynolds number graphically, enter figure 24 with the proper values of velocity and pipe diameter. From the point of intersection of the rectangular axes, draw a line at 45 degrees to the point where the line intersects the proper value of the kinematic viscosity. Following over horizontally from this point, the Reynolds number can be read from the scale at the extreme right of the graph. An example illustrated by the dotted line in figure 24 further illustrates the procedure.

[18] Keller, Dr. C., "Aerodynamic Experimental Plants for Hydraulic Machines," *Schweizerische Bauzeitung*, Vol. 110, No. 17, Oct. 23, 1937. Translated from the German by U.S. Waterways Experiment Station, Translation No. 39-4, Vicksburg, Miss.

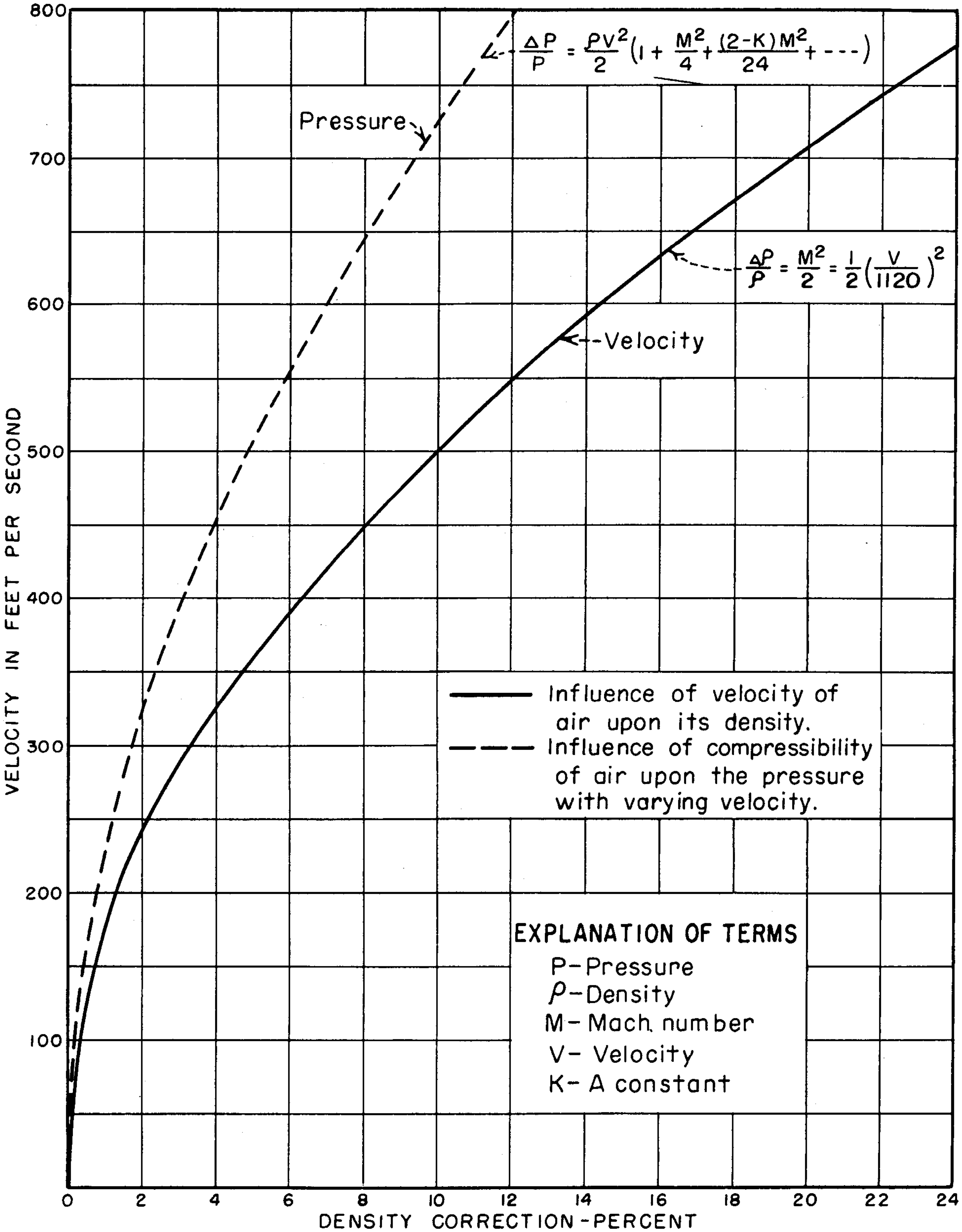


FIGURE 23.—*Correction in density of air due to compressibility at high velocities (curves drawn for one atmosphere pressure and 20° C.).*

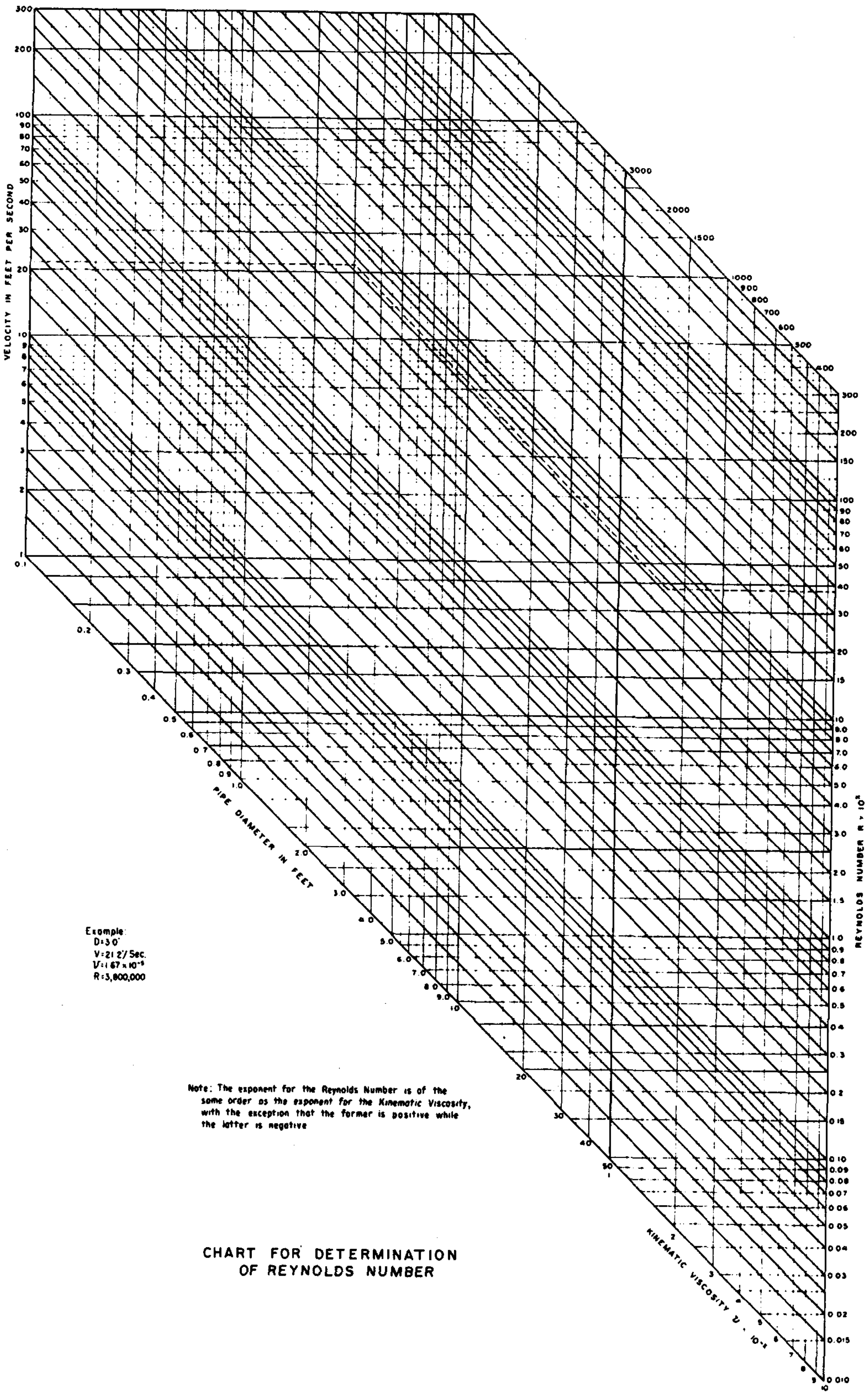


FIGURE 24.—*Use of this chart in the determination of the Reynolds number is described in the section on "Application of Results," beginning on page 45.*

TABLE VII.—*Kinematic viscosity of dry air*

$$\nu = \frac{\text{ft.}^2}{\text{sec.}} \times 10^{-4}$$

Temp. F.°	Pressure—inches of mercury																				
	20	20.5	21	21.5	22	22.5	23	23.5	24	24.5	25	25.5	26	26.5	27	27.5	28	28.5	29	29.5	29.92
0	1.90	1.86	1.81	1.77	1.73	1.69	1.65	1.62	1.58	1.55	1.52	1.49	1.46	1.43	1.41	1.38	1.36	1.33	1.31	1.29	1.27
10	1.97	1.92	1.88	1.83	1.79	1.75	1.71	1.68	1.64	1.61	1.58	1.55	1.52	1.49	1.46	1.43	1.41	1.38	1.36	1.34	1.32
20	2.04	1.99	1.95	1.90	1.86	1.81	1.77	1.74	1.70	1.67	1.63	1.60	1.57	1.54	1.51	1.49	1.46	1.43	1.41	1.38	1.36
30	2.12	2.07	2.02	1.97	1.93	1.88	1.84	1.80	1.77	1.73	1.70	1.66	1.63	1.60	1.57	1.54	1.51	1.49	1.46	1.44	1.42
40	2.20	2.15	2.09	2.04	2.00	1.95	1.91	1.87	1.83	1.79	1.76	1.72	1.69	1.66	1.63	1.60	1.57	1.54	1.52	1.49	1.47
50	2.27	2.22	2.17	2.12	2.07	2.02	1.98	1.94	1.90	1.86	1.82	1.78	1.75	1.72	1.69	1.66	1.63	1.60	1.57	1.54	1.52
60	2.35	2.30	2.24	2.19	2.14	2.09	2.04	2.00	1.96	1.92	1.88	1.84	1.81	1.77	1.74	1.71	1.68	1.65	1.62	1.59	1.57
70	2.44	2.38	2.32	2.27	2.22	2.17	2.12	2.07	2.03	1.99	1.95	1.91	1.88	1.84	1.80	1.77	1.74	1.71	1.68	1.65	1.63
80	2.51	2.46	2.40	2.34	2.29	2.24	2.19	2.14	2.10	2.05	2.01	1.97	1.94	1.90	1.86	1.83	1.80	1.76	1.74	1.70	1.68
90	2.60	2.54	2.48	2.42	2.36	2.31	2.26	2.21	2.17	2.12	2.08	2.04	2.00	1.96	1.93	1.89	1.86	1.82	1.79	1.76	1.74
100	2.68	2.61	2.55	2.49	2.43	2.38	2.33	2.28	2.23	2.18	2.14	2.10	2.06	2.02	1.98	1.95	1.91	1.88	1.85	1.82	1.79
110	2.77	2.70	2.64	2.58	2.52	2.46	2.41	2.36	2.31	2.26	2.22	2.17	2.13	2.09	2.05	2.01	1.98	1.94	1.91	1.88	1.85
120	2.85	2.79	2.72	2.66	2.60	2.54	2.48	2.43	2.38	2.33	2.29	2.24	2.20	2.15	2.11	2.08	2.04	2.00	1.97	1.93	1.91
130	2.94	2.87	2.80	2.74	2.67	2.61	2.55	2.50	2.45	2.40	2.35	2.30	2.26	2.22	2.18	2.14	2.10	2.06	2.03	1.99	1.96
140	3.03	2.96	2.89	2.82	2.76	2.69	2.63	2.58	2.53	2.47	2.43	2.38	2.33	2.29	2.24	2.20	2.17	2.13	2.09	2.06	2.03
150	3.12	3.05	2.98	2.91	2.84	2.78	2.71	2.66	2.60	2.55	2.50	2.45	2.40	2.36	2.31	2.27	2.23	2.19	2.15	2.12	2.09
160	3.21	3.13	3.06	2.98	2.92	2.85	2.79	2.73	2.67	2.62	2.57	2.51	2.47	2.42	2.38	2.33	2.29	2.25	2.21	2.17	2.14
170	3.31	3.26	3.15	3.08	3.01	2.94	2.87	2.81	2.76	2.70	2.65	2.59	2.55	2.50	2.45	2.41	2.36	2.32	2.28	2.24	2.21
180	3.40	3.32	3.24	3.16	3.09	3.02	2.95	2.89	2.83	2.77	2.72	2.66	2.62	2.56	2.52	2.47	2.43	2.38	2.34	2.30	2.27
190	3.49	3.41	3.33	3.25	3.17	3.10	3.03	2.97	2.91	2.85	2.80	2.74	2.69	2.63	2.58	2.54	2.49	2.45	2.41	2.37	2.33
200	3.59	3.50	3.42	3.34	3.26	3.19	3.12	3.06	2.99	2.93	2.87	2.81	2.76	2.71	2.66	2.61	2.56	2.52	2.48	2.43	2.40
210	3.70	3.61	3.52	3.44	3.36	3.29	3.21	3.15	3.08	3.02	2.96	2.90	2.85	2.79	2.74	2.69	2.64	2.59	2.55	2.51	2.47

TABLE VIII.—*Specific weight of dry air*

$$\gamma=\frac{\text{lb.}}{\text{ft.}^3}\times 10^{-2}$$

Temp. F.°	Pressure—inches of mercury																					
	20	20.5	21	21.5	22	22.5	23	23.5	24	24.5	25	25.5	26	26.5	27	27.5	28	28.5	29	29.5	29.92
0	5.77	5.91	6.05	6.20	6.35	6.49	6.63	6.78	6.92	7.06	7.21	7.35	7.50	7.64	7.78	7.93	8.07	8.22	8.36	8.51	8.63
10	5.64	5.78	5.93	6.07	6.21	6.35	6.49	6.63	6.77	6.91	7.05	7.20	7.34	7.48	7.62	7.76	7.90	8.04	8.18	8.33	8.44
20	5.53	5.66	5.80	5.94	6.08	6.22	6.36	6.50	6.63	6.77	6.91	7.05	7.19	7.32	7.46	7.60	7.74	7.88	8.01	8.15	8.27
30	5.41	5.55	5.68	5.82	5.96	6.09	6.22	6.36	6.50	6.63	6.77	6.90	7.04	7.17	7.31	7.44	7.58	7.71	7.85	7.99	8.10
40	5.30	5.44	5.57	5.70	5.84	5.97	6.10	6.23	6.37	6.50	6.63	6.76	6.90	7.03	7.16	7.30	7.43	7.56	7.69	7.83	7.94
50	5.20	5.33	5.46	5.59	5.72	5.85	5.98	6.11	6.24	6.37	6.50	6.63	6.76	6.89	7.02	7.15	7.28	7.41	7.54	7.67	7.78
60	5.10	5.23	5.36	5.48	5.61	5.74	5.87	5.99	6.12	6.25	6.38	6.50	6.63	6.76	6.89	7.01	7.14	7.27	7.40	7.52	7.63
70	5.01	5.13	5.26	5.38	5.51	5.63	5.76	5.88	6.01	6.13	6.26	6.38	6.51	6.63	6.76	6.88	7.01	7.13	7.26	7.38	7.49
80	4.91	5.03	5.16	5.28	5.40	5.53	5.65	5.77	5.89	6.02	6.14	6.26	6.39	6.51	6.63	6.76	6.88	7.00	7.12	7.25	7.35
90	4.82	4.94	5.06	5.18	5.30	5.42	5.54	5.67	5.79	5.91	6.03	6.15	6.27	6.39	6.51	6.63	6.75	6.87	6.99	7.11	7.21
100	4.74	4.86	4.97	5.09	5.21	5.33	5.45	5.57	5.68	5.80	5.92	6.04	6.16	6.28	6.40	6.52	6.63	6.75	6.87	6.99	7.09
110	4.65	4.77	4.88	5.00	5.12	5.23	5.35	5.47	5.58	5.70	5.82	5.93	6.05	6.17	6.28	6.40	6.51	6.63	6.75	6.86	6.96
120	4.57	4.69	4.80	4.92	5.02	5.14	5.26	5.37	5.49	5.60	5.72	5.83	5.95	6.06	6.17	6.29	6.40	6.52	6.63	6.75	6.84
130	4.50	4.61	4.72	4.83	4.95	5.06	5.17	5.28	5.40	5.51	5.62	5.73	5.85	5.96	6.07	6.18	6.30	6.41	6.52	6.63	6.73
140	4.42	4.53	4.64	4.75	4.86	4.97	5.08	5.19	5.30	5.41	5.52	5.64	5.75	5.86	5.97	6.08	6.19	6.30	6.41	6.52	6.61
150	4.35	4.46	4.56	4.67	4.78	4.89	5.00	5.11	5.22	5.33	5.43	5.54	5.65	5.76	5.87	5.98	6.09	6.20	6.30	6.41	6.50
160	4.28	4.38	4.49	4.60	4.70	4.81	4.92	5.03	5.13	5.24	5.34	5.45	5.56	5.67	5.77	5.88	5.99	6.09	6.20	6.31	6.40
170	4.21	4.31	4.42	4.53	4.63	4.74	4.84	4.95	5.05	5.16	5.26	5.37	5.47	5.58	5.68	5.79	5.90	6.00	6.10	6.21	6.30
180	4.14	4.25	4.35	4.46	4.56	4.66	4.76	4.86	4.97	5.08	5.18	5.28	5.39	5.49	5.59	5.70	5.80	5.90	6.01	6.11	6.20
190	4.08	4.18	4.28	4.39	4.49	4.59	4.69	4.79	4.90	5.00	5.10	5.20	5.30	5.41	5.51	5.61	5.71	5.81	5.92	6.02	6.10
200	4.02	4.12	4.22	4.32	4.42	4.52	4.62	4.71	4.82	4.92	5.02	5.12	5.22	5.32	5.42	5.52	5.62	5.72	5.82	5.93	6.01
210	3.96	4.06	4.16	4.26	4.35	4.45	4.55	4.65	4.75	4.85	4.95	5.05	5.15	5.24	5.34	5.44	5.54	5.64	5.74	5.84	5.92

Where horseshoe conduits are to be considered, the Reynolds number is usually computed for an equivalent circular cross section, or it may be computed by substituting four times the hydraulic radius for D. In the case of rectangular conduits or rectangular air ducts flowing full, four times the hydraulic radius can safely be used for D, provided that the cross section is not extremely irregular and provided that the flow is turbulent. This practice would be greatly in error for viscous flow and questionable for flow at values of Reynolds number less than 500,000. The mean hydraulic radius has been selected as the length criterion for other than circular pipes on the supposition that the resistance for pipes of the same area is proportional to the fluid in contact with the pipe walls.

Roughness Coefficients Other Than f

Some engineers are accustomed to evaluating roughness of a pipe surface in terms of C in the Chezy formula or n in the Kutter and Manning expressions rather than with respect to the Darcy coefficient f. Although the Chezy formula will undoubtedly continue in use for some time for open-channel flow, it is losing ground rapidly in the field of closed conduits flowing full. The reason should be obvious after reviewing the method outlined in this monograph in which dynamic similarity is maintained regardless of the fluid used and practically all plottings are expressed in dimensionless terms.

The Chezy formula is

$$v=C\sqrt{rs}, \tag{2}$$

the Manning expression for C is

$$C=\frac{1.486}{n}\, r^{1/6}, \tag{3}$$

and the Kutter expression for C is

$$C=\frac{41.66+\dfrac{1.811}{n}+\dfrac{0.00281}{s}}{1+\left(41.66+\dfrac{0.00281}{s}\right)\dfrac{n}{r^{1/2}}} \tag{4}$$

The various roughness coefficients in the above formulas may be transferred to f by the following expressions:

$f=\dfrac{8g}{C^2}$ in expression (2)

$f=\dfrac{116.7n^2}{r^{1/3}}$ in expressions (3) and (4).

The dimensions in the above expressions are feet and seconds. In applying the latter expression for f to both the Manning and Kutter formulas, it is recognized that a small difference exists in the value of n. When it is considered, however, that the selection of n is usually dependent on the judgment and experience of the individual, the difference assumes little importance.

Application of Results

THE FOLLOWING examples were prepared to illustrate the use of the foregoing information.

Example 1 (Friction loss in conduit carrying water)

Suppose it is desired to estimate the friction loss in 2,000 feet of straight, new, 36-inch-diameter, continuous-interior steel pipe carrying 150 second-feet of water at 40° F. The pipe has been factory dipped in hot asphalt.

From figure 20, the kinematic viscosity of water at 40° F. is 1.67×10^{-5}.

$$V=\frac{Q}{A}=\frac{150}{7.069}=21.22 \text{ feet per second.}$$

Entering the rectangular coordinates of figure 24 with $V=21.2$ and $D=3.0$, then following down on a 45° angle to a kinematic viscosity of 1.67×10^{-5}, the corresponding Reynolds number is approximately 3,800,000.

From figure 15, hot-asphalt-dipped, continuous-interior pipe shows a value of $\epsilon=0.0003$.

$$\frac{\epsilon}{D}=\frac{0.0003}{3.0}=0.00010$$

Entering figure 4 with this value of ϵ/D and a Reynolds number of 3.8×10^6, the friction factor f is 0.0124.

The frictional resistance in 2,000 feet of this pipe will be:

$$h_f=f\frac{L}{D}\frac{V^2}{2g}=0.0124\frac{2{,}000}{3.0}\frac{(21.2)^2}{64.4}$$

$$=57.8 \text{ feet of water.}$$

Example 2 (Determination of velocity in an air duct)

A horizontal rectangular air duct is employed for the purpose of relieving extremely low pressures in a hydraulic conduit. The duct is of concrete and is smooth, straight, and continuous, measuring 3 by 4 feet in section and 500 feet long. The duct begins in a well-rounded entrance with a loss of $0.10\frac{V^2}{2g}$. The differential pressure measured between the atmosphere and the lower end of the duct is 0.60 foot of water for an air temperature of 60° F. (elevation sea level). The average velocity in the duct is desired.

From figure 14,

$$\epsilon=0.0003$$

and

$$\frac{\epsilon}{D}=\frac{\epsilon}{4r}=\frac{0.0003}{3.43}=0.00009.$$

Entering figure 4 with the above value of ϵ/D and an assumed value of $R_n=2\times10^6$,

$$f=0.0126.$$

Writing the Bernoulli equation between the entrance (1) and the exit (2) of the conduit,

$$\frac{P_1}{\gamma}=\frac{P_2}{\gamma}+\frac{V^2}{2g}+\text{losses.}$$

The losses=

$$0.10\frac{V^2}{2g}+0.0126\times\frac{500}{3.43}\frac{V^2}{2g}=1.94\frac{V^2}{2g}$$

$$\frac{P_1-P_2}{\gamma}=2.94\frac{V^2}{2g}.$$

The specific weight of dry air at 60° F. and standard pressure is 0.0763 (see table VIII).

$$\frac{0.60\times62.5}{0.0763}=2.94\frac{V^2}{2g}.$$

$$\frac{V^2}{2g}=167 \text{ and } V=104 \text{ feet per second.}$$

As the Reynolds number was estimated, it is necessary to check back on that figure.

From table VII, the kinematic viscosity of dry air at sea level for 60° F. is 1.57×10^{-4}.

$$R_n=\frac{104\times3.43\times10^4}{1.57}=2{,}270{,}000.$$

Figure 4 shows no appreciable change in the value of f for this change in the Reynolds number; thus, the correct velocity is 104 feet per second.

Example 3 (Pressure drop across a fan in a tunnel)

The Moffat Tunnel on the Denver & Rio Grande Western Railroad in Colorado is straight and 6.21 miles long (32,798 feet). A cross section consists of vertical side walls rising 14 feet 8 inches above the ties, surmounted by a circular arch with a radius of 8 feet. The tunnel is located at an average elevation of approximately 9,200 feet. About one-half of the tunnel is lined with concrete and the other one-half is hewn through rock. Fans located at the east portal blow 401,000 cubic feet of free air per minute through the tunnel. It is desired to know the differential pressure across the fan if the temperature of the air is 30° F.

Assume that the average cross section of the unlined section of tunnel is the same as the lined portion and that $f=0.08$ for the unlined portion. Although the lined section is fairly smooth, assume that the overall rugosity of the surface $\epsilon=0.002$ foot to compensate for ballast and ties.

From figure 22 the standard atmospheric pressure at an altitude of 9,200 feet is 21.2 inches of mercury.

Entering table VII with a temperature of 30° F. and a pressure of 21.2 inches of mercury, it is found that the kinematic viscosity of the air flowing through the tunnel is 2.0×10^{-4}. The area of the tunnel above the ties is 335.2 square feet. The diameter of a circle having an equivalent area is 20.66 feet.

The average velocity in the tunnel will be

$$\frac{401{,}000}{60\times335.2}=19.94 \text{ feet per second.}$$

Entering figure 24 with the above values of V, D, and ν, the Reynolds number, $R_n=2{,}000{,}000$.

$$\frac{\epsilon}{D}=\frac{0.002}{20.66}=0.00010.$$

Entering figure 4 with this value and $R_n=2{,}000{,}000$, $f=0.0129$.

The pressure drop necessary to produce the required flow will be

$$h_f=0.0129\times\frac{16{,}399}{20.66}\times\frac{(19.94)^2}{2g}=63.2 \text{ feet of air}$$

for the concrete lined section, and

$h_f=0.080\times4{,}884=392$ feet of air (pressure drop) for the unlined portion.

From table VIII, the specific weight of dry air at 30° F. for an atmospheric pressure of 21.2 inches of mercury is 0.0574 pound per cubic foot.

The total pressure drop due to friction in the tunnel is then

$$(63.2+392)\,\frac{0.0574}{144}$$

$$=0.181 \text{ p.s.i., or } 0.419 \text{ foot of water.}$$

This is also the total differential pressure across the fan.

Example 4 (Head and discharge that will just permit a penstock to flow full)

A steel pipe, triple-riveted throughout, 6.0 feet in diameter, with a circular bell-mouth entrance, begins at the upstream face of a dam and continues 1,000 feet downstream on a constant slope of 0.10. The surface has been protected with a brush coat asphalt similar to that shown in figure 13B.

Assuming the entrance loss to be negligible, it is desired to know the head on the entrance and the discharge which will just permit the tunnel to flow full throughout its entire length with water at 50° F.

From figure 17, $\epsilon=0.006$ for this triple-riveted pipe, and

$$\frac{\epsilon}{D}=\frac{0.006}{6}=0.001.$$

Assuming $R_n=20\times10^6$, figure 4 shows $f=0.020$.

Writing the Bernoulli equation between the entrance (1) and the exit (2) of the pipe:

$$Z_1+\frac{P_1}{\gamma}=\frac{V^2}{2g}+\text{losses}$$

$$0.10\times1{,}000+\frac{P_1}{\gamma}=\frac{V^2}{2g}+0.020\times\frac{1{,}000}{6}\frac{V^2}{2g}$$

$$100+\frac{P_1}{\gamma}=\frac{V^2}{2g}+3.33\frac{V^2}{2g}$$

$$\frac{V^2}{2g}=\frac{\frac{P_1}{\gamma}+100}{4.33}.$$

When the friction slope equals the energy slope (which is 100 feet vertical in 1,000 feet horizontal), the pipe will just flow full.

Assuming values of $\frac{P_1}{\gamma}$ in the above expression, the following values are obtained:

$\frac{P_1}{\gamma}$	$\frac{V^2}{2g}$	$h_f=3.33\frac{V^2}{2g}$	V	Q c.f.s.
70	39. 3	130. 8	----------	----------
50	34. 6	115. 5	----------	----------
40	32. 4	107. 6	----------	----------
30	30. 0	*100*	44. 0	1, 245

Thus, the head on the centerline of the entrance to the pipe will be 30 feet and the discharge 1,245 second-feet when the pipe just begins to flow full.

Rechecking the friction factor for the discharge of 1,245 second-feet,

$$R_n=\frac{VD}{\nu}=\frac{44\times6\times10^5}{1.41}=18{,}700{,}000.$$

Figure 4 shows that the change in the Reynolds number does not affect the value of f; thus, the above solution is correct.

APPENDIX

Table A. Friction Tests of Concrete Pipe

Description and References

Curve 1.—Smooth cement surface; discharge rated by a current meter placed in the tailrace; about 10 percent of the line located on a small degree of curvature ($r/D=30$). About 5 percent subtracted from the overall measured losses as an estimate of entrance losses. The writers estimate that the plotted losses are about 1 percent greater than normal. This was a reliable test. ("Correnti Uniformi entro Grandi Condotte e Grandi Canali, Milano," by Giuliode Marchi, Milan, Italy, 1932–36; Library Data File, USBR, 91–241.)

Curve 2.—Smooth surface resulting from use of steel forms; discharge rated by Gibson method. The section measured was straight. The velocities are probably 3 percent in error. Combining all errors, the friction factor was probably not more than 4 percent in error. (*Transactions*, ASCE, Vol. 101, 1936, p. 1409; also Library Data File, USBR, 91–241.)

Curve 3.—Precast in steel forms 6 feet long; discharge rated by color movement, current meter, and Cipoletti weir. All joints were carefully calked on the inside. The alinement was straight. There was a gentle vertical bend near the inlet and one near the outlet. (*Bulletin No. 852*, by Fred C. Scobey, USDA, Washington, D.C., 1924, p. 38.)

Curve 4.—Lining and the joints smooth; discharge rated by pitot tube. The alinement of the first section was nearly straight and there was a gentle sinuous curve vertically in the second section. This pipe was precast in 12-foot oiled steel forms. (*Engineering News-Record,* Apr. 29, 1926, p. 678.)

Curve 5.—These experiments were reported by Bazin to be "perfect in bore." The alinement was straight and the results indicate an unusually smooth pipe. (*Bulletin No. 852*, USDA, Washington, D.C., 1924, p. 79.)

Curve 6.—Lining finished with a brush coat. The finish coat wore off on the bottom but brush marks were still visible on the sides. The approach and the alinement were straight. The inlet was rounded. The readings were taken during flood flows, the discharge being rated by current meter. (*Transactions*, ASCE, Vol. 93, 1929, p. 1588.)

Curve 7.—Lining finished with a brush coat. The finish coat wore off on the bottom but brush marks were still visible on the sides. The alinement was straight, the approach curved, and the inlet rounded. The readings were taken during flood flows, the discharge being rated by current meter. (Reference same as for Curve 6.)

Curve 8.—Tests by E. Kemler involving observations on 1,500 to 2,000 diameters of brass pipe 0.103 inch to 5.0 inches in diameter. The Nikuradse tests, indicated as plotted points (Curve 11, fig. 9), were included in the data that produced the Kemler curves. (*Transactions*, ASME, Hydraulics Section, Vol. 55, 1933, pp. 7–32.)

Curve 9.—Hand-troweled cement finish; discharge rated by current meter placed in the tailrace. There were seven horizontal curves and two large vertical curves. The tests are questionable. (Reference same as for Curve 1.)

Curve 10.—Some rough spots remained on the surface after the steel forms were removed. This was a poor test, no account being taken of the change in size and shape of the cross section. The alinement was irregular, with six horizontal bends and two vertical bends. The estimated error in the results is ± 15 percent. (Letter dated March 5, 1931, from the Pacific Gas & Electric Co., San Francisco, Calif.)

Curve 11.—Smooth pipe; the plotted points designated Curve 11 in figure 9 denote tests by J. Nikuradse on brass pipe from 0.033 inch in diameter to 3.28 inches in diameter. The equation through these points is good for extrapolation from $R=30^6$ to 10^8. (*Forschungsheft 356.* Verein Deutscher Ingenieure, 1932, p. 30.)

Curve 12.—Steel forms were used and the concrete was rubbed with carborundum brick. The discharge was rated by color movement. The line included five bends on 800-foot radii with short tangents between. This is equivalent to a curve length of 3,060 feet and a radius of 1,665 feet ($r/D=92$). The bend loss (± 5 percent) and surge tank losses were not considered. The data used were taken from a curve passing through 42 observations. (*Bulletin No. 852*, USDA, Washington, D.C., 1924, p. 83; supplemented by correspondence with the Ontario Power Co. in June 1931 and April 1935, including a map and a profile.

Curve 13.—Hand-troweled cement finish; discharge rated by current meter placed in the tailrace. This was a very reliable test. The pipe was straight, free from bends and entrance losses, and was equipped with three excellent mercury manometers. The line was built in 1917. (Reference same as for Curve 1.)

Curve 14.—Smooth cement surface; generator rating of discharge. It is reported that losses were high because of underestimated intake losses and poor location of the lower piezometer. The writers estimate that these factors make the plotted points 7 percent high. (References same as for Curve 1.)

Curve 15.—On this test, oiled forms were used and a neat cement brush coat. The lining was not smooth. The pipe was probably new at the time of the test, and the discharge was rated by a weir below the plant. Surge chamber losses were neglected. The regained velocity head loss h_v was assumed equal to the entrance losses. The invert was placed by hand without forms and it presented a rather rough, uneven appearance. (*Proceedings*, June 1923, Convention, Pacific Coast Electrical Association, p. 139; *Engineering News-Record*, Oct. 11, 1923, p. 598; and Library Data File, USBR, 91–241.)

Curve 16.—Surface originally smooth, had become somewhat eroded in 4 years. Discharge was rated by color movement. The line was precast in 4-foot lengths in oiled steel forms. Joints were smooth. The water flowing in this line contains sharp basalt particles which have eroded the bottom of the intake like a sandblast. (*Bulletin No. 852*, USDA, Washington, D.C., 1924, p. 51.) The water enters the pipe in a very turbulent state and the erosion extends 150 feet from the intake. (*Bulletin No. 852*, USDA, Washington, D.C., 1924, p. 36; also Drawing No. 33.19(b) in the Denver Office of USBR.)

Curve 17.—Use of steel forms in place have resulted in rough joints but with a smooth surface between joints. The line contains a sharp 90° bend and two slight vertical bends in the reach measured. About 19 diameters upstream there is the last of two bends and constrictions resulting from repair work. The exit head loss was ignored and the results are not consistent. The concrete joints protrude as much as 0.15 foot in places. The effect of the bends was not considered in the computations. (*Bulletin No. 852*, USDA, Washington, D.C., 1924, p. 81; *Transactions*, ASCE, Vol. 73, September 1911, pp. 399 and 460; "Catskill Water Supply of New York," by Lazarus White, John Wiley & Sons, Inc., New York, N.Y., 1913, pp. 66 and 73; and *Engineering Record*, Jan. 1, 1910, p. 26; Sept. 17, 1910, p. 312; Mar. 11, 1911, p. 279; and Feb. 28, 1914, p. 240.)

Curve 18.—Surface polished. Friction values taken from curve prepared by E. W. Spies. ("Turbulente Stromungon in geraden und gekrummten glotten Rohrleitungen bei hohen Reynolds schen Zahlen," by Romano Gregorig, Dipl. Masch-Ingenieure, Eidgenossischen Technischen Hochschule in Zurich, No. 695, 1933, D.F. 91–26.)

Curve 19.—Precast in oiled steel forms with 12-foot lengths. The joints were smooth and carefully laid. Discharge was rated by Venturi meter. In the first test there were 29 bends; in the second, the line was slightly sinuous; and, in the third, the line was nearly straight. (*Engineering News-Record,* May 28, 1925, p. 897.)

Curve 20.—Smooth surface; discharge rated by color movement. The line was quite straight in horizontal alinement. Vertical curves were long and gentle. The reach includes five 6-inch valves and three manholes. (*Bulletin No. 852,* USDA, Washington, D.C., 1924, p. 35.)

Curve 21.—Smooth surface; sections precast in 6-foot steel forms. Discharge was rated by color movement. The alinement was straight. The reach includes eight 6-inch valves, two 6-inch blowoffs, and four 12-inch by 14-inch manholes. The inside surface was painted with a rich cement grout. (*Bulletin No. 852,* USDA, Washington, D.C., 1924, p. 41.)

Curve 22.—Smooth surface; discharge rated by water meter. The conduit in the concrete was formed by a 36.5-foot length of smooth, straight rubber hose. (*Technical Memorandum No. 339,* USBR, Denver, Colo., June 15, 1933.)

Curve 23.—Sections precast in oiled steel forms, 4 feet long, steam cured; discharge rated by color movement. The surface is reported as "unusually smooth," but for about half the line is curved gently and no allowance has been made for this curvature in the computations. (*Bulletin No. 852,* USDA, Washington, D.C., 1924, p. 39.)

Curve 24.—Surface formed by troweled pneumatically applied mortar. (References same as for Curve 18.)

Curve 25.—Use of steel forms in place has resulted in rough joints but with a smooth surface between joints. The line contains one sharp 90° bend in the reach measured. The concrete was poured against oiled steel forms but the joints were not smoothed. (*Bulletin No. 852,* USDA, Washington, D.C., 1924, p. 82; *Engineering Record,* Apr. 2, 1910, p. 460.)

Curve 26.—Smooth steel forms were used by the Tennessee Valley Authority (TVA) on the Apalachia Tunnel. Discharge was rated by current meter. The tunnel consists of three types of lining—concrete, steel, and unlined rock. The concrete section contains four long radius bends in the test section. The entire tunnel has a total of six bends.

Curve 27.—Prestressed concrete pipe cast over steel forms, no bends, joints 19.7 feet apart, rated by rectangular weir and moving screen, test reliable. (*Houille Blanche,* May–June 1947, p. 198.)

Curve 28.—Centrifugally cast concrete pipe, surface irregular, no bends, joints 13.2 feet apart, rated by rectangular weir and moving screen, test reliable. (*Houille Blanche,* May–June 1947, p. 198.)

Curve 29.—Gentle curves in alinement, does not describe condition of pipe except it was new at time of test. (*Bulletin No. 852,* USDA, Washington, D.C., October 1920.)

Curves 30 and 31.—Smooth, precast concrete section, 16 feet long, care in alinement of joints considered average, general alinement consisted of long easy curves, rated by color and salt velocity methods, test reliable. (*U.S. Bureau of Reclamation Field Report No. 589.*)

Curve 32.—Same as Curve 30, except test section consisted of 51,341 feet of 48-inch-diameter precast concrete pipe and 3,632 feet of 48-inch-diameter steel pipe.

Curve 33.—Same as for Curve 30.

Curve 34.—Precast concrete pipe in 16-foot sections with grouted joints. Discharge measured by a 36-inch by 72-inch Venturi meter. The alinement is straight. The effects of the bends were not considered in the computations. (Unpublished tests, conducted by Fred C. Scobey, 1947.)

Curves 35–40.—Same as Curve 34, except the alinement has numerous curves.

Curve 41.—Collapsible full-circle oiled steel forms were used. Discharges were measured by the Gibson method and pitometer traverse. Both the grade and alinement were straight. (Unpublished tests by the USBR, 1960.)

Curve 42.—The sidewalls and arch were placed first against steel forms in reaches of 200 feet. The invert was screeded. Discharge was measured by both the salt and color velocity method.

The grade was level and the alinement was straight. (*Hydraulic Laboratory Report HYD-460*, USBR, 1960.)

Curve 43.—Same as Curve 42, except only the color velocity method of measuring discharge was used.

Curve 44.—The sidewalls and arch were placed first against steel forms in reaches of 200 feet. The invert was screeded. Discharge was measured by both the salt and color velocity method. The grade changed from a −2.1 percent to level to −1.5 percent, and the alinement had one curve with a deflection angle of 111.5° and a 100-foot radius. The effects of the bends were not considered in the computations. (*Hydraulic Laboratory Report HYD-460*, USBR, 1960.)

Curve 45.—Same as Curve 44, except only the color velocity method of measuring discharge was used.

Curve 46.—The screeded invert was placed first. The sidewalls and arch were then constructed using the continuous pour method. Discharge was measured by the salt velocity method. The grade has several changes in slope ranging from level to −0.50 percent. The alinement has one curve with a deflection of 43.5° and a 50-foot radius. The effects of the bends were not considered in the computations. (*Hydraulic Laboratory Report HYD-460*, USBR, 1960.)

Curve 47.—Sections were cast against steel forms in 25-foot lengths. Alinement of the joints was good. Discharge was measured by salt velocity method. The concrete surface was clean and free of biological growths. The vertical deflection angles between slopes were accomplished in 5° or less. The alinement was straight; the effects of the bends were not considered in the computations. (*Hydraulic Laboratory Report HYD-460.*)

Curve 48.—Precast concrete pipe in 16-foot sections with grouted joints. Discharge was measured by the salt velocity method and checked by a 36-inch by 72-inch Venturi meter. The alinement has one curve with a deflection angle of 10°06′ and a 1,550-foot radius. The effects of the bends were not considered in the computations. (*Hydraulic Laboratory Report HYD-460*, USBR, 1960.)

Curve 49.—Same as Curve 8, except the alinement has a curve with a deflection angle of 6°25′ and a 1,600-foot radius.

Curve 50.—Same as Curve 8, except the alinement has a curve with a deflection angle of 42°40′ and a 2,000-foot radius.

Curve 51.—Same as Curve 8, except the alinement has numerous curves.

Curve 52.—Precast concrete pipe in 16-foot sections with grouted joints. Discharge was measured by the salt velocity method and checked by a 36-inch by 72-inch Venturi meter. The concrete was clean and free from biological growth. The alinement was straight. The effects of bends were not considered in the computations. (*Hydraulic Laboratory Report HYD-460*, USBR, 1960.)

Curve 53.—Same as Curve 52, except the alinement has numerous curves.

Curve 54.—Same as Curve 52, except the alinement has numerous curves.

Curve 55.—The tunnel is horseshoe-shaped with the exception of a short length of circular section at the downstream end. The arched roof and sidewalls were placed first, using nontelescopic steel forms in sections ranging from 80 to 160 feet. The invert was screeded and finished using wooden floats. Discharge was measured by the Gibson method. The change in grade is never more than 1 percent. The alinement has two curves, a deflection of 8½° having a 1,094-foot radius and another with deflection of 20°30′ having a 606-foot radius. The losses due to the transition to a short length of circular section and also those due to the bends were not considered in the computations. (Paper presented at the ASCE Convention, 1959, Washington, D.C.)

Curve 56.—The circular concrete lining was poured in two stages, the invert portion first by forming the bottom 60° with a steel screed, wood float, and steel trowel. The arch, which constituted the remaining 300°, was constructed in one continuous pour around the retractable oiled steel forms 50 to 85 feet long. Discharge was measured with a current meter. The grade has numerous changes and the alinement contains 11 curves, but the data used were in three of the straight reaches away from the influence of bends. (*The Engineering Journal*, July 1959.)

Curve 57.—Thirty 8.0-foot concrete cast pipe sections were used in the test. The zone of flow establishment varied from 60 to 100 feet, dependent on the pipe roughness, leaving an effective length of 140 to 180 feet for determination of the friction coefficients. Volumetric tanks were used to measure the discharge. The test reach was constructed with "Average Joints," joints that were simulated from measurements of field-installed pipe. Alinement and grade were straight. (*Technical Paper No. 22, Series B*, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.)

Curve 58.—Same as Curve 57, except the test section was tamped pipe.

Curve 59.—Same as Curve 57, except the test section was tamped pipe.

Curve 60.—Precast concrete pipe, 69-inch inside diameter with trowelled mortar joints. Discharge measurements were made by color-velocity using pontacyl pink, a fluorometer, and a long-form Venturi meter. The 102,967 feet of pipe used in the measurements had been in service for about 15 years delivering municipal water (Hydraulic Laboratory Report No. HYD 885, USBR, 1968).

Table B. Friction Tests of Continuous-Interior Steel Pipe (Steel and Cast Iron)

Description and References

Curve 1.—Lap-welded wrought steel pipe, bell-and-spigot joints, 17-foot lengths, coal-tar dipped; alinement straight; rated volumetrically and by Venturi meter—reliable test. (Curve 302, *Bulletin No. 150*, USDA, by Fred Scobey, Washington, D.C., January 1930.)

Curve 2.—Lap-welded wrought steel pipe, bell-and-spigot joints, 19-foot lengths, coal-tar dipped; alinement straight; rated volumetrically and by Venturi meter—reliable test. (Curve 304, *Bulletin No. 150*, USDA, by Scobey, Washington, D.C., January 1930.)

Curve 3.—Bell-and-spigot joint steel pipe, coal-tar dipped; alinement straight; rated by color method—reliable test. (Curve 308, Scobey, USDA, *Bulletin No. 150.*)

Curve 4.—Wrought steel pipe, patent joints, 20-foot lengths, coal-tar dipped; alinement straight; rated by Venturi meter—reliable test. (Curve 310, Scobey, USDA, *Bulletin No. 150.*)

Curve 5.—Coupling jointed, lap-welded steel pipe, asphalt-dipped; 36.5 percent of alinement on curves having radii of 100 to 717 feet; rated by Venturi meter—fair test. (Curve 312, Scobey, USDA, *Bulletin No. 150.*)

Curve 6.—Full-welded steel pipe, made in 14-foot single plate sections, butt welded throughout, dipped in thin asphalt enamel; 11,000 feet of this pipe consists of 133 short curves on 14-foot chords, with greatest angle at any one pipe joint being 16°; aggregate of bends total 18 complete circles; rated by rectangular steel weir—reliable test. (Curve 313, Scobey, USDA, *Bulletin No. 150.*)

Curve 7.—Butt-joint riveted pipe (rivet heads countersunk); alinement straight; coated with hot asphalt and linseed oil, rated by weir and slide gate—fair test. (Curve 316, Scobey, USDA, *Bulletin No. 150.*)

Curve 8.—Butt-joint riveted pipe (rivet heads countersunk); alinement straight; coated with hot asphalt and linseed oil, rated by weir and slide gate—fair test. (Curve 318, Scobey, USDA, *Bulletin No. 150.*)

Curve 9.—Steel lock-bar pipe (continuous-interior) coated with mixture coal tar and asphalt; rated by Venturi meters—reliable test. (Curve 314, Scobey, USDA, *Bulletin No. 150.*)

Curve 10.—Butt-welded longitudinal seams, girth seams hand lap welded every 14 feet; dipped in hot asphaltum; rated by Venturi meter—reliable test. (Curve 162, Scobey, USDA, *Bulletin No. 150.*)

Curve 11.—Same as for Curve 10.

Curve 12.—Steel pipe, longitudinal joints welded, girth joints belled and lead filled; coating in excellent condition; test section 19½ diameters from P.I. of 55° vertical bend—fair test. (Marchetti, "Determinazioni sperimentati relative al moto uniforme nelle condotte forzate per forza motrice," *L'Energia Elettrica*, May, June, and August, 1934.)

Curve 13.—Lap-welded bump-joint pipe; test section contained two vertical bends of approximately 20° each; rated by weir and current meter—fair test. ("Test of Friction Losses Made on Large Penstocks," R. A. More, E.N.R., No. 15, 1923, p. 598.)

Curve 14.—Cast iron pipe, bell-and-spigot lead joints every 16.4 feet; spun bitumastic coating; rated with Anderson traveling screen and Rehbock weir. (*La Houille Blanche*, No. 3, May–June 1947, p. 191.)

Curve 15.—Rolled steel plate, butt-welded longitudinal joints; field section consists of three lengths each 2 meters long with two butt-welded transverse joints; flexible rubber compression butt field joint 6 meters apart; no protective coating on pipe, rated by traveling screen and weir. (*La Houille Blanche*, No. 3, May–June 1947, p. 191.)

Curve 16.—Butt joints throughout welded steel pipe, hot-asphalt coated; test section contained one long-radius bend; rated from USGS river gaging station—reliable test. (*Proceedings*, ASCE, April 1947, p. 451.)

Curve 17.—Full-welded steel pipe, butt joints throughout, asphalt-coated surface; practically entire line consists of four long radius bends, aggregating about 180° total; rated by 6-foot-diameter Howell-Bunger valve—test good. (Field test on Howell-Bunger valves at Ross Dam, USBR Field Trip Report No. 244, by J. N. Bradley, Apr. 9, 1947, Denver, Colo.)

Curve 18.—Galvanized steel pipe, butt joints throughout; no paint, excellent condition; alinement straight; rated by laboratory weir—reliable test. (Model studies of penstocks for outlet works, *Bulletin No. 2*, Part VI, Boulder Canyon final reports, USBR, p. 31.)

Curves 19, 20, and 21.—Full-welded steel, butt joints throughout; heavy asphalt coating; straight pipe in most cases; rated by pitot tube—results appear questionable. (*Transactions*, ASCE, Vol. 109, 1944, p. 59.)

Curve 22.—Continuous steel pipe, flanged and bolted butt joints; numerous barnacles averaging 1.2 mm. in height; calibrated with weir—results reliable. (*Revue Generale De L'Hydraulique*, No. 40, July–August 1947, p. 171, Curves 23 through 37.)

Curves 23, 24, and 25.—Continuous-interior, butt-welded joints; some barnacles; K averaged 0.18 mm. at time of test; calibrated by weir—test reliable.

Curves 26 and 27.—Sheet steel pipe; joints consist of one flared end and one straight end which, when fitted together, resemble bell-and-spigot joint; sealing is accomplished by welded bead on outside of joint; some barnacles with average $K=1.30$ mm.; rated with weir and Venturi meter—test considered reliable.

Curves 28, 29, and 30.—Sheet steel pipe with flanged and bolted butt joints; incrustation averaging $K=0.4$ mm.; rated by weirs calibrated by current meter.

Curves 31 and 32.—Sheet steel pipe with one flared end and one straight end which, where fitted together, resemble bell-and-spigot joint; sealing accomplished by welded bead on outside; surface quite smooth, average $K=0.22$ mm.; rated by Venturi meter—test considered reliable.

Curves 33 and 34.—Sheet steel pipe, butt welded longitudinal seams; transverse joints consist of one end tapered in and one belled out; the tapered end fits into the belled end and welded both inside and out; joint is not truly continuous; pipe contains barnacles. $K=3.20$ mm.; rated by weir and Venturi meter—test reliable.

Curves 35 and 36.—Same pipes as Curves 33 and 34 with a lining of smooth tar added, $K=0.10$ mm.; rated by weir and Venturi meter—test reliable.

Curve 37.—Same as Curves 31 and 32.

Curves 38, 39, 40, and 41.—Steel pipes, asbestos-cement covered, inner coating of centrifugally applied tar, sleeve-covered butt joints; pipe interior continuous, straight test sections; rated by orifice meter laboratory test; 41 not truly continuous interior because of four prongs extending inside of pipe at each joint. ("Perdite di Carico per Regime Uniforme Nelle Condotte Dalmine di Cemento—Amianto Con Anima di Acciaio, Rivestite Internamente di Bitume Centrifugato"—Dell Instituto di Idraulica e Costrizioni Idrauliche Del Politecnico di Milano—Milano Societa Editrice Riveste Industrie Elettriche 1944.)

Curve 42.—Bolted sleeve coupling every third or fourth joint; coated with bitumastic enamel centrifugally applied; rated by Venturi meters—test reliable. (*Engineering News-Record*, Vol. 112, Feb. 1, 1934, p. 135.)

Curve 43.—New wrought iron pipe; straight sections. ("Experiments upon the flow of water in pipes and pipe fittings," John R. Freeman, a treatise published by the ASME, 1941.)

Curve 44.—New cast iron pipe; straight sections. ("Experiments upon the flow of water in pipes and pipe fittings," John R. Freeman, a treatise published by the ASME, 1941.)

Curve 45.—New, smooth, butt welded throughout, transverse joints 5.3 feet apart; alinement straight; clear water. (*La Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curve 46.—Butt welded throughout; test made after 2 years of operation, straight alinement; very clear water. (*La Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curves 47, 48, 49, and 50.—Butt welded throughout; test made after 34 years of operation; no trace of incrustation. (*La Houille Blanche*, No. 5, September–October 1947, p. 418.)

Table C. Friction Tests of Girth-Riveted Steel Pipe

Description and References

Curve 1.—Installation Cogolo. Longitudinal seams welded, girth joints double riveted, bell and cone joints; varnished 3 years before test; well preserved—reliable test. (*L'Energia Elletrica*, May 1934, p. 360.)

Curve 2.—Installation Temu. Longitudinal seams welded, girth joints single riveted, bell and cone joints; no incrustation or rust—test reliable. (*L'Energia Ellectrica*, June 1934, p. 437.)

Curve 3.—Installation Temu. Longitudinal seams welded, girth joints double riveted; no rust or incrustation—good test. (*L'Energia Ellectrica*, June 1934, p. 438.)

Curve 4.—Installation Temu. Same as Curve 3. (*L'Energia Ellectrica*, June 1934, p. 438.)

Curve 5.—Installation Di Ponte. Same type pipe and joints as Curve 2; varnished less than 1 year before test—results reliable. (*L'Energia Ellectrica*, June 1934, p. 439.)

Curve 6.—Installation Di Ponte. Same type pipe and joints as Curve 2; in service less than 1 year. (*L'Energia Ellectrica*, June 1934, p. 440.)

Curve 7.—Installation Di Ponte. Same type pipe and joints as Curve 2; in service less than 1 year. (*L'Energia Ellectrica*, June 1934, p. 441.)

Curve 8.—Installation Di Ponte. Same type of pipe and joint as Curve 3; in service less than 1 year; some oxidation—good test. (*L'Energia Ellectrica*, June 1934, p. 442.)

Curve 9.—Installation Barbellino. Longitudinal joints welded, funnel-shaped transverse joints double riveted; varnished 2 years before test; inside in good condition—results questionable. (*L'Energia Ellectrica*, August 1934, p. 615.)

Curve 10.—Installation Barbellino. Same as Curve 9. Page 616.

Curve 11.—Installation Barbellino. Same as Curve 9. Page 619.

Curve 12.—Longitudinal joints welded; transverse joints consist of flared and crimped ends riveted with single row of rivets; interior slightly rusty—good test. (*Revue Generale De L'Hydraulique*, No. 40, July–August 1947, p. 171.)

Curve 13.—Same as Curve 12 with double row of rivets around transverse joints.

Curves 14 and 15.—Transverse joints flared and crimped pipe ends riveted with three rows of rivets, longitudinal joints welded; interior slightly rusty—results reliable. (*Revue Generale De L'Hydraulique*, No. 40, July–August 1947, p. 171.)

Curves 16, 17, 18, 19, and 20.—Butt-welded longitudinal joints, riveted transverse joints spaced 24.6 feet apart; test made after 15 years of service. (*La Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curves 21 and 22.—Butt-welded longitudinal joints, riveted transverse joints spaced 21.3 feet apart; test made after 19 years of service. (*La Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curves 23, 24, and 25.—Each conduit consists of 820 feet of butt-welded longitudinal joint and 328 feet of riveted longitudinal joint; transverse joints are riveted at intervals of 26.2 feet in the welded section and riveted at intervals of 5.9 feet in the riveted section; tests made after 19 years of service; conduit painted with bituminous enamel. (*La Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curve 26.—36-inch lockbar steel pipe, straight in plan but includes nine vertical bends; pipe contained slimy algae growth from ⅛- to ¼-inch thick; rated by color method. (USDA, *Technical Bulletin No. 150.*)

Curve 27.—36-inch lockbar steel pipe; rated by Venturi meter. (USDA, *Technical Bulletin No. 150.*)

Curve 28.—42-inch lockbar steel pipe, in 30-foot lengths; taper joints; single-riveted between units; dipped in pitch; walls in excellent condition; rated by Venturi meters. (USDA, *Technical Bulletin No. 150.*)

Curve 29.—97-inch lap-welded longitudinal seams, bump-joint-riveted girth joints; reach contained one expansion joint and three vertical bends ranging from 15½° to 23°; water measured by suppressed Francis weir. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 30.—108-inch lap-welded longitudinal seams, bump-joint-riveted girth joints; reach contained three expansion joints and two vertical bends of about 20° each; water measured by suppressed Francis weir. (USDA, *Technical Bulletin No. 150*, January 1930.)

Table D. Friction Tests of Full-Riveted Steel Pipe

Description and References

Curve 1.—Installation "Farneta." Full-riveted pipe, adjacent sections telescoped into each other, length of sections 1.5 meters; longitudinal sections double riveted, girth joints single riveted; inside coating poor but no incrustation or corrosion—reliable test. (*L'Energia Elletrica*, May 1934, p. 343.)

Curve 2.—Installation "Farneta." Pipe characteristics similar to Curve 1. (*L'Energia Elletrica*, May 1934, p. 343.)

Curve 3.—Installation "Cogolo." Construction similar to Curve 1. Coating in good condition; in service 3 years—reliable test. (*L'Energia Elletrica*, May 1934, p. 343.)

Curve 4.—Installation Temu. Full-riveted pipe, longitudinal joint triple riveted, girth joints single riveted; adjacent sections telescoping into each other—fair test. (*L'Energia Elletrica*, June 1934, p. 435.)

Curve 5.—Installation Barbellino. Full-riveted pipe, longitudinal joint triple riveted, girth joints single riveted; adjacent sections telescoping into each other; surface smooth—reliable test. (*L'Energia Elletrica*, August 1934, p. 613.)

Curve 6.—Installation Barbellino. Full-riveted pipe, single rows of rivets; adjacent sections telescoping; coating in good condition—good test. (*L'Energia Elletrica*, August 1934, p. 613.)

Curve 7.—Installation Barbellino. Full lap-riveted pipe, longitudinal joints triple riveted, girth joints single riveted—fair test. (*L'Energia Elletrica*, August 1934, p. 613.)

Curve 8.—Okanogan project, Washington. Full-riveted pipe, adjacent sections telescoping; joints dipped in asphaltum; large amount of silt and dirt in pipes—results questionable. (Curve 1, *Bulletin No. 150*, USDA, by Fred Scobey, Washington, D.C., January 1930.)

Curve 9.—New straight pipe, sheet iron, covered with bitumen; longitudinal seams riveted, screw joints; slightly inclined upward; head loss by manometers; discharge by calibrated tanks—good test. (USDA, *Bulletin No. 150*, Scobey, Curve 2.)

Curve 10.—Pipe similar to pipe in Curve 9. (Scobey, Curve 10.)

Curve 11.—Rochester, N.Y., conduit No. 2 from overflow No. 1 to Mount Hope Reservoir on southern division, 26 miles long, cylinder joints;

quantity by rise in reservoir, loss of head by mercury gages—results questionable. (USDA, *Bulletin No. 150*, Scobey, Curve 40.)

Curve 12.—East Jersey Water Co., New Jersey. Full-riveted pipe, taper joints; interior coating unusually smooth; discharge by Venturi meter; loss of head by Bourdon-type gages—good test. (USDA, *Bulletin No. 150*, Scobey, Curve 48.)

Curve 13.—Penstock, Halsey powerhouse, Pacific Gas & Electric Co., California. Of riveted steel plates, butt jointed, triple riveted; double coated with graphite, paint brushed on. New pipe; discharge by Venturi meter, head loss by differential gage. (USDA, *Bulletin No. 150*, Scobey, Curve 65.)

Curve 14.—Another section of pipe in Halsey power penstock (Curve 13), lap riveted with double row of rivets; same testing apparatus. (Scobey, Curve 72.)

Curve 15.—Penstock, Wise powerhouse, Pacific Gas & Electric Co. Lap joint double rivets, cylinder joints; discharge by Venturi meter, head loss by manometers—good test. (Scobey, Curve 72.)

Curve 16.—Same penstock as in Curve 15. Lap joints, single rivets. (Scobey, Curve 73.)

Curve 17.—Same penstock as in Curve 15. Butt-strap riveted. (Scobey, Curve 74.)

Curve 18.—Combined reaches of penstocks in Curves 15, 16, and 17. (Scobey, Curve 75.) 6-foot sections.

Curve 19.—Oak Grove No. 3 penstock, Portland Electric Power Co., Portland, Oreg. Cylinder jointed, full-riveted steel pipe; shop painted with red lead, field coated with graphite; discharge by multiple pitot tube (Proebstel) method—good test. (Scobey, Curve 78.)

Curve 20.—Full-riveted pipe, double-riveted longitudinally. Girth joints lap riveted with single row of rivets. Interior slightly rusty—reliable test. (*Revue Generale de L'Hydraulique*, No. 40, July–August 1947, p. 171.)

Curve 21.—Longitudinal joints double riveted, transverse joints lapped with single row of rivets, 7.87 feet between joints, interior incrusted. (*Revue Generale de L'Hydraulique*, No. 40, July–August 1947, p. 147.)

Curve 22.—Same as Curve 21, except triple-riveted longitudinal joints with 9.8 feet between transverse joints.

Curve 23.—Same as Curve 21, except longitudinal joints triple-riveted, transverse joints lapped with double row of rivets; interior incrusted. (*Revue Generale de L'Hydraulique*, No. 40, July–August 1947, p. 171.)

Curve 24.—Two rows longitudinal rivets, one row rivets at transverse joints 6.5 feet apart; test made after 1 year of service; good alinement; water carries sand and pipe is well scoured. (*Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curves 25, 26, 27, 28, and 29.—Five identical conduits; test made after 33 years of service; two rows longitudinal rivets, one row rivets at transverse joints spaced 6.5 feet apart; numerous bends; light incrustation; rivet heads are worn somewhat; transports cloudy water. (*Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curve 30.—Represents results of three similar conduits; two rows rivets on longitudinal joints, one row rivets at transverse joints spaced 6.5 feet apart; conduit in service 14 years at time of test; alinement straight; conduit incrusted, water clear. (*Houille Blanche*, No. 5, September–October 1947, p. 418.)

Curve 31.—11-foot diameter; longitudinal joints double riveted, girth joints single riveted; constructed with in-and-out or cylinder courses, rivet heads round and prominent, cylinder joints; reach includes seven vertical bends each less than 20 degrees; painted on inside with brush coat of hydrocarbon oil; velocities determined by color method. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 32.—129-inch diameter; butt joints throughout, triple riveted; straight alinement but short; discharge measured over Francis weir. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 33.—103-inch diameter, lap-riveted wrought iron pipe; cylinder joints; very short straight reach; rather rusty but no noticeable tuberculation. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 34.—84-inch lap-riveted pipe with cylinder joints; reach contained 10 vertical bends and 10 air valves; original coating was graphite paint applied with brush but tuberculation was present after 2 years of operation; discharge measured by Venturi meter. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 35.—77.5-inch lap-riveted steel pipe; has had numerous applications of asphalt and tar paints; test was made 7 years after last application; test section unusually short; discharge measured by weir. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 36.—72-inch butt jointed, triple-riveted, strap construction; alinement fairly straight; graphite coated; flow determined by measuring fall of water surface in forebay. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 37.—72-inch lap jointed, double riveted; test section contained one horizontal and two vertical bends; painted with two brush coats of graphite; rated by Venturi meter. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 38.—72-inch butt jointed, triple-riveted; reach fairly short; discharge measured by Venturi meter. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 39.—42-inch lap-riveted, taper joints, asphalt coated; discharge measured by Venturi meter. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 40.—38-inch lap-riveted, cylinder joints; quantity measured by rise in reservoir. (USDA, *Technical Bulletin No. 150*, January 1930.)

Curve 41.—36-inch riveted slip-joint pipe, 10-gage steel; flathead rivets; alinement straight; discharge measured by color method and Venturi meter. (USDA, *Technical Bulletin No. 150*, January 1930.)

Table E. Friction Tests of Spiral-Riveted Steel Pipe

Description and References

Curve 1.—Flathead riveted experimental line at Cornell University. Four 20-foot lengths of asphalt-coated pipe, flange jointed; water running with the laps; loss of head by differential water columns; discharge measured in calibrated basin; new pipe. (USDA, *Technical Bulletin No. 150*, Scobey, Curve 502, January 1930.)

Curve 2.—Same pipe as Curve 1, 1 year later, same testing apparatus; flathead rivets and thin shell smoothed off by asphalt coat giving good surface; water flowing with laps. (USDA, *Technical Bulletin No. 150*, Scobey, Curve 504, January 1930.)

Curve 3.—Same as Curve 2 with water flowing against laps. (Scobey, Curve 506.)

Curve 4.—New experimental pipe, flathead rivets, asphalt dipped; water running with laps. (Scobey, Curve 512.)

Curve 5.—Same as Curve 4, water running against laps. (Scobey, Curve 514.)

Curve 6 through Curve 13.—Experimental pipe, Purdue Engineering Experiment Station. New spiral-riveted pipe, sections held together by bolted steel flanges; pipe made from No. 16 gage galvanized sheet steel; sheets about 1 foot wide with about 1-inch overlap for riveting; inside rivet heads are flathead. (*Bulletin No. 8*, Purdue Engineering Experiment Station.)

Curve 6.—4-inch pipe, flow with laps.
Curve 7.—4-inch pipe, flow against laps.
Curve 8.—6-inch pipe, flow with laps.
Curve 9.—6-inch pipe, flow against laps.
Curve 10.—8-inch pipe, flow with laps.
Curve 11.—8-inch pipe, flow against laps.
Curve 12.—10-inch pipe, flow with laps.
Curve 13.—10 inch pipe, flow againt laps.

Table F. Friction Tests of Wood-Stave Pipe

Description and References

Curve 1.—Continuous wood-stave pipe of Douglas fir; gentle horizontal curves, no vertical curves; velocity obtained by color method. (USDA, *Professional Paper No. 376*, November 1916.)

Curve 2.—Continuous wood-stave pipe, Douglas fir; gentle horizontal bends, no vertical bends, water free of sediment; discharge measured by submerged round-crested weir and current meter. (USDA, *Professional Paper No. 376*, November 1916.)

Curve 3.—Continuous wood-stave pipe, Douglas fir; gentle horizontal and vertical curves, water free of sediment; velocity by color method and current meter. (USDA, *Professional Paper No. 376*, November 1916.)

Curves 4 and 5.—Continuous stave pipe, fir; numerous horizontal and vertical curves but not excessively sharp; discharge measured by Venturi meter. (USDA, *Professional Paper No. 376*, November 1916.)

Curves 6 and 7.—Continuous wood-stave pipe, Douglas fir; inside surface unusually smooth; continuous downslope alinement; discharge measured by 18-foot weir. (USDA, *Professional Paper No. 376*, November 1916.)

Curve 8.—Continuous stave fir pipe; gentle curves joined by short tangents, minimum radius of curvature 289 feet; pipe laid on even gradient with one exception; growths of spongilla in scattered bunches on inside surface of pipe, each measuring about one-fourth square inch in area and projecting about three-sixteenth inch; growth was not present on bottom; rated by current meter. (USDA, *Professional Paper No. 376*, November 1916.)

Curve 9.—Continuous wood-stave pipe, Douglas fir; inside surface unusually smooth; continuous downslope alinement; discharge measured by 18-foot weir. (USDA, *Professional Paper No. 376*, November 1916.)

Curve 10.—Continuous stave redwood pipe; smooth, new inverted siphon with steep legs joined by vertical curve; high velocity prevents accumulation of silt; rated by color method and current meter. (USDA, *Professional Paper No. 376*, November 1916.)

Curve 11.—Continuous stave fir pipe, practically straight; no growth in pipe; rated by current meter. (USDA, *Professional Paper No. 376*, November 1916.)

Curves 12 and 13.—Continuous stave Douglas fir pipe, practically straight; rated by 6-foot Cipolletti weir and current meter; friction loss rather high. (USDA *Professional Paper No. 376*, November 1916.)

Curve	Darcy Weisbach f	Reynolds number R	
1	.0097	1.55	x10^6
	.0114	2.0	
	.0107	2.5	
	.0107	3.0	
2	.0108	3.40	x10^6
	.0117	3.51	
	.0107	4.40	
	.0115	4.91	
	.0105	5.53	
	.0102	5.94	
	.0104	6.70	
	.0109	7.02	
	.0108	7.46	
	.0108	8.40	
	.0108	8.80	
	.0108	1.03	x10^7
	.0112	1.12	
	.0100	1.25	
	.0107	1.38	
	.0105	1.51	
	.0105	1.69	
3	.0132	1.32	x10^6
	.0139	1.74	
	.0123	1.83	
	.0153	2.01	
	.0125	2.20	
4	.0142	1.08	x10^6
	.0127	1.46	
	.0117	1.08	
	.0120	1.46	
5	.0126	6.43	x10^5
	.0130	7.40	
	.0133	7.80	
	.0132	9.00	
	.0131	1.01	x10^6
	.0129	1.03	
	.0128	1.05	
	.0128	1.25	
	.0127	1.42	
6	.00670	1.12	x10^7
	.00670	1.17	
	.00720	1.30	
	.00600	1.42	
	.00760	1.56	
	.00690	1.80	
	.00785	1.81	
	.00670	1.90	
	.00640	1.95	
	.00640	2.00	
	.00720	2.28	
	.00650	2.30	
	.00610	4.00	
	.00790	4.25	
7	.0096	1.03	x10^7
	.0080	1.04	
	.0093	1.40	
	.0105	1.51	
	.0076	1.60	
	.0100	1.89	
	.0090	2.06	
	.0080	2.11	
	.0105	2.17	
	.0103	2.48	
	.0100	2.65	
	.0084	2.98	
8	.0305	1.5	x10^4
	.0232	5.0	
	.0198	1.0	x10^5
	.0169	2.0	
	.0137	5.0	
	.0281	1.5	x10^4
	.0213	5.0	
	.0182	1.0	x10^5
	.0155	2.0	
	.0125	5.0	
9	.0095	2.68	x10^6
	.0087	4.18	
	.0085	5.69	
	.0076	7.40	
	.0078	9.80	
10	.0108	7.45	x10^6
	.0101	8.80	
	.0118	1.03	x10^7
	.0117	1.09	
	.0124	1.14	
	.0126	1.18	
	.0127	1.22	
	.0126	1.24	
	.0129	1.33	
11	.0314	1.08	x10^4
	.0290	1.20	
	.0288	1.40	
	.0279	1.66	
	.0278	1.70	
	.0258	2.20	
	.0258	2.30	
	.0250	2.60	
	.0228	2.93	
	.0238	3.15	
	.0226	3.52	
	.0226	3.69	
	.0226	3.73	
	.0232	3.70	
	.0224	3.85	
	.0224	3.94	
	.0221	4.20	
	.0228	4.36	
	.0216	4.48	
	.0215	4.65	
	.0216	4.80	
	.0210	5.05	
	.0208	5.30	
	.0191	5.30	
	.0206	5.75	
	.0201	5.85	
	.0188	6.20	
	.0200	6.35	
	.0195	6.60	
	.0196	7.01	
	.0190	7.15	
	.0192	7.40	
	.0189	7.62	
	.0183	7.62	
	.0186	8.20	
	.0190	8.35	
	.0184	8.80	
	.0183	9.00	
	.0182	9.70	
	.0181	1.07	x10^5
	.0177	1.08	
	.0175	1.16	
	.0173	1.16	
	.0169	1.26	
	.0173	1.28	
	.0167	1.39	
	.0167	1.48	
	.0165	1.46	
	.0165	1.66	
	.0162	1.70	
	.0163	1.73	
	.0155	1.80	
	.0158	1.82	
	.0156	1.98	
	.0157	2.13	
	.0150	2.33	
	.0150	2.40	
	.0149	2.64	
	.0147	2.67	
	.0146	2.84	
	.0144	2.88	
	.0147	2.95	
	.0147	3.00	
	.0143	3.20	
	.0140	3.49	
	.0140	3.65	
	.0139	4.00	x10^5
	.0134	4.02	
	.0135	4.38	
	.0133	4.49	
	.0133	4.80	
	.0133	4.95	
	.0133	5.65	
	.0128	6.00	
	.0128	6.10	
	.0126	6.38	
	.0128	6.70	
	.0124	6.72	
	.0129	7.00	
	.0124	7.30	
	.0127	7.40	
	.0124	7.74	
	.0120	8.70	
	.0121	9.05	
	.0117	9.90	
	.0118	1.03	x10^6
	.0117	1.10	
	.0116	1.15	
	.0117	1.20	
	.0113	1.20	
	.0117	1.23	
	.0115	1.29	
	.0113	1.33	
	.0112	1.37	
	.0113	1.40	
	.0113	1.45	
	.0111	1.55	
	.0106	1.61	
	.0107	1.72	
	.0107	1.86	
	.0107	1.96	
	.0105	2.10	
	.0105	2.14	
	.0104	2.18	
	.0099	2.32	
	.0103	2.34	
	.0100	2.56	
	.0098	2.70	
	.0099	2.83	
	.0099	3.02	
	.0096	3.27	
12	.0078	5.88	x10^6
	.0081	1.18	x10^7
	.0080	1.76	
	.0077	2.33	
	.0070	2.94	
13	.0111	1.60	x10^6
	.0097	1.70	
	.0115	2.18	
	.0094	2.33	
	.0083	3.16	
	.0080	3.56	
	.0107	3.72	
	.0083	4.20	
	.0103	4.95	
14	.0108	1.92	x10^6
	.0115	2.48	
	.0094	3.15	
	.0099	3.75	
	.0103	4.50	
	.0102	5.06	
	.0107	5.50	
15	.0131	5.25	x10^6
	.0128	7.15	
	.0125	9.18	
16	.0155	1.01	x10^6
	.0172	1.04	
	.0164	1.07	
	.0172	1.09	
	.0195	1.17	
	.0193	1.17	
	.0184	1.20	
17	.0116	1.64	x10^6
	.0110	2.16	
	.0130	2.93	
	.0103	2.93	
	.0103	3.89	
	.0137	3.90	
	.0142	4.77	
	.0108	4.86	
18	.0103	2.2	x10^6
	.0103	2.84	
	.0101	2.30	
	.0101	3.03	
19	.0120	8.9	x10^5
	.0120	9.4	
	.0130	9.4	
20	.0148	6.0	x10^5
	.0140	6.25	
	.0132	6.40	
21	.0120	3.80	x10^5
	.0130	5.90	
	.0135	8.65	
	.0122	1.08	x10^6
	.0134	1.09	
	.0153	1.14	
	.0143	1.14	
22	.0415	9.9	x10^3
	.0350	1.08	x10^4
	.0339	1.98	
	.0330	2.12	
	.0331	2.40	
	.0310	2.78	
	.0325	2.78	
	.0339	3.08	
	.0375	3.08	
	.0368	3.75	
	.0323	3.75	
	.0268	1.63	
	.0250	1.70	
	.0253	2.55	
	.0245	2.55	
	.0248	3.05	
	.0247	3.70	
	.0250	4.15	
	.0255	4.28	
	.0255	4.95	
	.3265	5.60	
23	.0168	2.92	x10^5
	.0154	3.41	
	.0153	4.02	
	.0147	4.75	
	.0155	5.00	
	.0148	5.60	
	.0142	6.50	
	.0146	7.25	
	.0142	8.40	
24	.0087	7.8	x10^6
	.0087	9.8	
25	.0124	1.64	x10^6
	.0110	2.18	
	.0124	2.94	
	.0106	2.96	
	.0127	3.89	
	.0110	3.90	
	.0117	4.60	
	.0116	4.78	
26	.0110	4.6	x10^6
	.0114	5.1	
	.0121	5.6	
	.0121	6.0	
	.0124	6.4	
	.0130	6.7	
	.0128	7.1	
	.0114	4.8	
	.0120	5.8	
	.0132	7.7	
	.0131	8.6	
	.0132	9.4	
	.0137	1.02	x10^7
	.0134	1.09	
	.0136	1.15	
	.0136	1.21	
	.0135	1.27	
	.0136	1.32	
	.0136	1.36	
	.0134	1.47	
27	.0141	5.13	x10^5
	.0134	5.43	
	.0129	6.46	
	.0138	8.32	
	.0131	8.51	
	.0129	8.91	
	.0126	9.12	
	.0120	1.03	x10^6
	.0123	1.07	
	.0126	1.09	
	.0115	1.26	
	.0119	1.27	
	.0116	1.32	
	.0118	1.32	
	.0115	1.39	
	.0115	1.46	
	.0110	1.53	
	.0115	1.55	
	.0116	1.55	
28	.0146	6.31	x10^5
	.0157	6.31	
	.0151	7.76	
	.0155	7.76	
	.0141	8.91	
	.0149	9.12	
	.0141	1.00	x10^6
	.0149	1.01	
	.0148	1.01	
	.0138	1.01	
	.0136	1.27	
	.0141	1.41	
	.0141	1.48	
	.0138	1.50	
	.0141	1.53	
29	.01500	6.88	x10^5
	.01475	1.06	x10^6
	.01090	1.34	
	.01400	1.55	
	.01381	1.77	
	.01388	1.96	
30	.0200	6.035	x10^5
	.0159	8.453	
	.0149	9.386	
	.0153	1.1936	x10^6
	.0152	1.5149	
	.0150	1.6783	
31	.0196	4.400	x10^5
	.0101	7.968	
	.0122	1.115	x10^6
	.0119	1.2429	
	.0113	1.5838	
	.0112	2.0038	
	.0111	2.225	
32	.0127	4.864	x10^5
	.0123	8.911	
	.0117	1.2502	x10^6
	.0113	1.3922	
	.0110	2.2525	
	.0108	2.504	
33	.0148	1.515	x10^6
	.0149	1.678	
	.0150	1.678	
	.0165	1.678	
	.0140	1.678	
	.0139	1.678	
	.0124	1.678	
	.0116	1.678	
34	.0103	1.44	x10^6
	.0110	1.45	
	.0111	1.52	
	.0114	1.55	
35	.0119	9.99	x10^5
	.0113	1.47	x10^6
	.0112	1.45	
	.0104	1.74	
	.0103	1.87	
	.0107	1.90	
	.0106	2.00	
	.0107	2.11	
	.0107	2.10	
36	.0105	1.12	x10^6
	.0107	1.64	
	.0111	1.62	
	.0104	1.96	
	.0107	2.09	
	.0104	2.13	
	.0106	2.31	
	.0105	2.38	
	.0105	2.38	
37	.0106	5.92	x10^5
	.0111	1.00	x10^6
	.0103	1.47	
	.0108	1.45	
	.0101	1.75	
	.0107	1.67	
	.0103	1.76	
	.0098	1.88	
	.0107	1.90	
	.0109	2.10	
	.0107	2.16	
	.0107	2.16	
38	.0123	6.7	x10^5
	.0121	1.13	x10^6
	.0113	1.73	
	.0107	1.81	
	.0110	2.17	
	.0107	2.17	
	.0110	2.53	
	.0109	2.32	
	.0106	2.44	
	.0105	2.44	
39	.0120	6.66	x10^5
	.0113	1.12	x10^6
	.0108	1.64	
	.0103	1.81	
	.0104	2.17	
	.0102	2.00	
	.0103	2.18	
	.0104	2.53	
	.0105	2.33	
	.0104	2.43	
	.0104	2.43	
40	.0102	6.67	x10^5
	.0107	1.13	x10^6
	.0103	1.63	
	.0102	1.80	
	.0099	2.00	
	.0096	2.06	
	.0100	2.50	
	.0101	2.15	
	.0101	2.36	
	.0100	2.44	
	.0101	2.44	
41	.01983	4.36	x10^5
	.01563	1.01	x10^6
	.01430	1.42	
	.01332	1.86	
	.01305	2.27	
	.01289	2.28	
	.01233	2.68	
	.01228	2.99	
	.01186	3.46	
	.01148	3.84	
	.01125	4.25	
	.01124	4.65	
	.01108	5.09	
	.01131	5.65	
	.01147	5.90	
42	.0151	3.13	x10^6
	.0149	3.19	
	.0147	3.69	
	.0142	3.81	
	.0142	4.40	
	.0146	4.45	
	.0130	5.97	
	.0136	6.02	
	.0140	7.45	
43	.0157	4.40	x10^6
	.0148	6.54	
	.0154	6.54	
	.0144	7.81	
	.0142	8.96	
	.0141	8.96	
	.0134	9.92	
	.0141	11.05	
	.0140	11.05	
44	.0131	2.51	x10^6
	.0139	2.55	
	.0126	2.95	
	.0126	3.05	
	.0121	3.52	
	.0119	3.56	
	.0112	4.78	
	.0117	4.82	
	.0105	5.96	
45	.0124	3.57	x10^6
	.0115	5.23	
	.0113	5.23	
	.0113	6.25	
	.0110	7.17	
	.0110	7.17	
	.0108	7.94	
	.0104	8.84	
	.0102	8.84	
46	.0123	2.01	x10^6
	.0123	2.01	
	.0122	3.52	
	.0122	3.52	
	.0113	5.09	
	.0113	5.09	
	.0113	6.11	
	.0113	6.11	
	.0111	8.43	
	.0111	8.43	
47	.0108	4.66	x10^6
	.0108	6.64	
	.0107	7.65	
	.0106	8.72	
48	.014	1.83	x10^6
	.014	2.17	
	.014	1.91	
	.014	1.86	
	.013	1.45	
	.014	2.42	
	.014	1.17	
	.014	9.34	x10^5
	.014	6.97	
	.014	2.22	x10^6
	.014	2.37	
	.014	2.45	
49	.016	1.47	x10^6
	.016	1.74	
	.015	1.53	
	.016	1.33	
	.015	1.16	
	.014	1.94	
	.015	9.36	x10^5
	.016	7.48	
	.018	5.58	
	.016	1.78	x10^6
	.016	1.90	
	.016	1.96	
50	.0160	1.47	x10^6
	.0158	1.74	
	.0149	1.53	
	.0149	1.33	
	.0151	1.16	
	.0151	9.36	x10^5
	.0152	7.48	
	.0155	5.58	
	.0148	1.78	x10^6
	.0142	1.89	
	.0155	1.96	
51	.0140	1.47	x10^6
	.0139	1.74	
	.0137	1.53	
	.0141	1.33	
	.0137	1.16	
	.0137	1.94	
	.0141	9.36	x10^5
	.0145	7.49	
	.0153	5.58	
	.0140	1.78	
	.0139	1.90	
	.0143	1.96	
52	.0172	1.49	x10^6
	.0174	1.40	
	.0176	1.43	
	.0177	1.47	
	.0178	1.47	
53	.0142	1.95	x10^6
	.0139	1.86	
	.0139	1.91	
	.0137	1.96	
	.0138	1.96	
54	.0140	1.952	
	.0136	1.91	
	.0137	1.96	
	.0137	1.96	
55	.0108	2.76	x10^7
	.0108	2.49	
	.0110	2.30	
	.0111	2.14	
	.0113	1.86	
	.0110	1.48	
	.0111	1.21	
56	.0076	4.35	x10^7
	.0075	3.87	
	.0074	3.25	
	.0075	5.66	
	.0078	4.60	
	.0075	4.16	
57	.01883	7.50	x10^4
	.01847	2.10	x10^5
	.01596	2.61	
	.01581	2.63	
	.01464	4.41	
	.01373	6.30	
	.01422	6.79	
	.01383	7.70	
	.01324	9.17	
	.01305	9.84	
	.01293	1.07	x10^6
	.01288	1.07	
	.01301	1.18	
	.01252	1.34	
	.01244	1.39	
	.01198	1.39	
	.01233	1.49	
	.01116	2.95	
	.01077	3.25	
	.01061	3.28	
	.01083	3.36	
	.01087	3.37	
	.01070	3.43	
58	.01727	1.03	x10^5
	.01669	1.12	
	.01705	1.34	
	.01637	1.38	
	.01746	1.38	
	.01588	2.16	
	.01650	2.22	
	.01650	2.22	
	.01604	3.04	
	.01594	3.70	
	.01582	3.75	
	.01551	4.02	
	.01602	4.35	
	.01557	5.05	
	.01641	5.15	
	.01578	5.97	
	.01596	7.87	
	.01622	9.02	
	.01583	9.50	
	.01624	1.28	x10^6
	.01606	1.30	
	.01643	1.34	
	.01610	1.49	
	.01596	1.70	
	.01573	1.88	
	.01553	1.88	
	.01591	1.94	
	.01594	2.17	
	.01558	2.18	
59	.01770	1.79	x10^5
	.01770	1.79	
	.01772	5.21	
	.01764	5.22	
	.01770	6.50	
	.01780	7.92	
	.01780	7.92	
	.01770	9.32	
	.01819	9.79	
	.01787	9.87	
	.01747	1.11	x10^6
	.01768	1.16	
	.01730	1.18	
	.01755	1.25	
	.01776	1.40	
	.01764	1.46	
60	.0110	3.15	x10^6

TABLE G.—*Analysis of friction data for concrete pipe (Curve coordinates (not shown on charts))*

Curve	Darcy Weisbach f	Reynolds number R	
1	.021	1.0485	$\times 10^{5}$
	.020	0.9835	
	.019	1.4083	
	.017	1.3710	
	.018	1.8891	
	.018	1.6051	
	.017	1.8493	
	.017	1.9818	
	.016	2.3192	
	.017	1.9828	
	.017	2.7040	
	.017	2.4843	
	.016	3.063	
	.017	3.023	
	.017	2.686	
	.017	3.598	
	.017	3.433	
	.017	3.807	
	.016	3.616	
	.017	3.915	
	.016	4.141	
2	.023	0.557	$\times 10^{5}$
	.020	1.178	
	.018	1.752	
	.018	2.320	
	.017	2.899	
	.017	3.479	
	.017	4.006	
	.017	4.639	
	.017	5.101	
	.016	5.575	
3	.022	2.973	$\times 10^{5}$
	.022	3.647	
	.021	3.719	
	.020	4.327	
4	.016	0.698	$\times 10^{5}$
	.017	1.337	
	.015	2.140	
	.016	2.853	
	.015	3.625	
	.0145	4.398	
	.014	4.889	
	.014	5.501	
	.014	6.094	
	.014	6.465	
5	.0134	7.371	$\times 10^{5}$
	.0138	8.179	
	.0142	9.003	
	.0143	9.828	
	.0146	1.064	$\times 10^{6}$
	.0148	1.146	
	.0151	1.227	
	.0155	1.309	
	.0156	1.317	
6	.018	4.948	$\times 10^{5}$
	.017	9.333	
	.017	1.031	$\times 10^{6}$
7	.016	1.867	$\times 10^{6}$
	.017	1.967	
	.017	1.999	
	.017	2.292	
	.017	2.541	
8	.019	1.946	$\times 10^{6}$
	.019	2.516	
	.019	2.733	
	.019	2.742	
9	.019	4.87	$\times 10^{5}$
	.019	5.46	
10	.0186	3.56	$\times 10^{5}$
	.0166	4.06	
	.0167	4.57	
	.0166	5.06	
	.0159	5.48	
11	.0190	3.88	$\times 10^{5}$
	.0166	4.42	
	.0165	4.99	
	.0163	5.54	
	.0154	5.98	
12	.0156	1.57	$\times 10^{6}$
	.0115	4.45	
	.0110	6.4	
13	.0097	9.3	$\times 10^{6}$
	.0092	1.26	$\times 10^{7}$
14	.0123	5.77	$\times 10^{5}$
	.0129	5.77	
	.0126	6.02	
	.0131	6.02	
	.0129	6.72	
	.0113	8.40	
	.0121	8.40	
	.0119	9.06	
	.0115	1.03	$\times 10^{6}$
	.0120	1.03	
	.0115	1.07	
	.0116	1.13	
	.0112	1.16	
	.0115	1.18	
	.0112	1.26	
	.0112	1.32	
	.0114	1.32	
	.0113	1.32	
	.0111	1.47	
	.0112	1.47	
15	.0145	5.37	$\times 10^{5}$
	.0144	5.50	
	.0132	6.61	
	.0135	7.25	
	.0129	7.78	
	.0123	9.89	
	.0123	1.02	$\times 10^{6}$
	.0120	1.15	
	.0121	1.28	
	.0118	1.41	
	.0118	1.50	
	.0118	1.53	
16	0.0130	4.6	$\times 10^{6}$
	0.0128	4.8	
	0.0136	5.1	
	0.0129	5.6	
	0.0132	5.8	
	0.0130	6.0	
	0.0130	6.4	
	0.0133	6.7	
	0.0133	6.7	
	0.0133	7.1	
	0.0139	7.7	
	0.0137	8.6	
	0.0137	9.4	
	0.0135	1.02	$\times 10^{7}$
	0.0137	1.09	
	0.0138	1.15	
	0.0138	1.21	
	0.0137	1.27	
	0.0137	1.32	
	0.0137	1.36	
	0.0136	1.40	
	0.0137	1.44	
	0.0136	1.47	
	.0085	1.88	
17	.0106	7.6	$\times 10^{6}$
	.0097	1.57	$\times 10^{7}$
	.0095	1.84	
	.0094	2.08	
	.0095	2.28	
	.0095	2.46	
	.0095	2.55	
	.0095	2.58	
18	.0180	1.8	$\times 10^{5}$
	.0170	2.6	
	.0172	3.8	
	.0157	4.45	
	.0150	5.0	
	.0157	5.7	
	.0155	6.3	
	.0141	7.2	
	.0135	7.3	
	.0135	8.4	
	.0138	8.5	
	.0133	8.6	
	.0152	3.0	
	.0149	3.8	
	.0140	4.7	
	.0150	5.2	
	.0135	6.0	
	.0140	6.1	
	.0150	6.7	
	.0140	7.7	
	.0142	8.2	
	.0141	9.1	
	.0130	9.4	
	.0142	9.8	
	.0130	1.09	$\times 10^{6}$
	.0138	1.10	
	.0130	1.10	
	.0126	1.25	
	.016	2.00	$\times 10^{5}$
	.0168	2.5	$\times 10^{5}$
	.0168	3.4	
	.0160	4.0	
	.0165	4.5	
	.0160	4.7	
	.0148	5.7	
	.0160	6.4	
	.0155	6.5	
	.0132	7.5	
	.0140	8.0	
	.0146	8.1	
	.0130	8.8	
	.0142	9.5	
	.0140	1.0	$\times 10^{6}$
	.0125	1.0	
	.0125	1.03	
	.0130	1.04	
19	.0134	1.0	$\times 10^{7}$
	.0134	1.5	
20	.0176	6.0	$\times 10^{6}$
	.0176	1.0	$\times 10^{7}$
21	.0202	5.0	$\times 10^{6}$
	.0202	7.0	
22	.024	5.0	$\times 10^{6}$
	.0225	7.0	
	.0223	1.0	
	.022	1.3	
	.022	1.6	
	.022	2.0	
	.022	2.3	
	.022	2.6	
	.022	3.2	
23	.012	1.5	$\times 10^{6}$
	.012	1.7	
	.012	2.2	
	.012	2.5	
	.012	2.8	
24	.0125	1.2	$\times 10^{6}$
	.0125	1.6	
	.0125	1.9	
	.0125	2.2	
	.0125	2.4	
	.0125	2.6	
	.0125	3.1	
25	.015	[illegible]	$\times 10^{6}$
	.014	[illegible]	
	.014	2.0	
	.014	2.2	
	.014	2.5	
	.014	2.9	
	.014	3.2	
26	.018	1.2	$\times 10^{6}$
	.0185	1.6	
	.019	2.1	
	.020	2.3	
	.021	2.5	
	.022	2.9	
	.021	3.5	
27	.012	1.1	$\times 10^{6}$
	.012	1.7	
	.011	2.0	
	.012	2.3	
	.011	2.8	
	.010	3.4	
28	.011	1.4	$\times 10^{6}$
	.0125	1.8	
	.012	2.4	
	.012	2.8	
	.012	3.4	
29	.0135	6.0	$\times 10^{5}$
	.0135	1.0	$\times 10^{6}$
	.015	1.2	
	.015	1.6	
	.015	2.0	
	.015	2.5	
	.015	3.1	
	.015	3.6	
30	.014	6.0	$\times 10^{5}$
	.0145	1.0	$\times 10^{6}$
	.0145	1.3	
	.0145	1.6	
	.0145	2.2	
	.0145	2.6	
	.0145	3.3	
	.0145	3.8	
31	.012	1.2	$\times 10^{6}$
	.012	1.4	
	.012	1.41	
	.0125	1.59	
	.0125	1.60	
	.0124	1.95	
	.0126	2.0	
	.0126	2.2	
	.0126	2.3	
	.0124	2.4	
	.0124	2.45	
	.015	2.6	
	.0124	2.8	
	.0123	2.9	
32	.0125	1.3	$\times 10^{6}$
	.0126	1.6	
	.0125	2.1	
	.0125	2.3	
	.012	2.4	
	.011	2.45	
	.012	3.1	
33	.025	1.05	$\times 10^{6}$
	.0249	1.5	
	.0251	2.0	
	.026	2.1	
	.026	2.5	
	.026	3.0	
34	.025	1.1	$\times 10^{6}$
	.026	1.6	
	.026	2.1	
	.026	2.2	
	.026	2.6	
	.0255	3.1	
35	.014	6.0	$\times 10^{5}$
	.012	1.1	$\times 10^{6}$
	.012	1.5	
	.0118	1.8	
	.0115	2.4	
	.0115	2.99	
36	.012	1.1	$\times 10^{6}$
	.012	1.6	
	.0115	1.9	
	.011	1.95	
	.011	2.5	
	.011	3.0	
37	.0125	1.3	$\times 10^{6}$
	.013	1.5	
	.0126	1.8	
	.0126	2.1	
	.0127	2.2	
	.0125	2.3	
	.0126	2.5	
	.0126	2.6	
38	.0166	1.696	$\times 10^{5}$
	.0190	6.696	$\times 10^{4}$
	.0178	1.160	$\times 10^{5}$
	.0172	1.430	
	.0201	6.814	$\times 10^{4}$
	.0262	2.124	
	.0246	3.029	
	.0220	4.638	
	.0152	3.163	$\times 10^{5}$
	.0154	2.635	
	.0159	2.452	
	.0161	2.217	
	.0156	2.566	
	.0153	3.296	
	.0160	2.015	
	.0159	2.411	
	.0155	2.845	
	.0151	3.288	
	.0147	4.211	
	.0150	3.549	
	.0148	3.896	
	.0155	2.810	
	.0160	2.292	
	.0166	1.871	
	.0151	3.418	
	.0170	1.513	
	.0177	1.184	
	.0152	3.158	
39	.0159	2.300	$\times 10^{5}$
	.0155	2.714	
	.0150	3.236	
	.0147	3.663	
	.0144	4.145	
	.0159	2.313	
	.0154	2.734	
	.0150	3.253	
	.0142	4.648	
	.0167	1.719	
	.0214	5.024	$\times 10^{4}$
	.0205	6.212	
	.0194	8.109	
	.0182	1.059	$\times 10^{5}$
	.0175	1.322	
	.0140	5.128	
40	.0119	1.335	$\times 10^{6}$
	.0122	1.137	
	.0145	4.457	$\times 10^{5}$
	.0136	6.064	
	.0148	3.903	
	.0155	3.026	
	.0166	2.167	
	.0143	4.828	
	.0121	1.203	$\times 10^{6}$
	.0132	7.533	$\times 10^{5}$
	.0129	8.465	
	.0128	9.042	
	.0134	6.744	
	.0139	5.539	
	.0127	9.351	
	.0126	9.814	
	.0174	1.521	
	.0178	1.422	
	.0196	8.720	$\times 10^{4}$
	.0184	1.219	$\times 10^{5}$
	.0125	1.130	$\times 10^{6}$
	.0131	8.532	$\times 10^{5}$
	.0128	9.741	
41	.0120	1.175	$\times 10^{6}$
	.0127	8.630	$\times 10^{5}$
	.0131	7.182	
	.0132	6.503	
	.0136	5.305	
	.0140	4.609	
	.0123	9.960	
	.0122	1.070	$\times 10^{6}$
	.0119	1.242	
	.0143	3.858	$\times 10^{5}$
	.0149	3.079	
	.0153	2.736	
	.0159	2.130	
	.0163	1.779	
42	.0212	1.755	$\times 10^{5}$
	.01754	3.30	
	.0144	6.64	
	.0143	8.14	
	.0138	9.83	
43	.0334	1.0	$\times 10^{4}$
	.0303	1.5	
	.0282	2.0	
	.0257	3.0	
	.0240	4.0	
	.0229	5.0	
	.0210	7.5	
	.0200	1.0	$\times 10^{5}$
	.0188	1.5	
	.0181	2.0	
	.0172	3.0	
	.0166	4.0	
	.0162	6.0	
	.0155	7.5	
44	.0334	1.0	$\times 10^{4}$
	.0303	1.5	
	.0284	2.0	
	.0259	3.0	
	.0244	4.0	
	.0233	5.0	
	.0215	7.5	
	.0206	1.0	$\times 10^{5}$
	.0196	1.5	
	.0190	2.0	
	.0182	3.0	
	.0177	4.0	
	.0174	5.0	
	.0170	7.5	
45	.0133	4.0	$\times 10^{6}$
	.0147	3.5	$\times 10^{5}$
46	.0124	4.5	$\times 10^{6}$
	.013	1.8	
47	.0143	5.4	$\times 10^{6}$
	.016	4.5	$\times 10^{5}$
48	.0135	7.85	$\times 10^{6}$
	.0142	1.65	
49	.0227	3.10	$\times 10^{6}$
	.0226	3.5	$\times 10^{5}$
50	.0275	4.3	$\times 10^{6}$
	.0275	1.1	

TABLE H.—*Analysis of friction data for continuous-interior steel pipe (Curve coordinates (not shown on charts))*

Curve	Darcy Weisbach f	Reynolds number R	
1	.0154	2.29	x10^6
	.0155	2.87	
	.0154	3.58	
	.0148	4.08	
	.0155	4.77	
	.0150	5.14	
	.0157	5.66	
2	.0214	1.58	x10^6
	.0192	2.79	
	.0200	3.15	
	.0187	4.46	
	.0194	4.75	
	.0193	6.20	
	.0191	6.25	
	.0192	6.41	
	.0192	6.50	
	.0189	6.71	
	.0191	6.72	
3	.0198	1.96	x10^6
	.0212	2.45	
	.0196	3.54	
	.0217	4.10	
	.0199	4.92	
	.0191	4.96	
	.0203	5.51	
	.0200	6.31	
4	.0204	2.15	x10^6
	.0212	2.15	
	.0227	2.69	
	.0204	3.20	
	.0200	3.89	
	.0212	4.50	
	.0202	5.40	
	.0201	5.45	
	.0206	6.04	
	.0207	6.92	
	.0207	7.02	
5	.0164	1.59	x10^6
	.0153	2.17	
	.0142	2.62	
	.0146	3.07	
	.0137	3.85	
	.0139	4.78	
	.0143	1.86	
	.0135	2.31	
	.0136	2.75	
	.0135	3.40	
	.0136	3.69	
	.0137	4.20	
	.0129	4.72	
6	.0184	1.26	x10^6
	.0171	1.99	
	.0164	2.98	
	.0170	3.49	
	.0169	4.01	
	.0161	4.58	
	.0163	5.13	
7	.0196	1.50	x10^6
	.0176	2.36	
	.0178	3.54	
	.0175	4.14	
	.0176	4.76	
	.0174	4.53	
	.0175	6.08	

Curve	Darcy Weisbach f	Reynolds number R	
8	.0183	1.50	x10^6
	.0192	2.36	
	.0184	3.54	
	.0182	4.14	
	.0187	4.76	
	.0182	5.43	
	.0182	6.08	
9	.0154	1.22	x10^6
	.0165	2.01	
	.0166	2.43	
	.0183	2.90	
	.0193	3.12	
	.0191	3.50	
	.0194	3.93	
	.0195	4.34	
10	.0184	1.26	x10^6
	.0161	2.08	
	.0166	2.51	
	.0155	3.00	
	.0167	3.22	
	.0164	3.61	
	.0169	4.06	
	.0167	4.48	
11	.0239	1.58	x10^6
	.0239	1.82	
	.0230	1.96	
	.0229	2.27	
	.0230	2.39	
	.0227	2.66	
	.0230	2.98	
	.0232	3.10	
12	.0120	1.1	x10^6
	.0120	1.6	
	.0120	1.8	
	.0130	2.2	
	.0130	2.4	
	.0140	2.8	
	.0135	3.1	
13	.0135	0.4	x10^6
	.0135	1.2	
	.0130	1.7	
	.0130	2.0	
	.0135	2.3	
	.0130	2.7	
	.0130	3.0	
	.0131	3.2	
14	.0175	1.4	x10^6
	.0152	1.8	
	.0176	2.1	
	.0165	2.4	
	.0170	2.7	
	.0170	2.9	
	.0150	3.8	
	.0150	4.6	
	.0149	5.2	
	.0150	6.0	
15	.021	0.5	x10^6
	.020	1.0	
	.019	1.5	
	.018	2.2	
	.018	2.5	
	.0175	2.8	
	.0175	3.0	

Curve	Darcy Weisbach f	Reynolds number R	
	.016	4.8	x10^6
	.016	5.4	
	.016	6.2	
16	.0176	5.6	x10^6
	.0180	2.8	
17	.0152	5.6	x10^6
	.0153	2.8	
18	.0176	5.6	x10^6
	.0180	2.8	
19	.0185	5.6	x10^6
	.0190	2.8	
20	.0152	1.45	x10^6
	.0157	8.0	x10^5
21	.0189	1.7	x10^6
	.0190	1.0	
22	.0174	2.2	x10^6
	.0180	1.0	
23	.0206	2.05	x10^6
	.0207	9.0	x10^5
24	.0221	2.1	x10^6
	.0225	9.0	x10^5
25	.0263	1.9	x10^6
	.0265	8.5	x10^5
26	.029	2.62	x10^5
	.029	4.04	
	.029	4.73	
	.035	5.78	
	.030	6.30	
	.029	8.12	
	.032	8.52	
	.028	9.80	
	.030	2.62	
	.028	4.04	
	.031	4.73	
	.034	5.78	
	.031	6.31	
	.032	8.53	
	.028	9.80	
27	.015	6.42	x10^5
	.015	7.98	
28	.019	7.80	x10^5
	.019	7.84	
29	.014	8.12	x10^6
	.014	1.12	x10^7
30	.015	7.22	x10^6
	.014	9.94	

TABLE J.—*Analysis of friction data for girth-riveted steel pipe (Curve coordinates (not shown on charts))*

Curve	Darcy Weisbach f	Reynolds number R	
1	.015	2.35	x10^6
	.0157	4.6	
	.0165	7.5	
2	.021	3.60	x10^6
	.0207	4.85	
3	.0205	1.0	x10^6
	.0165	4.0	
4	.0209	1.5	x10^6
	.0255	3.0	
	.0265	4.4	
	.0255	4.5	
5	.0172	8.8	x10^5
	.0160	1.7	x10^6
	.0162	2.43	
	.0161	3.05	
6	.0160	7.8	x10^5
	.0160	1.3	x10^6
	.0161	1.57	
7	.025	9.4	x10^5
	.024	1.17	x10^6
	.023	1.57	
8	.032	1.9	x10^4
	.033	2.6	
	.032	4.0	
9	.024	3.5	x10^4
	.024	5.5	
	.023	9.2	
	.021	1.55	x10^5
	.019	2.25	
	.017	3.3	
	.016	4.5	
	.016	4.5	
	.015	5.5	
	.015	6.2	
	.013	1.17	x10^6
10	.019	2.45	x10^5
	.017	3.45	
	.017	4.35	
	.016	5.8	
	.016	7.9	
	.015	9.3	
11	.028	1.99	x10^5
	.022	2.47	
	.021	2.89	
	.027	3.14	
	.023	3.45	
	.021	3.68	
	.020	3.88	
	.025	3.97	
	.021	4.10	
12	.024	7.58	x10^5
	.024	7.97	
	.023	1.05	x10^6
	.023	1.09	
	.022	1.31	
	.021	1.407	
	.022	1.55	
	.022	1.66	
	.022	1.69	
	.022	1.70	
	.022	1.80	
13	.014	1.42	x10^6
	.018	1.53	
	.017	1.88	
	.017	2.28	
	.018	3.02	
	.019	3.86	
	.019	4.68	
	.019	5.63	
	.019	6.35	
	.019	6.85	
	.018	7.26	
14	.012	1.42	x10^6
	.014	1.53	
	.014	1.88	
	.015	2.28	
	.016	3.02	
	.017	3.86	
	.016	4.68	
	.016	5.63	
	.016	6.35	
	.016	6.85	
	.016	7.26	
15	.019	2.44	x10^6
	.020	3.28	
	.020	4.60	
	.019	6.00	
16	.017	2.44	x10^6
	.017	3.28	
	.018	4.60	
	.017	6.00	
17	.018	2.44	x10^6
	.019	3.28	
	.019	4.60	
	.019	6.00	
18	.018	2.44	x10^6
	.019	3.28	
	.019	4.60	
	.018	6.00	
19	.022	1.79	x10^6
	.019	2.36	
	.017	2.73	
	.017	3.42	
	.017	3.90	
	.015	4.31	
	.016	4.67	
	.016	4.99	
	.016	5.60	
	.016	6.00	
	.016	6.27	
20	.0175	0.4	x10^6
	.0190	1.0	
	.0160	1.4	
	.0175	1.7	
	.0175	2.0	
	.0175	2.2	
	.0175	2.5	
	.0175	2.8	
21	.019	1.2	x10^6
	.020	1.6	
	.020	2.2	
	.020	2.5	
	.0175	2.9	
	.0175	3.4	
	.0175	3.8	
22	.0185	1.2	x10^6
	.0180	1.7	
	.0180	2.2	
	.0175	2.6	
	.0172	3.0	
	.0170	3.5	
	.0168	3.9	
23	.021	1.2	x10^6
	.018	1.7	
	.018	2.3	
	.0175	2.7	
	.018	3.2	
	.0176	3.6	
	.0174	4.0	
24	.0158	9.35	x10^6
	.0158	1.4	
25	.0180	5.65	x10^6
	.0180	1.4	
26	.0170	5.65	x10^6
	.0171	1.4	
27	.0180	5.65	x10^6
	.0180	1.4	
28	.0170	5.65	x10^6
	.0171	1.4	
29	.0185	5.65	x10^6
	.0189	1.4	
30	.0225	5.6	x10^6
	.0228	2.25	
31	.021	3.37	x10^6
	.021	3.40	
	.020	3.41	
	.020	3.57	
	.020	3.62	
32	.014	7.04	x10^6
	.013	9.7	
33	.017	3.08	x10^5
	.018	6.16	
	.020	9.24	
	.021	1.23	x10^6
	.021	1.54	
	.022	1.85	
	.022	2.15	
	.023	2.46	
	.023	2.77	
34	.026	1.25	x10^6
	.026	1.95	
	.025	2.62	
	.026	3.52	
	.026	3.52	
	.025	5.40	
35	.027	5.61	x10^5
	.028	7.18	
	.028	7.94	
	.029	1.03	x10^6
	.029	1.15	
	.028	1.20	
	.029	1.28	
	.029	1.37	
	.028	1.52	
36	.023	9.08	x10^5
	.020	1.07	x10^6
	.019	1.30	
37	.012	9.86	x10^5
	.014	1.06	x10^6
	.014	1.30	
	.015	1.58	
	.016	2.09	
	.017	2.67	
	.016	3.24	
	.016	3.90	
	.016	4.40	
	.016	4.74	
	.016	5.02	
38	.014	9.86	x10^5
	.016	1.06	x10^6
	.017	1.30	
	.017	1.58	
	.018	2.09	
	.019	2.68	
	.019	3.25	
	.019	3.90	
	.019	4.40	
	.019	4.74	
	.018	5.04	
39	.024	5.25	x10^5
	.024	5.52	
	.023	7.28	
	.023	7.55	
	.022	9.08	
	.021	9.75	
	.022	1.07	x10^6
	.022	1.15	
	.022	1.17	
	.022	1.18	
	.022	1.25	
40	.020	1.44	x10^5
	.019	1.84	
	.021	2.03	
	.021	2.30	
	.019	2.51	
	.019	2.60	
	.019	2.75	
	.022	2.80	
	.020	2.82	
41	.016	4.49	x10^5
	.017	9.74	
	.019	1.42	x10^6
	.019	1.70	
	.018	1.76	

Table K.—*Analysis of friction data for full-riveted steel pipe (Curve coordinates (not shown on charts))*

Curve	Darcy Weisbach f	Reynolds number R	
1	.026	3.82	x10^4
	.025	4.29	
	.024	5.51	
	.024	6.53	
	.023	8.16	
	.023	8.66	
	.022	8.89	
	.022	9.90	
	.022	1.07	x10^5
	.021	1.18	
	.021	1.18	
	.021	1.29	
	.021	1.32	
	.021	1.45	
	.020	1.58	
2	.027	3.49	x10^4
	.026	4.95	
	.025	5.49	
	.025	5.79	
	.025	6.90	
	.024	6.94	
	.024	8.41	
	.023	9.94	
	.023	1.12	x10^5
	.022	1.19	
	.022	1.28	
	.022	1.39	
	.022	1.44	
	.022	1.51	
	.022	1.57	
	.022	1.60	
3	.027	5.28	x10^4
	.028	6.29	
	.026	7.68	
	.025	8.00	
	.024	9.38	
	.024	9.43	
	.026	9.52	
	.024	1.15	x10^5
	.022	1.33	
	.023	1.36	
	.023	1.55	
	.023	1.62	
	.022	1.68	
4	.024	6.19	x10^4
	.023	8.19	
	.021	9.14	
	.021	1.31	x10^5
	.020	1.44	
	.020	1.51	
	.020	1.75	
	.020	1.99	
	.020	2.07	
	.020	2.08	
5	.024	5.02	x10^5
	.022	8.58	
	.022	8.99	
	.021	1.07	x10^6
	.021	1.09	
	.020	1.29	
	.021	1.11	
	.020	1.67	
	.019	2.02	
	.019	2.18	
	.019	2.19	
6	.0255	.33	x10^5
	.0240	.50	
	.0231	.67	
	.0225	.83	
	.0212	1.00	
	.0215	1.17	
	.0212	1.33	
	.0209	1.50	
	.0206	1.67	
	.0203	1.83	
	.0201	2.00	
	.0199	2.17	
	.0197	2.33	
	.0195	2.50	
	.0193	2.67	
	.0192	2.83	
	.0190	3.00	
	.0189	3.17	
	.0187	3.33	
	.0186	3.50	
	.0185	3.67	
6	.0184	3.83	x10^5
	.0182	4.00	
	.0181	4.17	
	.0180	4.33	
	.0179	4.50	
	.0178	4.67	
	.0178	4.83	
	.0177	5.00	
7	.0303	.33	x10^5
	.0293	.50	
	.0285	.67	
	.0279	.83	
	.0275	1.00	
	.0272	1.17	
	.0269	1.33	
	.0266	1.50	
	.0264	1.67	
	.0262	1.83	
	.0259	2.00	
	.0258	2.17	
	.0256	2.33	
	.0254	2.50	
	.0252	2.67	
	.0251	2.83	
	.0250	3.00	
	.0248	3.17	
	.0247	3.33	
	.0246	3.50	
	.0245	3.67	
	.0244	3.83	
	.0243	4.00	
	.0242	4.17	
	.0241	4.33	
	.0240	4.50	
	.0240	4.67	
	.0239	4.83	
	.0238	5.00	
8	.0264	.625	x10^5
	.0259	.75	
	.0253	1.00	
	.0248	1.25	
	.0244	1.50	
	.0241	1.75	
	.0238	2.00	
	.0236	2.25	
	.0234	2.50	
	.0232	2.75	
	.0230	3.00	
	.0228	3.25	
	.0227	3.50	
	.0225	3.75	
	.0224	4.00	
	.0223	4.25	
	.0222	4.50	
	.0221	4.75	
	.0220	5.00	
	.0219	5.25	
	.0218	5.50	
	.0218	5.75	
	.0217	6.00	
	.0216	6.25	
	.0215	6.50	
	.0215	6.75	
	.0214	7.00	
	.0214	7.25	
	.0213	7.50	
9	.0278	.625	x10^5
	.0276	.75	
	.0271	1.00	
	.0268	1.25	
	.0265	1.50	
	.0262	1.75	
	.0260	2.00	
	.0259	2.25	
	.0257	2.50	
	.0256	2.75	
	.0255	3.00	
	.0254	3.25	
	.0253	3.50	
	.0252	3.75	
	.0251	4.00	
	.0250	4.25	
	.0249	4.50	
	.0249	4.75	
	.0248	5.00	
	.0248	5.25	
	.0247	5.50	
	.0247	5.75	
9	.0246	6.00	x10^5
	.0246	6.25	
	.0245	6.50	
	.0245	6.75	
	.0245	7.00	
	.0244	7.25	
	.0244	7.50	
10	.0301	.833	x10^5
	.0293	1.00	
	.0283	1.33	
	.0276	1.67	
	.0271	2.00	
	.0267	2.33	
	.0263	2.67	
	.0260	3.00	
	.0257	3.33	
	.0255	3.67	
	.0253	4.00	
	.0251	4.33	
	.0249	4.67	
	.0247	5.00	
	.0246	5.33	
	.0244	5.67	
	.0243	6.00	
	.0242	6.33	
	.0241	6.67	
	.0239	7.00	
	.0238	7.33	
	.0237	7.67	
	.0236	8.00	
	.0235	8.33	
11	.0323	.833	x10^5
	.0313	1.00	
	.0300	1.33	
	.0292	1.67	
	.0286	2.00	
	.0281	2.33	
	.0277	2.67	
	.0273	3.00	
	.0270	3.33	
	.0267	3.67	
	.0264	4.00	
	.0262	4.33	
	.0259	4.67	
	.0257	5.00	
	.0255	5.33	
	.0253	5.67	
	.0252	6.00	
	.0250	6.33	
	.0249	6.67	
	.0248	7.00	
	.0246	7.33	
	.0245	7.67	
	.0244	8.00	
	.0243	8.33	
12	.0280	1.25	x10^5
	.0264	1.67	
	.0254	2.08	
	.0246	2.50	
	.0239	2.91	
	.0234	3.33	
	.0229	3.75	
	.0224	4.16	
	.0220	4.58	
	.0217	5.00	
	.0214	5.41	
	.0211	5.83	
	.0208	6.25	
	.0205	6.67	
	.0203	7.08	
	.0201	7.50	
13	.0302	1.25	x10^5
	.0285	1.67	
	.0273	2.08	
	.0263	2.50	
	.0254	2.91	
	.0247	3.33	
	.0242	3.75	
	.0236	4.16	
	.0232	4.58	
	.0228	5.00	
	.0225	5.41	
	.0221	5.83	
	.0218	6.25	
	.0215	6.67	
	.0213	7.08	
	.0210	7.50	

TABLE L.—*Analysis of friction data for spiral-riveted steel pipe (Curve coordinates (not shown on charts))*

Curve	Darcy Weisbach f	Reynolds number R	
1	.0106	3.14	$\times 10^6$
	.0088	3.52	
	.0104	3.64	
	.0100	4.25	
	.00106	5.48	
2	.0113	4.75	$\times 10^6$
	.0132	4.89	
	.0124	4.95	
	.0135	5.04	
	.0135	5.14	
	.0130	5.21	
	.0130	5.34	
	.0124	5.47	
	.0122	6.56	
	.0125	6.56	
3	.0292	3.94	$\times 10^5$
	.0313	4.16	
	.0213	6.50	
	.0191	8.92	
	.0175	9.42	
	.0188	1.008	$\times 10^6$
	.0178	1.037	
	.0200	1.056	
	.0179	1.119	
4	.0186	4.73	$\times 10^5$
	.0187	5.00	
	.0178	8.55	
	.0180	8.71	
	.0173	1.132	$\times 10^6$
	.0173	1.200	
	.0181	1.300	
	.0174	1.339	
	.0176	1.391	
	.0175	1.418	
	.0179	1.505	
	.0176	1.780	
	.0169	1.884	
	.0170	1.940	
	.0175	2.080	
5	.0548	2.14	$\times 10^5$
	.0330	2.18	
	.0483	2.68	
	.0117	3.28	
	.0278	4.88	
	.0246	5.94	
	.0240	5.00	
	.0232	5.36	
	.0196	5.96	
	.0201	7.60	
	.0210	7.95	
	.0180	8.58	
	.0187	8.90	
	.0182	1.025	$\times 10^6$
	.0178	1.079	
	.0182	1.100	
	.0177	1.266	
	.0169	1.386	
	.0173	1.435	
	.0150	1.451	
	.0162	1.460	
	.0169	1.466	
6	.0166	3.86	$\times 10^5$
	.0149	4.69	
	.0142	5.74	
	.0133	7.44	
	.0127	8.89	
	.0126	9.50	
	.0124	1.055	$\times 10^6$
	.0122	1.172	
	.0117	1.218	
7	.0136	6.03	$\times 10^5$
	.0126	7.35	
	.0117	8.66	
	.0157	1.00	$\times 10^6$
	.0153	1.04	
8	.0193	7.32	$\times 10^5$
	.0191	7.38	
	.0181	8.55	
	.0171	9.85	
	.0173	9.95	
	.0168	1.10	$\times 10^6$
	.0165	1.20	
	.0162	1.27	
	.0162	1.36	
	.0161	1.42	
	.0155	1.53	
9	.0114	6.72	$\times 10^5$
	.0111	8.25	
	.0120	1.03	$\times 10^6$
10	.0118	9.00	$\times 10^5$
	.0119	1.07	$\times 10^6$
	.0134	1.32	
	.0131	1.36	
	.0129	1.38	
11	.0211	9.20	$\times 10^5$
	.0217	9.32	
	.0212	9.62	
	.0203	1.02	$\times 10^6$
	.0201	1.05	
	.0201	1.05	
	.0201	1.07	
	.0198	1.18	
	.0199	1.22	
	.0195	1.23	
	.0193	1.28	
12	.0258	4.08	$\times 10^5$
	.0239	4.77	
	.0229	5.76	
	.0233	5.80	
	.0217	7.14	
	.0169	7.42	
	.0210	8.50	
13	.0310	1.07	$\times 10^5$
	.0308	1.35	
	.0266	1.74	
	.0259	2.07	
	.0258	2.42	
	.0231	3.13	
	.0163	7.50	

TABLE. M.—*Analysis of friction data for wood-stave pipe (Curve coordinates (not shown on charts))*

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