American Water Works Association

ANSI/AWWA C401-83
(Revision of AWWA C401-77)

AWWA STANDARD PRACTICE
for
THE SELECTION OF ASBESTOS-CEMENT DISTRIBUTION PIPE 4 IN. THROUGH 16 IN. (100 mm THROUGH 400 mm), FOR WATER AND OTHER LIQUIDS

AMERICAN NATIONAL STANDARD

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AMERICAN WATER WORKS ASSOCIATION
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Foreword

This foreword is for information only and is not a part of AWWA C401.

I. History of Standard

The information contained in this standard was first published as *AWWA Handbook H2,* with AWWA Board of Directors' approval on Jan. 17, 1964. The designation was later changed to, AWWA C401-64. Originally, it covered sizes 4–36 in. (100–900 mm) although the design was primarily based on service conditions generally related to smaller (4–16 in. [100–400 mm]) distribution sizes. In 1977 the standard was revised. The title was changed to indicate the pipe is intended for use in distribution systems, and the size range was changed to limit the maximum size covered by this standard to 16-in. (400-mm) diameter pipe.

II. Major Revisions

Major revisions in this edition consist of the following:

1. The format has been completely revised so that the various sections in this standard correspond to the numbered sections in AWWA C403, Standard Practice for the Selection of Asbestos–Cement Transmission and Feeder Main Pipe, Sizes 18 in. Through 42 in.
2. Bedding condition descriptions and load factors used in calculating earth loads have been revised to correspond to those contained in ASCE Manual of Engineering Practice No. 37, *Design and Construction of Sanitary and Storm Sewers* (1976).
3. The three-edge vee-shaped bearing method of ASTM C500 has been specified for crush testing.
4. The appendix has been enlarged to present data on flow calculations using the Hazen and Williams formula and data on surge pressure analysis.
5. The impact factor table was revised to conform with impact factors recommended by the American Association of State Highway and Transportation Offices (AASHTO).
6. Metric conversion of all dimensions and physical requirements are included in this standard (Table F.1). Metric dimensions are direct conversions of customary US inch-pound units and are not those specified in International Standards Organization (ISO) standards.

Table F.1

Conversion Factors

Inch-Pound System	Multiply By	To Obtain
Inches	25.4	Millimetres
Feet	0.3048	Metres
Pounds Per Square Inch	6.894757	Kilopascals
Pounds	4.44822	Newtons
Pounds Per Foot	0.014594	Kilonewtons Per Metre
Pounds Per Square Foot	0.0478803	Kilonewtons Per Square Metre
Pounds Per Cubic Foot	16.0185	Kilograms Per Cubic Metre

American Water Works Association

ANSI/AWWA C401-83
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AWWA Standard Practice for

The Selection of Asbestos-Cement Distribution Pipe, 4 in. Through 16 in. (100 mm Through 400 mm), for Water and Other Liquids

Section 1—General

Sec. 1.1 Scope

This standard has been prepared so that design engineers may quickly determine the correct pressure classification of asbestos-cement distribution pipe to use under various combinations of internal pressure (static, operating, and surge) and external load (earth and superimposed live loads). Combined loading curves depicting the relationship between hydrostatic loading and external loading capabilities are included to expedite the selection of the correct pipe strength classification.

NOTE: Information to assist the engineer in selecting the most economical size of pipe is in the appendices. Appendix A contains a friction loss of head chart based on the Hazen and Williams formula. Appendix B is a detailed analysis of surge pressure factors. Appendix C includes tables to assist the engineer in determining the yearly power costs to overcome friction loss of head. The appendices are for information only and are not part of AWWA C401.

1.1.1 *Pressure classes.* Pipe pressure class designations of 100, 150, and 200 refer to the similarly numbered classes specified in AWWA C400, Standard for Asbestos-Cement Distribution Pipe, 4 in. Through 16 in. (100 mm Through 400 mm) NPS, for Water and Other Liquids."

1.1.2 *Installation.* Detailed coverage of the installation of asbestos-cement pipe can be found in AWWA C603, Standard for Installation of Asbestos-Cement Pressure Pipe.

Sec. 1.2 References

This standard references the following documents. They form a part of this standard to the extent specified herein. In any case of conflict, the requirements of this standard shall prevail.

SCHLICK, W. J. Supporting Strengths for Cast-Iron Pipe for Water and Gas Service. Bull. 146. Iowa State Col. Engrg. Exp. Sta. (June 1940).

Design and Construction of Sanitary and Storm Sewers. Manual of Engrg. Prac. No. 37. Amer. Soc. Civ. Engrs. New York (1976).

KERR, S. L. Practical Aspects of Water Hammer, *Jour. AWWA*, 40:6:699 (June 1948).

MARSTON, ANSON. The Theory of External Loads on Closed Conduits in the Light of Latest Experiments. Bull. 96. Iowa State Col. Engrg. Exp. Sta. (1930).

ASTM* C500, Methods of Testing Asbestos-Cement Pipe.

Sec. 1.3 Symbols and Abbreviations

B_c = Outside diameter of a pipe, in feet (metres).

B_d = Width of trench measured at the top of pipe, in feet (metres).

B. F. = Bedding factor, which is a load factor correlating three-edge vee-shaped bearing test loads to field loads associated with specific bedding conditions.

B_T = Maximum width of a tunnel excavation, in feet (metres).

c = Coefficient of soil cohesion, in pounds per square foot (kilonewtons per square metre).

C_c = Load coefficient for the positive projecting embankment condition. It is a function of the ratio H/B_c, the projection ratio p, and the settlement ratio r_{sd}.

C_d = Load coefficient for the trench condition. It is a function of the ratio H/B_d and the backfill material.

C_n = Load coefficient for the negative projecting embankment condition, as well as the imperfect ditch condition. It is a function of the ratio H/B_d, the projection ratio p', and the settlement ratio r_{sd}.

C_s = Load coefficient for concentrated or distributed superimposed loads. It is a function of the ratio $B_c/2H$ and the ratio $L/2H$ for concentrated loads, or the ratio $D/2H$ and the ratio $M/2H$ for distributed loads.

C_T = Load coefficient for tunnel conditions. It is a function of the ratio H/B_T and the type of soil surrounding the tunnel.

D = Width of the area over which the distributed superimposed load acts, in feet (metres).

F = Impact factor.

H = Depth of cover, in feet (metres), for all conditions except the tunnel condition. For the tunnel condition, H is the distance from the ground surface to the top of the tunnel excavation, in feet (metres).

k = Rankine's ratio of lateral earth pressure to vertical pressure.

L = Effective length of the pipe, in feet (metres). For pipe less than 3 ft (1 m), the actual length of the section should be used. For all other lengths, an effective length of 3 ft (1 m) should be used.

M = Length of the area over which the distributed superimposed load acts, in feet (metres).

P = Internal pressure, in pounds per square inch (kilopascals), that the pipe will withstand when no external load exists.

P_c = Concentrated loads, in pounds (kilonewtons†).

P_d = Distributed load, in pounds per square foot (kilonewtons per square metre†).

P_o = Static, working, or operating pressure, in pounds per square inch (kilopascals).

P_s = Surge pressure or water hammer, in pounds per square inch (kilopascals).

*American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

†Note: P_c and P_d are loads measured as a mass. However, to use them in equations using SI units the mass unit must be converted to force by multiplying times 9.807 (g, the acceleration of gravity).

P_T = Total internal pressure, in pounds per square inch (kilopascals), above which, in combination with some external load W_T applied in three-edge vee-shaped bearing, the pipe will withstand.

p = Projection ratio for the positive projecting embankment condition. It is defined as the ratio of the distance that the top of the pipe projects above the original ground surface in feet (metres) to the outside diameter of the pipe in feet (metres). (See Figure 10A.)

p' = Projection ratio for the negative projecting and imperfect ditch condition. It is defined as the ratio of the vertical distance from the original ground surface down to the top of the pipe, in feet (metres), divided by the width of the trench, in feet (metres), for negative projection, and as the ratio of the vertical distance from the top of the excavated trench down to the top of the pipe, in feet (metres), divided by the diameter of the pipe, in feet (metres), for the imperfect ditch condition. (See Figure 10B and Figure 11.)

r_{sd} = Settlement ratio for positive projection, negative projection, and imperfect ditch conditions.

S.F. = Safety factor.

μ = The coefficient of internal friction of backfill material.

μ' = The coefficient of friction between backfill material and the trench wall.

W = External load, in pounds per linear foot (kilonewtons per metre), of pipe in the three-edge vee-shaped bearing test that the pipe will withstand when no hydrostatic pressure exists.

W_E = Total earth load, in pounds per linear foot (kilonewtons per metre), to which the pipe is subjected.

W_S = Total superimposed load, in pounds per linear foot (kilonewtons per metre), of pipe transmitted through the burial environment to the pipe by factors other than the earth loads.

W_{sc} = The concentrated superimposed load, in pounds per linear foot (kilonewtons per metre), of pipe transmitted through the burial environment to the pipe by factors other than the earth loads.

W_{sd} = Distributed superimposed load, in pounds per linear foot (kilonewtons per metre), of pipe transmitted through the burial environment to the pipe by factors other than the earth loads.

W_T = Total external load, in pounds per linear foot (kilonewtons per metre), of pipe applied in three-edge vee-shaped bearing above which, in combination with some internal pressure P_T, the pipe will withstand.

w_e = Weight of earth, in pounds per cubic foot (kilonewtons per cubic metre*).

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*Density, as used in the equations in this standard, refers to force exerted per unit volume under the acceleration of gravity, rather than mass per unit volume. Where true density is known in pounds per cubic foot, that value should be used in equations using US customary units; where true density is known in kilograms per cubic metre, it must be converted to newtons per cubic metre by multiplying times 9.807 (g, the acceleration of gravity) before the value is used in equations using SI units.

Section 2—General Design

Sec. 2.1 Strength and Design Factors

The strength of asbestos–cement distribution pipe must be sufficient to withstand the combined forces of all types of internal pressures (static, operating, and surge) and external loadings (earth, live, and impact). Sound engineering practice also requires that adequate safety factors be applied to strength requirements to ensure performance under other than ideal or calculated loading conditions. The magnitude of these safety factors is inversely proportional to the confidence that the designer has in engineering estimates of actual operating conditions. Safety factors are included under Sec. 5.

2.1.1 *Bedding conditions.* The bedding conditions described below and shown in Figure 1 have been selected as representative of typical installation conditions encountered in the field.

2.1.1.1 Class A—concrete cradle or concrete arch bedding. This class of bedding may take either of two forms:

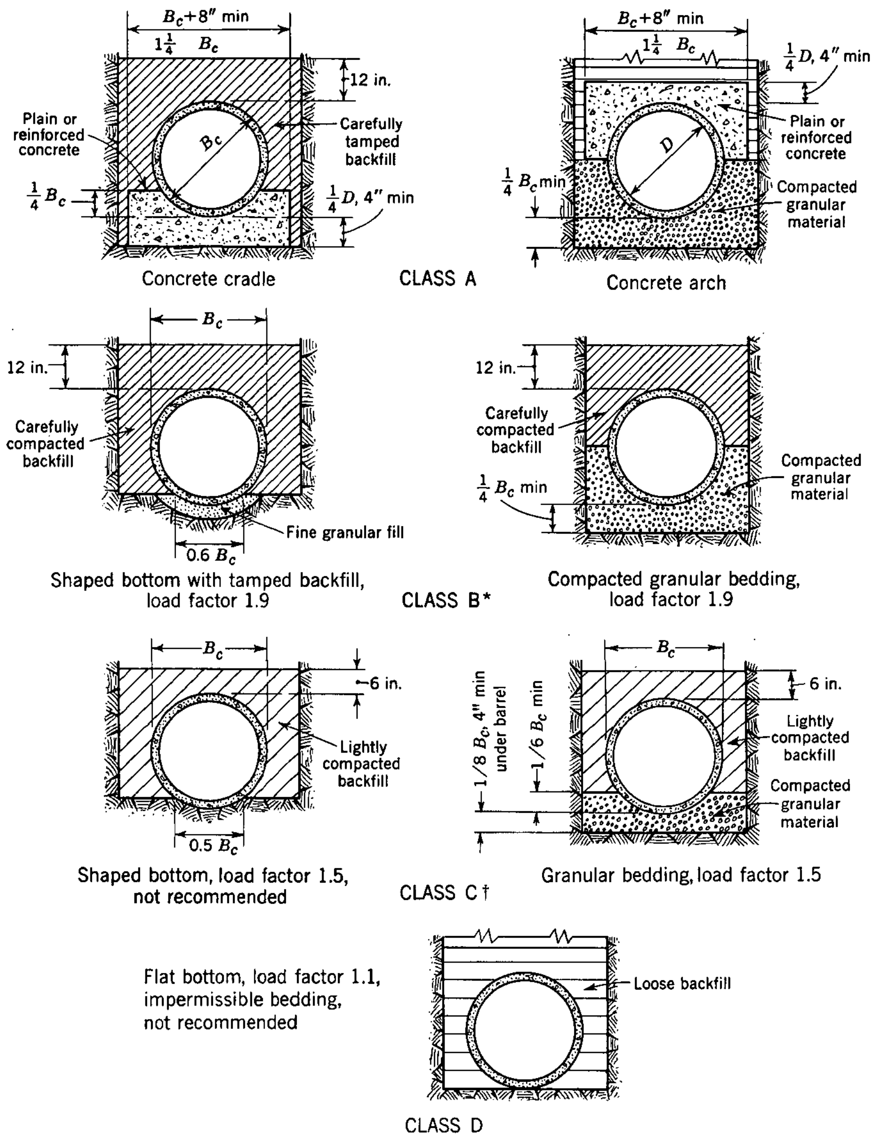
2.1.1.1.1 Concrete cradle. The pipe shall be bedded in a monolithic cradle of plain or reinforced concrete having a minimum thickness of one-fourth the outside pipe diameter (minimum of 4 in. [100 mm]) under the barrel and extending up the sides for a height equal to one-fourth the outside diameter. The cradle shall have a width at least equal to the outside diameter of the pipe barrel plus 8 in. (200 mm). Backfill shall be compacted above the cradle and extending to 12 in. (300 mm) above the crown of the pipe. The load factor for Class A concrete cradle bedding is 2.2 for plain concrete with lightly compacted (85 percent to 95 percent proctor or 40 percent to 70 percent relative density) backfill; 2.8 for plain concrete with carefully compacted (95 percent proctor or 70 percent relative density) backfill; and 3.4 for reinforced concrete with $p = 0.4$ percent, in which p is the ratio of the area of steel to the area at the invert.

2.1.1.1.2 Concrete arch. The pipe shall be bedded in carefully compacted granular material having a minimum thickness of one-fourth the outside pipe diameter (minimum of 4 in. [100 mm]) between barrel and bottom of trench excavation and extending halfway up the sides of the pipe. The top half of the pipe shall be covered with a monolithic plain or reinforced concrete arch having a minimum thickness of one-fourth the outside diameter (minimum of 4 in. [100 mm]) at the crown and having a minimum width equal to the outside pipe diameter plus 8 in. (200 mm). The load factor for Class A concrete arch type bedding is 2.8 for plain concrete; up to 3.4 for reinforced concrete with $p = 0.4$ percent; and up to 4.8 for reinforced concrete with $p = 1.0$ percent, in which p is the ratio of the area of steel to the area of concrete at the crown.

2.1.1.2 Class B—first class bedding. Class B bedding may be achieved by either of two construction methods:

2.1.1.2.1 Shaped bottom with carefully compacted backfill. The bottom of the trench excavation shall be shaped to conform to a cylindrical surface with a radius at least 2 in. (50 mm) greater than the radius to the outside of the pipe and with a width sufficient to allow six-tenths of the width of the pipe barrel to be bedded in fine granular fill placed in the shaped excavation. Carefully compacted backfill shall be placed at the sides of the pipe to a thickness of at least 12 in. (300 mm) above the top of the pipe. Shaped trench bottoms are difficult to achieve under current construction techniques.

2.1.1.2.2 Compacted granular bedding with carefully compacted backfill.



*Carefully compacted backfill: 95% proctor or 70% relative density.
†Lightly compacted backfill: 85-95% proctor or 40-70% relative density.

Figure 1. Classes of Bedding for Conduits in Trench

NOTE: In rock trench, excavate at least 6 in. (150 mm) below the coupling of the pipe except where concrete cradle is used.

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The pipe shall be bedded in compacted granular material placed on a flat trench bottom. The granular bedding shall have a minimum thickness of one-fourth the outside pipe diameter (minimum of 4 in. [100 mm]) and shall extend halfway up the pipe barrel at the side. The remainder of the backfill to a minimum depth of 12 in. (300 mm) over the top of the pipe shall be filled with highly compacted material.

2.1.1.2.3 The load factor for either construction method is 1.9.

2.1.1.3 Class C—ordinary bedding. Class C ordinary bedding may be achieved by either of two construction methods:

2.1.1.3.1 Shaped bottom. The pipe shall be bedded with "ordinary" care in an earth foundation formed in the trench bottom by a shaped excavation that will fit the pipe barrel with reasonable closeness for a width of at least 50 percent of the outside pipe diameter. The side fills and area over the pipe to a minimum depth of 6 in. (150 mm) above the top of the pipe shall be filled with lightly compacted fill. The shaped bottom bedding is not recommended for pipeline construction because it is impractical and costly.

2.1.1.3.2 Compacted granular bedding with a lightly compacted backfill. The pipe shall be bedded in compacted granular material placed on a flat trench bottom. The granular bedding shall have a minimum thickness of 4 in. (100 mm) under the barrel and shall extend one-tenth to one-sixth of the outside diameter up the pipe barrel at the sides. The remainder of the backfill to a minimum depth of 6 in. (150 mm) over the top of the pipe shall be filled with lightly compacted backfill.

2.1.1.3.3 The load factor for either construction method is 1.5.

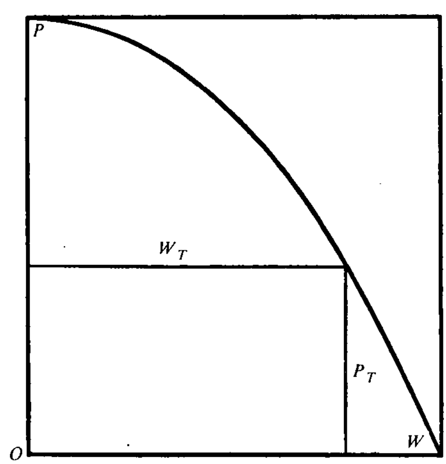
2.1.1.4 Class D—flat bottom trench, impermissible bedding. In this class of bedding, the bottom of the trench is left flat, and no care is taken to secure compaction of backfill at the sides and immediately over the pipe. The load factor for Class D bedding is 1.1.

2.1.1.4.1 Class D bedding is not recommended for pipeline construction. Under present construction conditions, Class B or C bedding with a compacted granular bedding is generally a more practical and economical method of installation.

Sec. 2.2 Combined Loading Theory

Tests of asbestos-cement pipe under various combinations of internal pressure and external crush load applied in three-edge vee-shaped bearing (see Sec. 2.3) shows that there is a relationship between the combined loads at the point of pipe fracture. This relationship can be represented by a parabolic curve as shown in Figure 2. The equation for the load pressure parabolic curve, which is known as the Schlick formula, may be expressed as:

$$W_T = W\sqrt{\frac{P - P_T}{P}} \qquad \text{Eq 1}$$



P *represents the internal pressure;* W *the external load.*

Figure 2. Load Pressure Curve

Sec. 2.3 Three-Edge Vee-Shaped Bearing Load

The combined loading curve shown in Figure 2 is calculated on the basis of crush strengths determined by laboratory tests employing the three-edge vee-shaped bearing test method (see ASTM C500, Methods of Testing Asbestos-Cement Pipe and Figure 3). Because the field-supporting strength of a pipe is influenced by the bedding conditions and by the lateral pressure acting against the sides of the pipe, it is necessary to apply a bedding load factor to the laboratory three-edge vee-shaped bearing loads to correlate them to the actual field loads. Since the external load equals the bedding factor times the vee-shaped bearing load, the bedding factor equals the external load divided by the three-edge vee-shaped bearing load. Figure 1 shows the load factors to be applied for each bedding class.

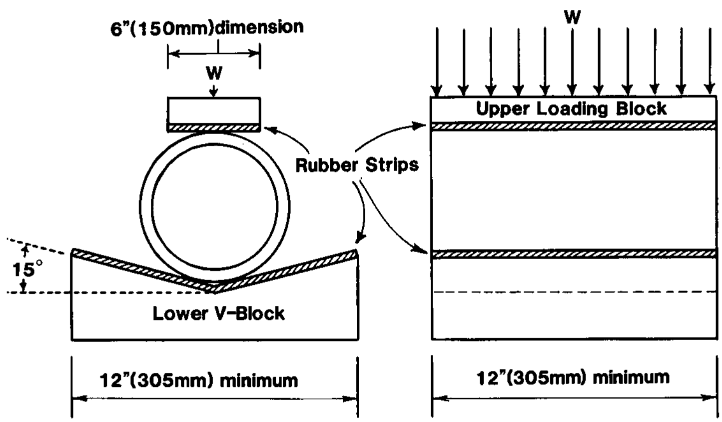


Figure 3. Assembly for Three-Edge Vee-Shaped Crushing Strength Test

Section 3—External Loads

Sec. 3.1 Introduction

For the design of asbestos-cement distribution pipe, external loads W_T are defined by the following equation:

$$W_T = \frac{W_E + W_S}{(B.F.)} \times (S.F.) \quad \text{Eq 2}$$

Sec. 3.2 Earth Loads

Earth loads W_E to which pipe is subjected are a function of the soil density, pipe diameter, depth of cover, and construction techniques employed in laying the pipeline. They depend on the interplay between the weight of the prism of earth directly over the pipe, called the interior prism, and the frictional shearing forces, plus or minus, transferred to that interior prism by the adjacent outside prisms of earth. The magnitude of earth loads varies with the construction technique employed. There are two major construction techniques normally encountered: trench and embankment. Another technique, the tunnel condition, is not normally found, but nevertheless, has unique design methods, which make its inclusion in this discussion necessary. Figure 4 shows these three construction techniques.

3.2.1 *Marston's equation.* For asbestos–cement distribution pipe design, earth loads are calculated by the general form of Marston's equation:

$$W_E = C w_e B_d^2 \qquad \text{Eq 3}$$

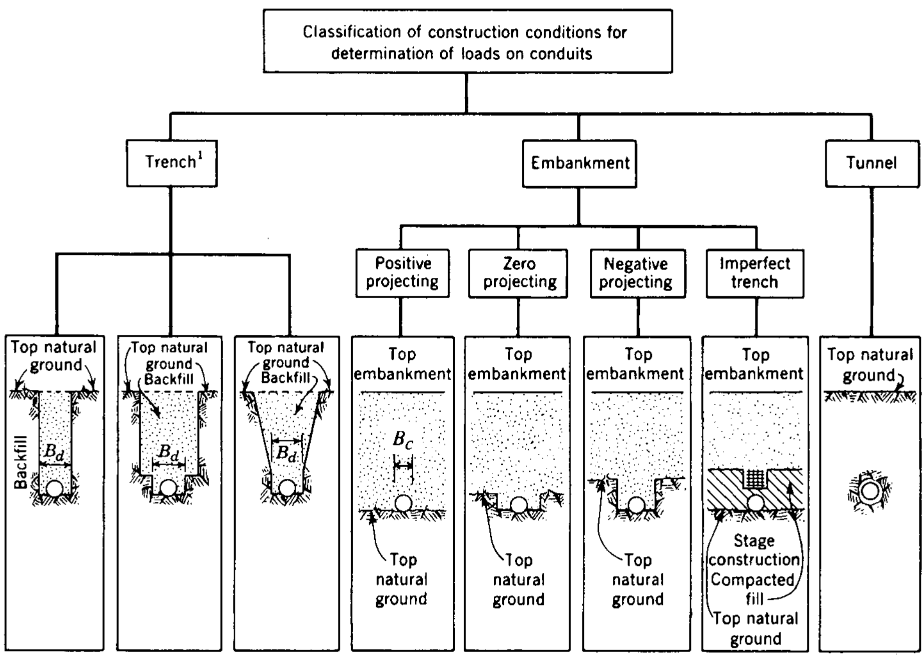
NOTE: Density as used in this equation and the following equations actually refers to force exerted per unit volume (pounds per cubic foot or kilonewtons per metre) under the acceleration of gravity, rather than mass per unit volume. Where true density is known in pounds per cubic foot, that value should be used in equations using US customary units; where true density is known in kilograms per cubic metre, it must be converted to newtons per cubic metre by multiplying times 9.807 (g, the acceleration of gravity) before the value is used in equations using SI units.

Soil densities w_e range in value from 100 to 135 lb/cu ft (16 to 21 kN/m^3). In the absence of actual site information, a value of 120 lb/cu ft (19 kN/m^3) is recommended for asbestos–cement distribution pipe design.

3.2.1.1 C is a coefficient that is dependent on:

1. Ratio of the height of fill to the width of trench or pipe diameter.
2. Shearing forces between the interior and adjacent earth prisms.
3. Direction and amount of relative settlement between interior and adjacent earth prisms for embankment conditions.

The calculations used to find the value



[1] B_d within required limit, otherwise conduit is positive projecting

Figure 4. Classification of Construction Techniques

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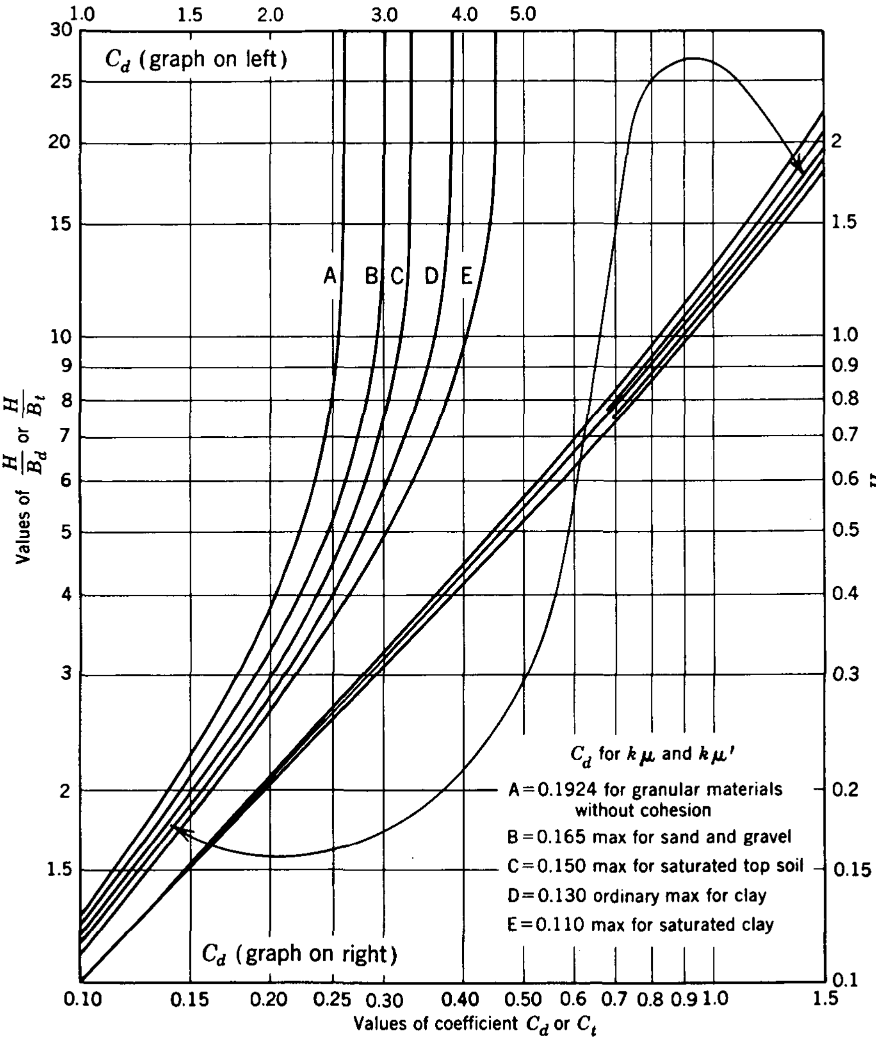

Figure 5. Values of C_d for Trench Conditions

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of the coefficient will depend on the installation conditions employed in laying the pipe.

3.2.1.2 Values for B_d and C must be determined to calculate earth loads by Eq 3 for the trench, embankment, and tunnel construction techniques. The following subsections describe the different conditions and explain the methods for finding the values needed to use Marston's equation for soil loading.

3.2.2 *Trench condition.* A trench condition is defined as that in which the pipe is installed in a narrow trench, generally less than two to three diameters in width, cut in undisturbed ground, and backfilled to the original ground surface, as illustrated in Figure 4. For this condition, Eq 3 is rewritten as:

$$W_E = C_d w_e B_d^2 \qquad \text{Eq 4}$$

3.2.2.1 The values of C_d are obtained from Figure 5, in which curves A, B, C, D, and E take into account the friction coefficient between the backfill and the sides of the trench for the various soil compositions likely to be encountered. Curve A is for granular materials without cohesions. Curve B is for sand and gravel. Curve C is for saturated top soil. Curve D is for clay. Curve E is for saturated clay.

3.2.3 *Embankment condition.* An embankment condition is defined as either that condition where the pipe is installed in a trench that is wider than two to three pipe diameters and that is cut in undisturbed ground, or that condition where the pipe is covered with fill above the original ground surface. Embankment conditions are further subdivided into positive and negative projecting pipe categories, depending on the location of the top of the pipe relative to the original undisturbed ground. A special case where compressible material is used as part of the backfill, called an imperfect trench, also is classified as an embankment condition. The various embankment conditions are illustrated in Figures 4 and 6.

3.2.4 *Positive projecting pipe condition.* A positive projecting pipe condition is defined as either that condition where the pipe is installed in a trench cut in undisturbed ground that is wider than two to three pipe diameters, or that condition where the top of the pipe is above the adjacent original ground surface and covered with fill above the original ground surface. For this condition, Eq 3 is rewritten as:

$$W_E = C_c w_e B_c^2 \qquad \text{Eq 5}$$

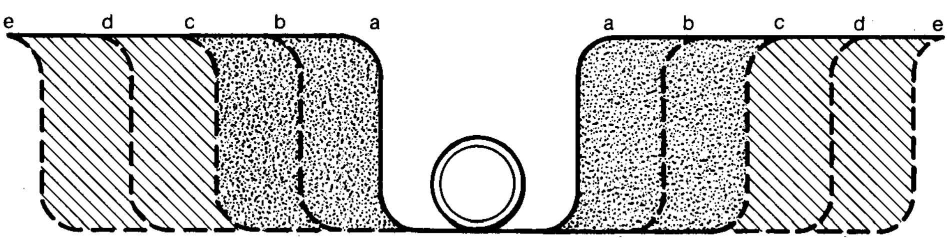
3.2.4.1 The values of C_c are obtained from Figure 7. C_c also may be obtained from Eq 6 when the following conditions exist simultaneously:

1. The ratio H/B_c is greater than 1.3
2. The product $p\ (r_{sd}) = 0.7$

$$C_c = 1.892H/B_c - 0.96 \qquad \text{Eq 6}$$

3.2.4.2 The recommended value for the settlement ratio r_{sd} is $+0.7$ for asbestos–cement distribution pipe design.

3.2.5 *Transition width.* It will be noted from the preceding discussion that under construction conditions where a trench is cut in undisturbed ground two methods of computing the earth load are



aa *and* bb *The trench width is less than the transition width; earth loads are computed by the trench equation (Eq 4).*
cc *The trench width is the transition width; earth loads are computed by either Eq 4 or Eq 5.*
dd *and* ee *The trench width is greater than the transition width; earth loads are computed by the positive projecting pipe embankment equation (Eq. 5). For a given depth of cover the earth loads resulting from trench widths* cc, dd, *and* ee *are equal.*

Figure 6. Embankment Conditions

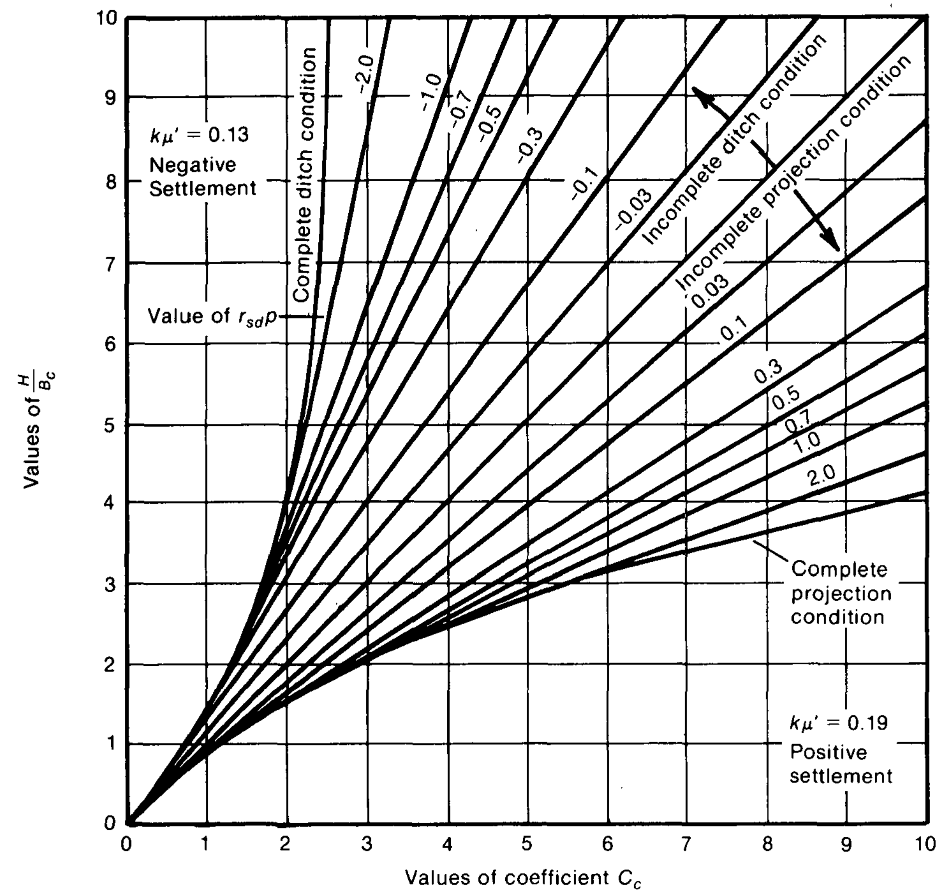


Figure 7. Values of C_c for Positive Projecting Pipe

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available: (1) the trench condition and (2) the positive projecting pipe embankment condition. The method chosen is dependent on the ratio of the trench width to the pipe diameter. As previously stated, when the trench width is less than two to three times the pipe diameter, earth loads are computed by the trench condition equation (Eq 4). The width of trench at which both methods of computation give equal loads is called the transition width. The earth load computed at the transition width is theoretically the maximum external earth load that can be transmitted to the pipe for any given depth of cover. For all trench widths greater than the transition width, earth loads are computed by the positive projecting pipe embankment condition equation (Eq 5). In this latter case and for a given depth of cover, the earth loads are equal to the load that results at the transition width and that is computed by the trench condition equation (Eq 4). (See Figure 6.)

3.2.5.1 The transition width is determined from Figure 8 by multiplying the applicable ratio B_d/B_c by the applicable pipe outside diameter B_c. The applicable ratio of trench width to pipe outside diameter, B_d/B_c, can be obtained from Figure 8 for any given ratio of backfill height to pipe outside diameter, H/B_c.

3.2.6 *Negative projecting pipe embankment condition.* A negative projecting pipe condition is defined as that condition where the pipe is installed in a relatively shallow trench wherein the top of the pipe is at some elevation below the original ground surface. The trench is then backfilled and compacted, and embankment is constructed thereon to finished grade (Figure 4). For this condition, Eq 3 is rewritten as:

$$W_E = C_n w_e B_d^2 \qquad \text{Eq 7}$$

3.2.6.1 The various values of C_n are obtained from Figure 9. For asbestos-cement pipe design the recommended value for the settlement ratio r_{sd} is zero.

3.2.6.2 When calculating earth loads under negative projecting pipe embankment conditions, consideration must be given to the transition width as defined in Sec. 3.2.5. For values of the ratio B_d/B_c less than those given in Figure 8, the load on a pipe is determined from Eq 7 for negative projecting pipes. However, as the trench width increases and the ratio B_d/B_c becomes greater than that given in Figure 8, the earth load should be determined from Eq 5 for positive projecting pipes. Adherence to the preceding rule will result in the most realistic earth loads for design purposes.

3.2.7 *Imperfect trench condition.* The imperfect trench condition occurs rather infrequently and is included for general information. The imperfect trench embankment condition refers to that construction technique wherein the pipe is first installed as a positive projecting pipe. A portion of the embankment is then built up to some elevation above the pipe top and thoroughly compacted as it is placed. A trench the same width as the pipe is then excavated directly over the pipe down to or near to its top and subsequently backfilled with loose compressible material. The remainder of the embankment is then built up to final elevation (Figure 11). For this condition, Eq 3 is rewritten as:

$$W_E = C_n w_e B_c^2 \qquad \text{Eq 8}$$

3.2.7.1 The various values of C_n are obtained from Figure 9. For asbestos–cement pipe design the recommended value for the settlement ratio r_{sd} is equal to -0.3.

3.2.8 *Tunnel conditions.* There are two types of tunnel construction encountered in normal pipe laying operation.

3.2 8.1 The first type is the most frequently encountered and occurs when a sleeve of a larger diameter than the specified pipe is first jacked through an embankment. The pipe is then placed into the sleeve without becoming an integral part of the tunnel construction. In this example, the sleeve supports the entire earth load and the pipe contained therein is not subjected to crushing loads. When selecting the required pipe classification for this condition, only the internal pressure needs to be considered for design.

3.2.8.2 The second type of tunnel condition is rarely encountered in distribution pipe work but is discussed here for completeness. It occurs when the pipe itself must carry the entire load. The area through which the pipeline must pass is bored and braced with the necessary supports. The pipe then is placed in the tunnel, and the void between the pipe and tunnel braces is backfilled with compacted earth, grout, or concrete. Once this operation is completed, the earth load automat-

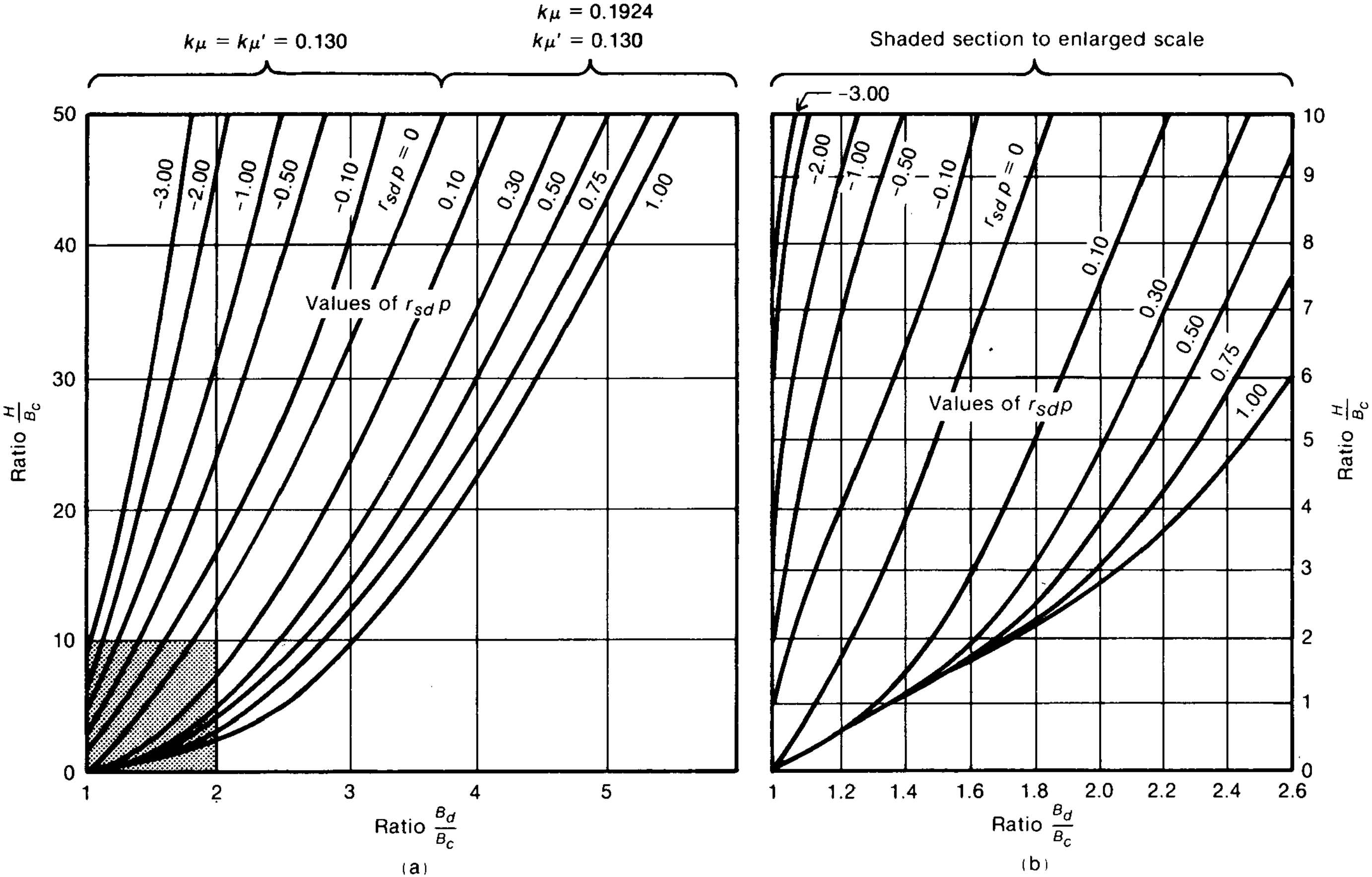

Figure 8. Values of B_d/B_c at Which the Trench and Positive Projecting Pipe Equations Give Equal Loads

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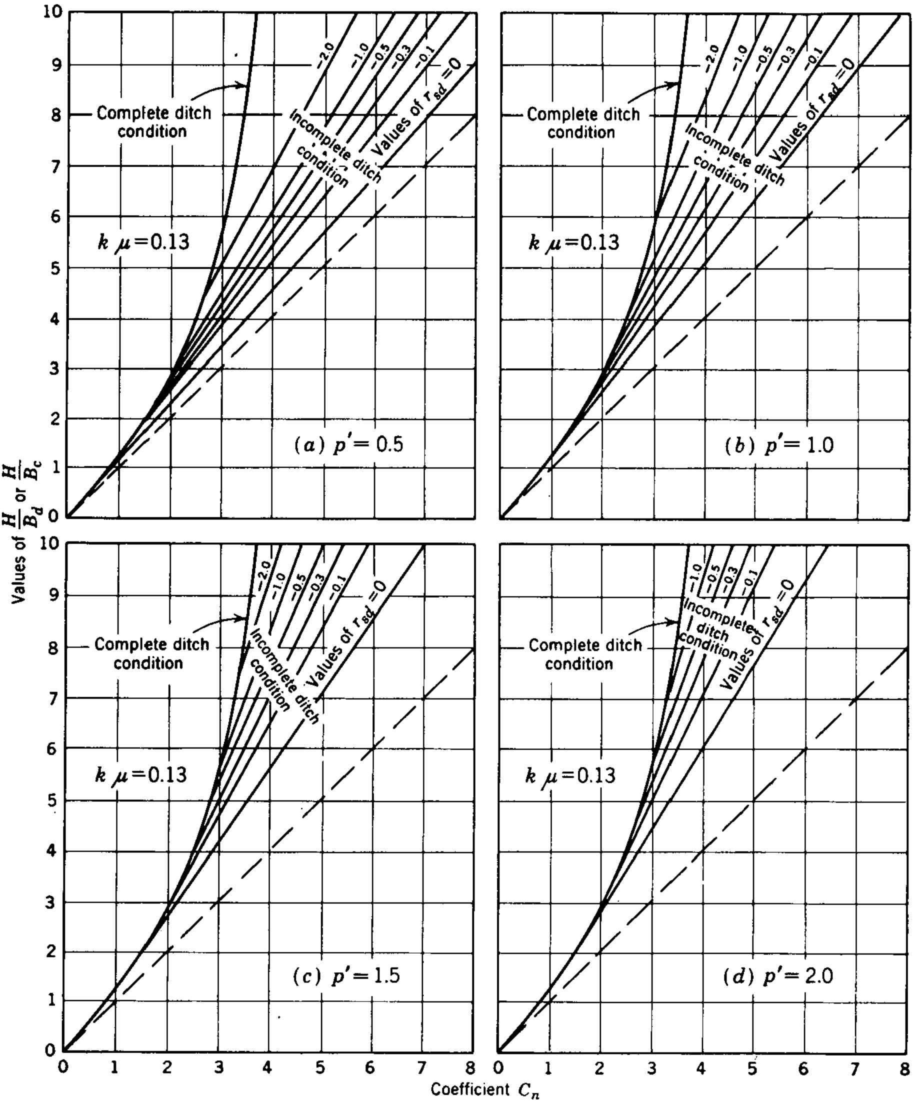

Figure 9. Values of C_n for Negative Projecting Pipe and Imperfect Ditch Conditions

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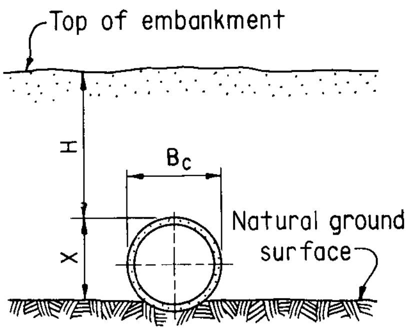

Figure 10A. Positive Projecting Pipe

Projection Ratio $= \frac{x}{B_c}$

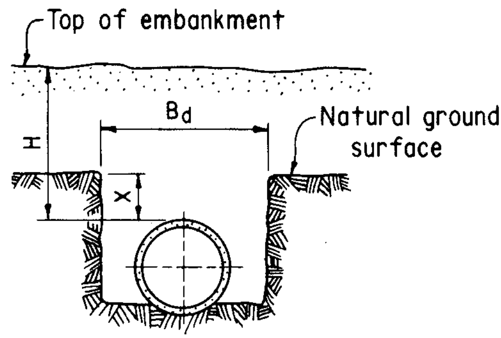

Figure 10B. Negative Projecting Pipe

Projection Ratio $= \frac{x}{B_d}$

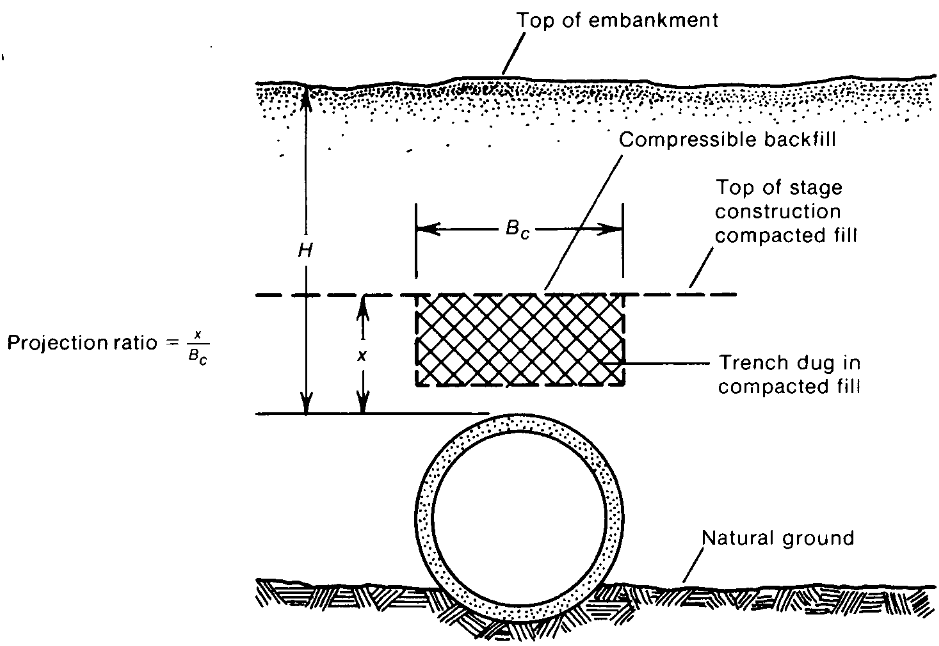

Figure 11. Projection Ratio p' **for the Imperfect Trench Embankment Condition**

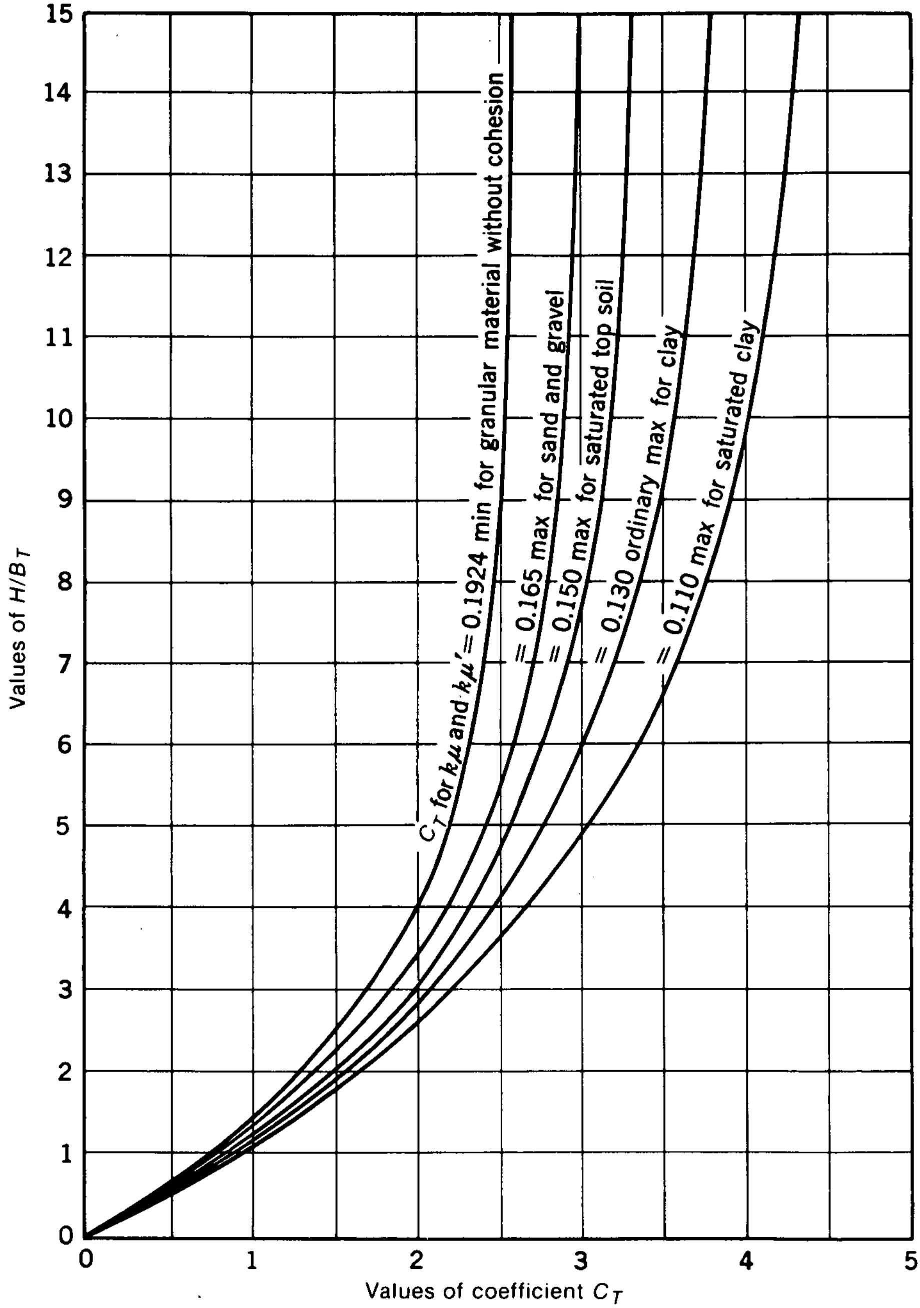

Figure 12. Values of C_T for Tunnel Conditions

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ically transfers from the tunnel supports to the pipe itself. For this condition, Eq 3 is rewritten as:

$$W_E = C_T B_T (w_e B_T - 2c) \qquad \text{Eq 9}$$

3.2.8.3 Values of C_T for different types of soil are obtained from Figure 12. If the value for the coefficient of cohesion is not available from laboratory tests, then the recommended safe design values in Table 1 are to be used.

Table 1

Recommended Safe Design Values of c for Tunnel Conditions

Materials	Values of *c* *lb/ft²* (*kN/m²*)
Clay, very soft	40 (1.63)
Clay, medium	250 (10.19)
Clay, hard	1000 (40.77)
Sand, loose dry	0 (0)
Sand, silty	100 (4.007)
Sand, dense	300 (12.23)
Top soil, saturated	100 (4.007)

3.2.8.4 When, in tunnel construction, the excavation becomes excessive, or when the void surrounding the pipe or tunnel lining is not carefully filled, or when the cohesion of the undisturbed material above the tunnel construction is destroyed by soil saturation or vibration, the earth load should be calculated using Eq 4 for trench conditions. Since it can be exceedingly difficult to either predict or assess whether the tunnel excavation is excessive, it is recommended that Eq 4 be used for most installations for safe asbestos-cement pipe design.

3.2.8.5 It should be noted that the preceding discussion is based on the premise that the tunnel would be constructed in homogeneous soils that do not create unusual pressures and stresses. Tunnel construction should not be utilized through materials that tend to squeeze or swell, such as some types of clay or shale, or through blocky and seamy rock. Under these conditions, the construction method described in Sec. 3.2.8.1 is recommended.

Sec. 3.3 Superimposed Loads

Superimposed loads W_s are external loads other than the normal earth loads transmitted to the pipe. There are two types of superimposed loads as illustrated in Figure 13: (1) concentrated W_{s1}, and (2) distributed W_{s2}. Superimposed loads are frequently referred to as live loads.

3.3.1 *Concentrated loads.* A concentrated load is a load caused by a single force, which may be either static or dynamic in nature. In normal pipe design, vehicular wheel loads are the most frequently encountered concentrated loads. The magnitude of the load produced by concentrated superimposed forces is determined by:

$$W_{sc} = \frac{C_s P_c F}{L} \qquad \text{Eq 10}$$

(see Tables 2 and 3)

3.3.2 *Distributed load.* A distributed load is a load caused by a uniform force distributed equally over a given area. The load may be either static or dynamic in nature. The magnitude of the load produced by distributed forces is determined by:

$$W_{sd} = C_s P_d F B_c \qquad \text{Eq 11}$$

(see Table 4)

Table 2

Impact Factors F

Depth of Cover *ft(m)*	Impact Factor *F*
1.0–2.0 (0.3–0.6)	1.2
2.0–3.0 (0.6–1.0)	1.1
3.0 or greater (1.0 or greater)	1.0

Table 3

Values of Load Coefficients C_s for Concentrated and Distributed Superimposed Loads Centered Vertically Over Conduit

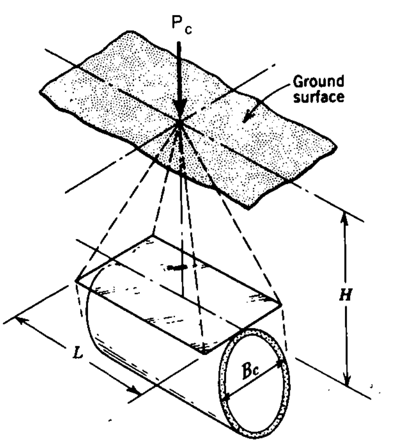
Pipe Size *in. (mm)*	Depth of cover *ft (m)*										
	2 (0.61)	2.5 (0.76)	3 (0.91)	4 (1.22)	5 (1.52)	6 (1.83)	8 (2.44)	10 (3.05)	12 (3.66)	16 (4.87)	20 (6.09)
4 (100)	0.105	0.076	0.055	0.033	0.022	0.016	0.009	0.006	0.004	0.002	0.0015
6 (150)	0.147	0.106	0.078	0.046	0.031	0.023	0.013	0.008	0.006	0.003	0.002
8 (200)	0.191	0.137	0.102	0.061	0.041	0.029	0.017	0.010	0.008	0.004	0.003
10 (250)	0.237	0.174	0.129	0.078	0.052	0.037	0.022	0.013	0.009	0.006	0.0035
12 (300)	0.279	0.202	0.153	0.092	0.062	0.044	0.025	0.016	0.011	0.007	0.004
14 (350)	0.317	0.232	0.175	0.106	0.071	0.050	0.030	0.018	0.013	0.008	0.005
16 (400)	0.354	0.259	0.197	0.121	0.081	0.057	0.034	0.021	0.015	0.009	0.0055

Table 4

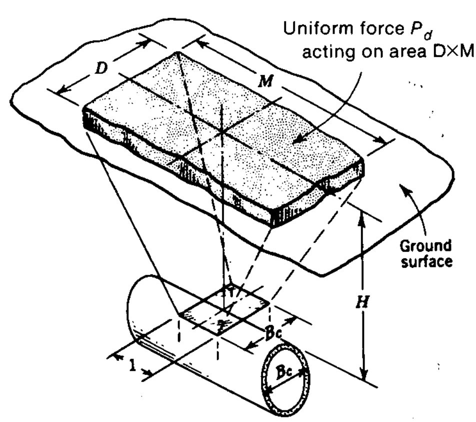
Superimposed (Wheel) Load—Single Wheel = 16 000 lb (7250 kg)

Cover Over Top of Pipe *ft (m)*	Pipe Diameter—*in. (mm)*					
	6 (150)*	8 (200)	10 (250)	12 (300)	14 (350)	16 (400)
	Wheel Load—*lb/ft (kN/m)*					
2 (0.61)	797 (11.6)	932 (13.6)	1272 (18.5)	1488 (21.7)	1691 (24.7)	1888 (27.5)
2.5 (0.76)	693 (10.1)	907 (13.2)	1076 (15.7)	1167 (17.0)	1237 (18.0)	1382 (20.2)
3 (0.91)	425 (6.20)	544 (7.93)	693 (10.1)	816 (11.9)	933 (13.6)	1048 (15.3)
4 (1.22)	256 (3.73)	331 (4.83)	421 (6.14)	490 (7.15)	565 (8.24)	645 (9.41)
5 (1.52)	176 (2.56)	218 (3.18)	277 (4.04)	330 (4.81)	378 (5.51)	432 (6.30)
6 (1.83)	149 (2.17)	197 (2.87)	245 (3.57)	235 (3.43)	267 (3.89)	304 (4.44)
8 (2.44)	69 (1.00)	91 (1.33)	112 (1.63)	139 (2.03)	160 (2.33)	181 (2.64)
10 (3.05)	43 (0.63)	59 (0.86)	74 (1.08)	85 (1.24)	96 (1.40)	112 (1.63)
12 (3.66)	37 (0.54)	48 (0.70)	53 (0.77)	59 (0.86)	69 (1.01)	80 (1.17)
16 (4.87)	21 (0.39)	27 (0.39)	32 (0.47)	37 (0.53)	43 (0.62)	48 (0.70)
20 (6.09)	5 (0.07)	11 (0.16)	16 (0.23)	21 (0.30)	26 (0.38)	29 (0.42)

*For 4-in. (100-mm) pipe use same value as for 6-in. (150-mm) pipe.



Concentrated superimposed load, w_{S1}, *vertically centered over pipe.*



Distributed superimposed load, w_{S2}, *vertically centered over pipe.*

Figure 13. Superimposed Loads

Section 4—Hydrostatic Pressure

Sec. 4.1 Introduction

For the design of asbestos–cement distribution pipe, the internal hydrostatic pressure P_T is defined by:

$$P_T = (P_o + P_s)\ \text{S.F.} \qquad \text{Eq 12}$$

S.F. is the design safety factor. Safety factors are based on judgment, past experiences, and sound engineering principles. For asbestos–cement distribution pipe, a safety factor of 4 is recommended when surge or water hammer is not calculated and added to operating pressure.

Sec. 4.2 Operating Pressure

The operating pressure P_o is the pressure that exists under normal or steady conditions of operation. The pressure may be induced by pumps, gravity (such as the head created by a reservoir or elevated water tank), or a combination of both pumps and gravity. Under a 100 percent gravity situation, the pressure in the line at a given point is somewhat higher when there is no flow and conditions are static. Under static conditions, the pressure at a given point, measured in feet (metres) of head, is equal to the difference between the elevation of that point and the water surface level at the reservoir. Under flowing conditions, the pressure at a given point is reduced by the amount of friction and other energy losses resulting from the flow of water from the reservoir to that point. The magnitude of this head loss may be found by using the Hazen and Williams chart in Appendix A. In piping systems that have long runs with relatively few fittings and accessories, the recommended value of C (coefficient of flow) is 140.

Sec. 4.3 Surge Pressure

Surge pressures P_s are of a transient nature and are caused by unsteady or changing conditions in the pipeline. The terms water hammer, surge, or transient pressure are often used interchangeably to refer to these pressures, which are of brief duration but often of considerable magnitude. A variety of conditions may cause surge pressures. These include a valve opening or closing, sudden movement of air in a line, or a pump starting or stopping. Surge pressures in a distribution system can be of considerable magnitude, particularly when fire hydrants are rapidly opened or closed. The magnitude of this surge is difficult to determine and it is generally beyond the control of the design engineer as it depends on the speed at which the firemen open or close the hydrants. For this reason, design criteria for asbestos–cement distribution pipe incorporate a large minimum fixed safety factor of 4 to the operating or pressure class of the pipe to allow for an unknown amount of surge pressure that will occur in the system. Appendix B presents a discussion of surge pressures and how they may be controlled for the engineer who determines that surge should be incorporated in hydrostatic design calculations.

Section 5—Design Criteria and Use Of Pipe Selection Charts

Sec. 5.1 Combined Loading Curves

Extensive testing and application of statistical analysis have shown that the strength characteristics of asbestos–cement pipe conform to the principles of the combined loading theory developed by the late W.J. Schlick. This theory, commonly discussed in terms of the Schlick formula represented graphically as a parabola, is used as the basis for the design and class selection of asbestos–cement distribution pipe. [See Figures 14A through 14G and Figures 14A(m) through 14G(m).]

5.1.1 *Curve development.* The families of selection curves presented in this standard were developed using the Schlick formula that establishes a functional relationship between external load and internal pressure. The external and internal load intercepts are tabulated in Table 5.

Sec. 5.2 Safety Factors

In the smaller diameters, the effect of water hammer generated by the opening and closing of fire hydrants can be of significant magnitude because of the high velocities generated by open hydrant flow conditions on small-diameter lines in distribution systems. It is difficult to evaluate accurately the magnitude of surges, and if calculated, it would be impractical to attempt to control the surge by the use of surge tanks or other devices. Rather than employ a rule-of-thumb surge allowance based on an assumed velocity change, a large minimum safety factor of 4 is applied to the class pressure rating of the pipe to take into account the undetermined surges.

5.2.1 *Design criteria.* The design criteria for asbestos–cement distribution pipe is based on a design point on the combined loading parabolic curve where the following minimum conditions are met: (1) a factor of safety of 4 times the pressure class of the pipe (2) a factor of safety of 2.5 times the three-edge vee-shaped bearing equivalent of an earth load calculated as 5 ft (1.52 m) depth of cover, a trench width equal to pipe inside diameter plus 2 ft (0.6 m) (or a positive projecting conduit condition if lesser), a soil density of 120 lb/cu ft (19 kN/m^3), and Class C bedding condition.

Sec. 5.3 Use of Selection Charts for Economical Design

The charts may be used conveniently by entering them through the depth of cover and bedding condition scale. The scales are correlated to the three-edge vee-shaped bearing equivalent of 2.5 times the earth load calculated using a soil density of 120 lb/cu ft (19 kN/m^3) and a trench width equal to the inside diameter of the pipe plus 2 ft (0.6 m) (or the positive projecting conduit condition if lesser).

5.3.1 *Design earth loads.* Table 6 gives the design earth load values, which are obtained by calculating the external earth load based on a trench width equal to the I.D. of the pipe plus 2 ft (0.6 m) (or the positive projecting conduit condition if lesser). The earth load is then divided by the appropriate bedding factor for the class of bedding and multiplied by a safety factor of 2.5. The design earth load values from Table 6 can then be used to enter the selection curve charts using the design external load values given at the top of the selection curve charts. The field supporting strength listed for pipe so selected has been proved conservative during many years of performance under various field conditions. When there is an external condition that would warrant considering all external loading factors and/or a change in the safety factor, the equivalent external load should be determined and the selection chart entered at the proper value of the design external load scale found at the top of the chart.

Sec. 5.4 Discussion

AWWA C403, Standard Practice for the Selection of Asbestos–Cement Transmission and Feeder Main Pipe, Sizes 18 in. Through 42 in., is a standard containing information similar to that contained herein but dealing with larger diameter pipes. In AWWA C403 the design is based on evaluation of all design conditions including surge pressures. Adequate factors of safety are applied to the combination of loads to which the pipeline will be subjected. The primary differences between AWWA C401 and AWWA C403 are those of differing methods of designing pipelines to account for interal and external load conditions. In the smaller sizes covered by AWWA C401, surge pressures can be of great magnitude and are difficult or impractical for the engineer to control in design. A large minimum safety factor of 4 is suggested to compensate for the unknown. In the larger sizes covered in AWWA C403, the design is based on an evaluation of surge pressure, which can be controlled in design. Calculated surge pressure is added to operating pressure before a safety factor of 2 is applied. For external loads, AWWA C401 considers only earth loads and a recommended safety factor of 2.5 is applied. In AWWA C403, both earth loads and live loads are added before a factor of safety of 1.5 is applied to the combination of these external loads. In summary, AWWA C403 design is based on a more detailed evaluation of the magnitude of surge pressure and live loadings, and factors of safety based on this more precise knowledge of actual operating conditions are applied.

Sec. 5.5 Illustrative Problem on Pipe Selection

The application of the curves to design is shown in the following problem:

Required: A 6-in. pipe to operate at a pressure of 120 psi at 8 ft depth of cover, bedding condition Class C, soil weight 120 lb/cu ft.

Solution: Enter the selection curve for 6-in. pipe at bedding condition Class C, 8-ft cover. The intersection of the 8-ft cover line with the 120-psi operating pressure line falls between pipe classes 100 and 150. Use 6 in., Class 150. The intersection of the 8-ft cover line with the Class 150 curve is at 140-psi operating pressure, or 560-psi design pressure. Therefore, the pressure safety factor equals 560/120 = 4.66, with a safety factor of 2.5 for external earth load.

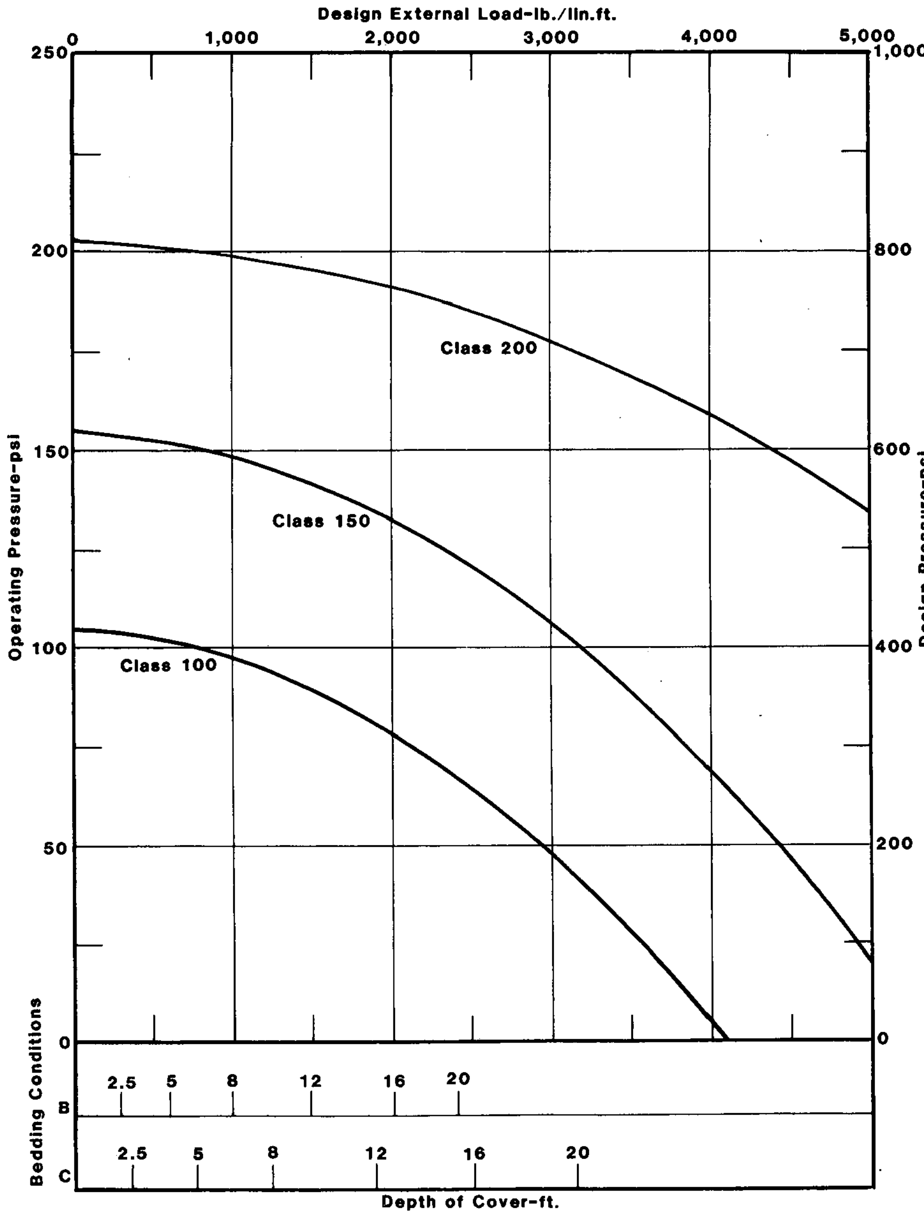


Figure 14A. Selection Curves for 4-in. Asbestos-Cement Pipe

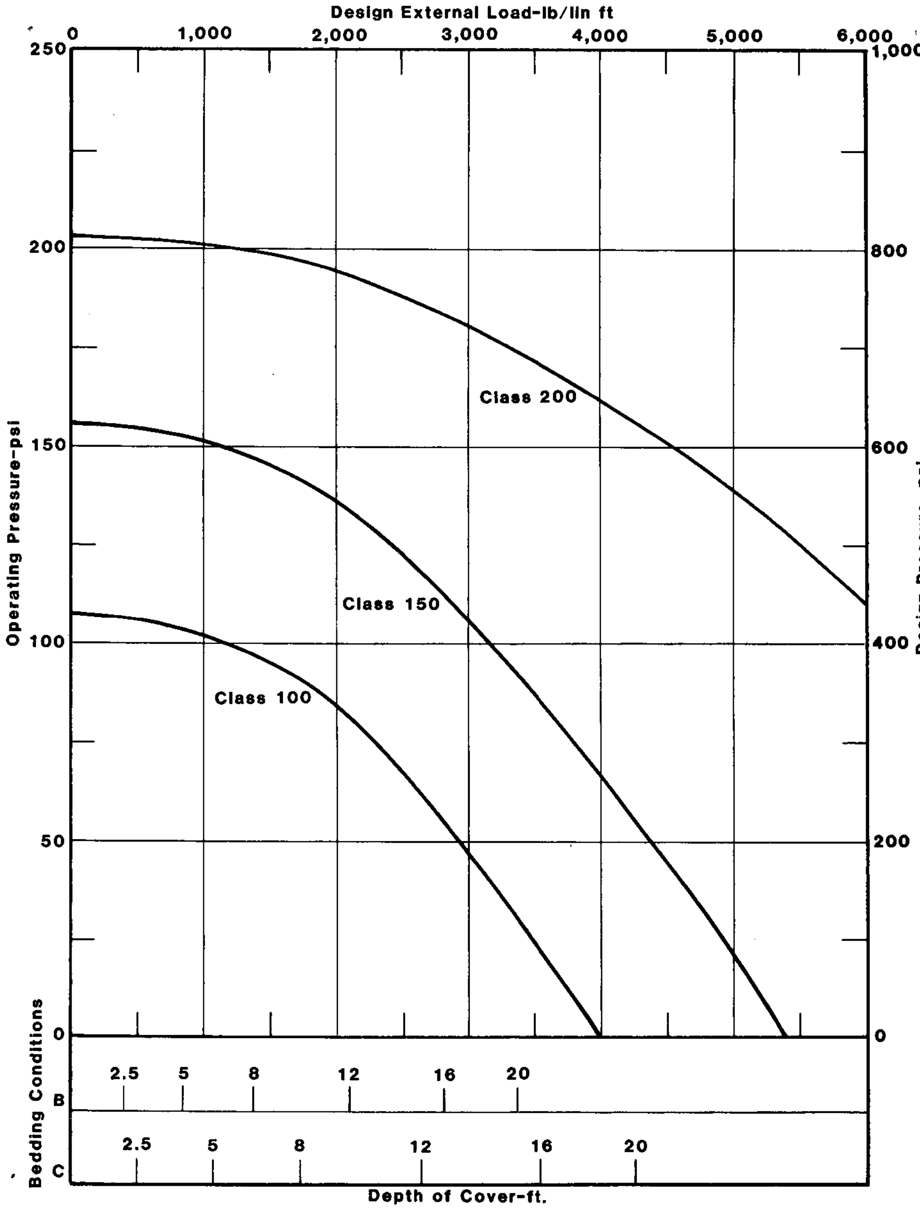


Figure 14B. Selection Curves for 6-in. Asbestos-Cement Pipe

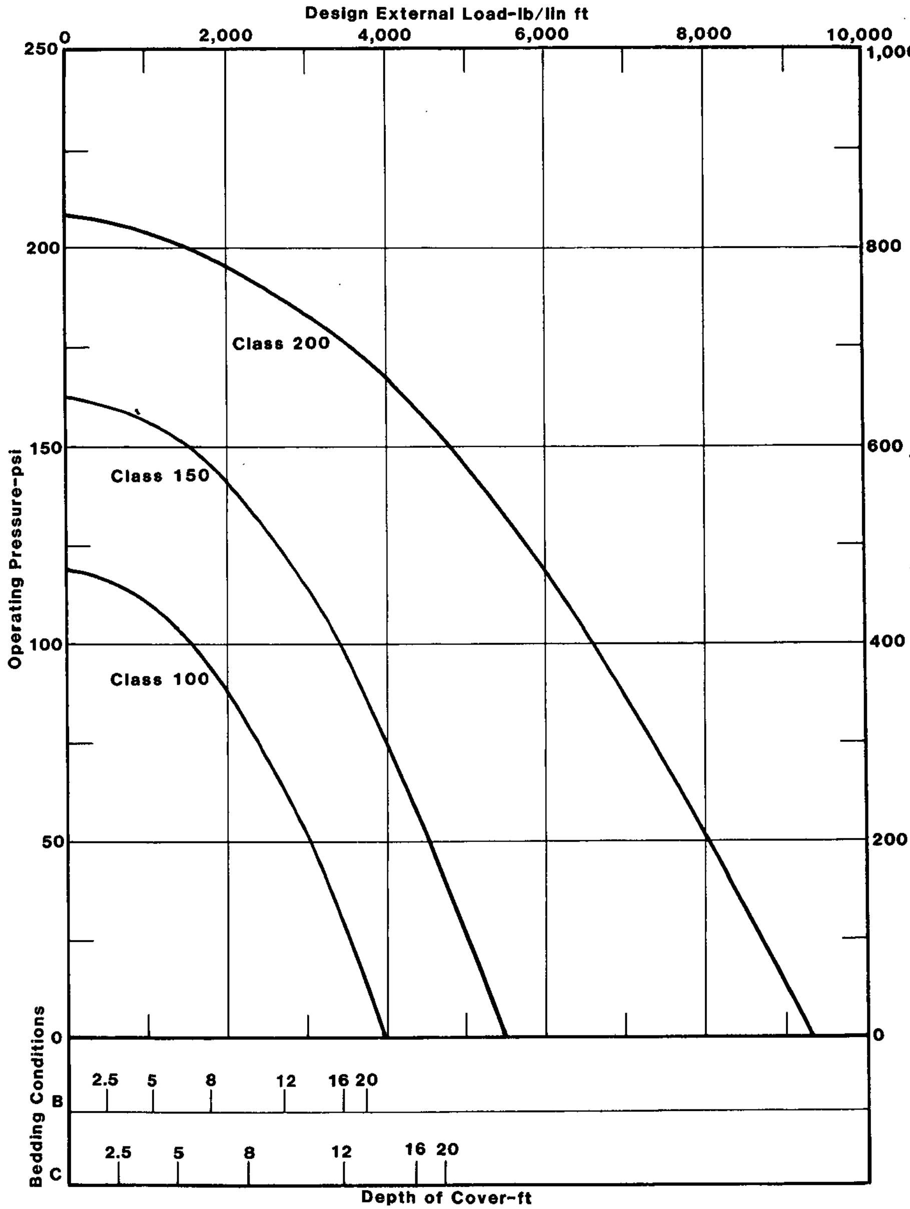


Figure 14C. Selection Curves for 8-in. Asbestos-Cement Pipe

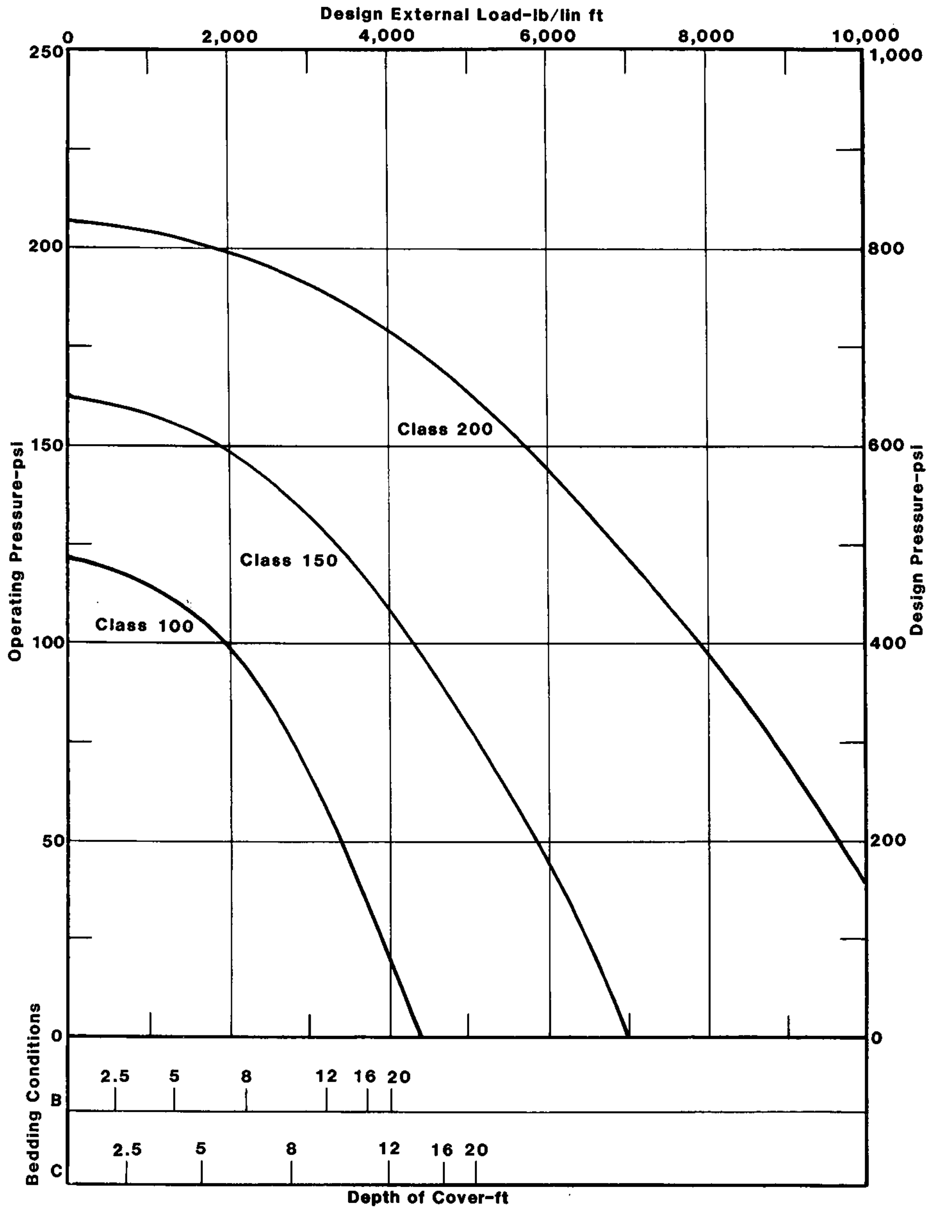


Figure 14D. Selection Curves for 10-in. Asbestos-Cement Pipe

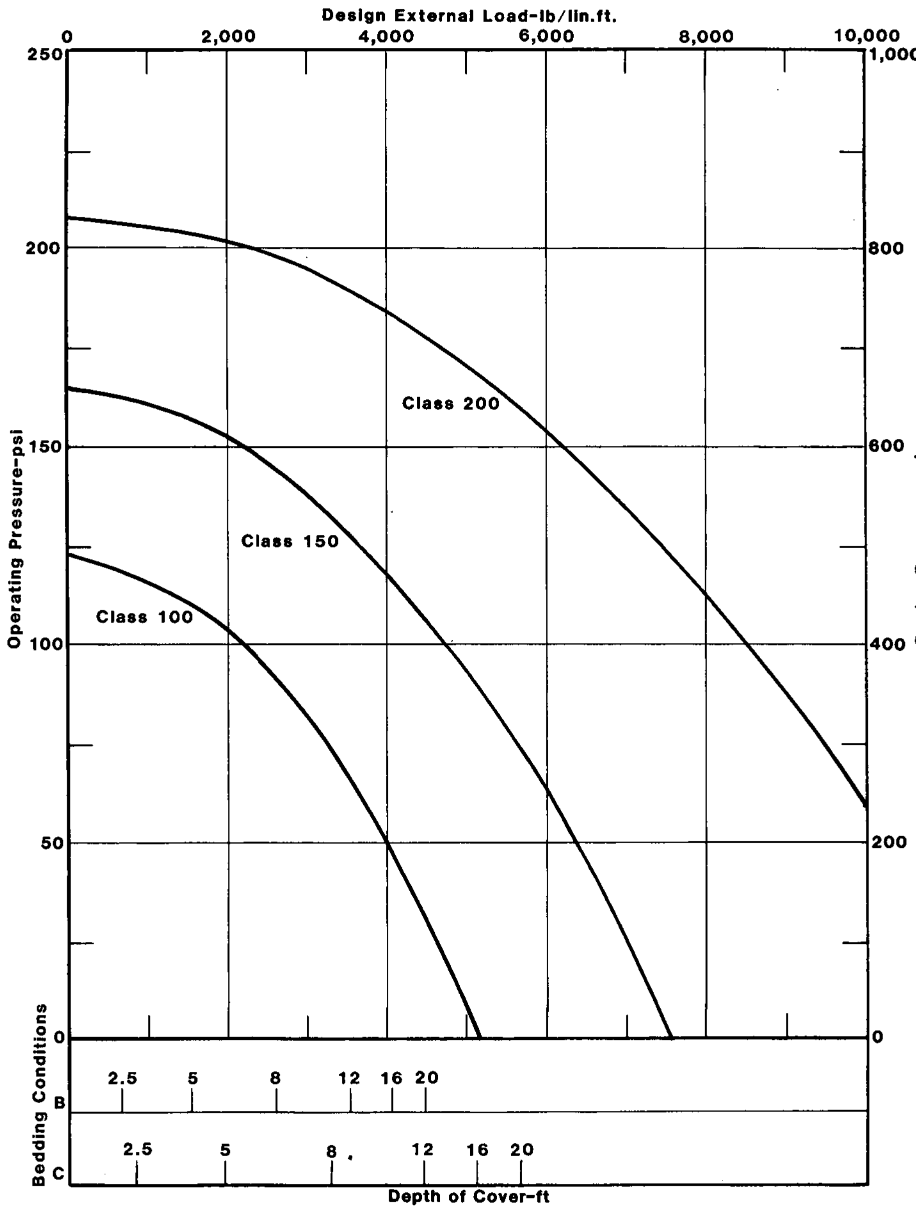


Figure 14E. Selection Curves for 12-in. Asbestos-Cement Pipe

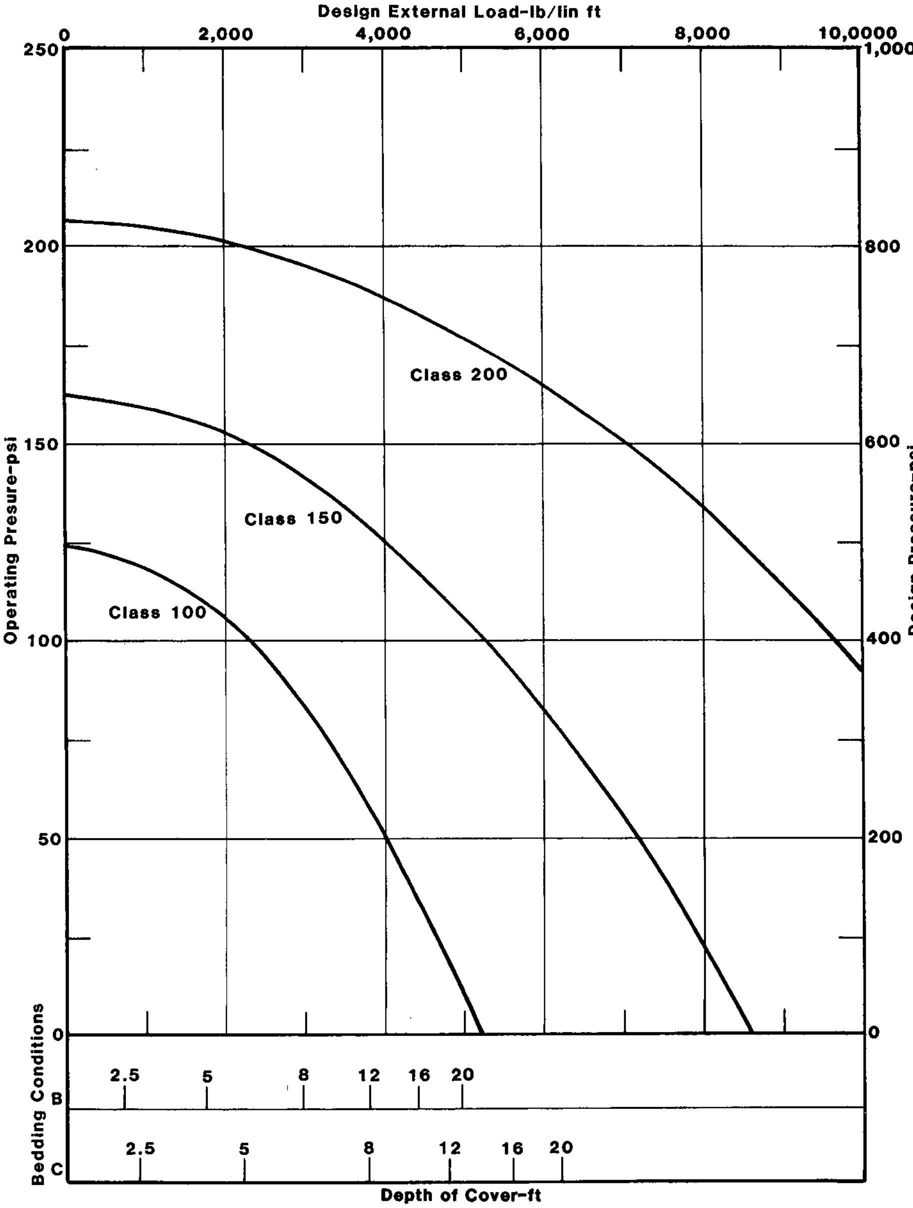


Figure 14F. Selection Curves for 14-in. Asbestos-Cement Pipe

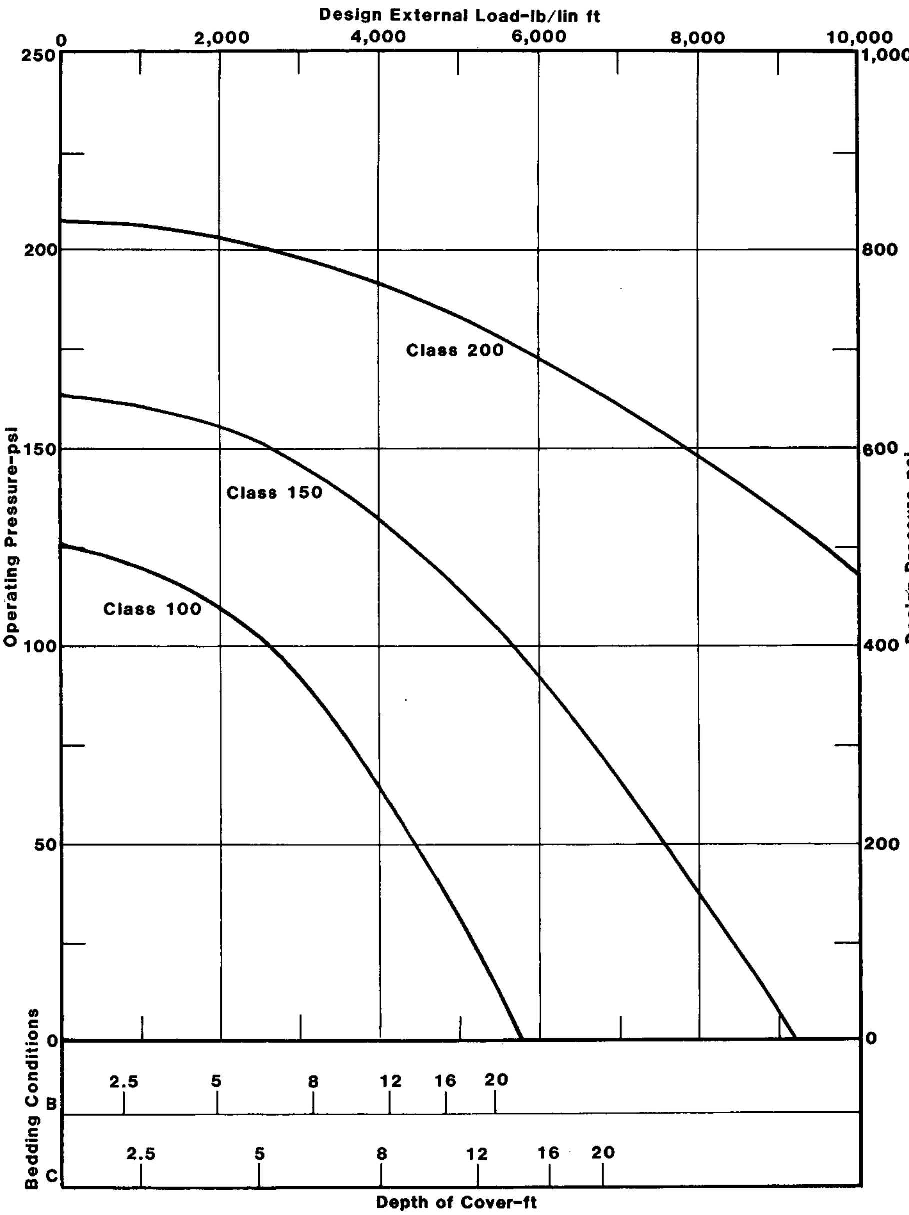


Figure 14G. Selection Curves for 16-in. Asbestos-Cement Pipe

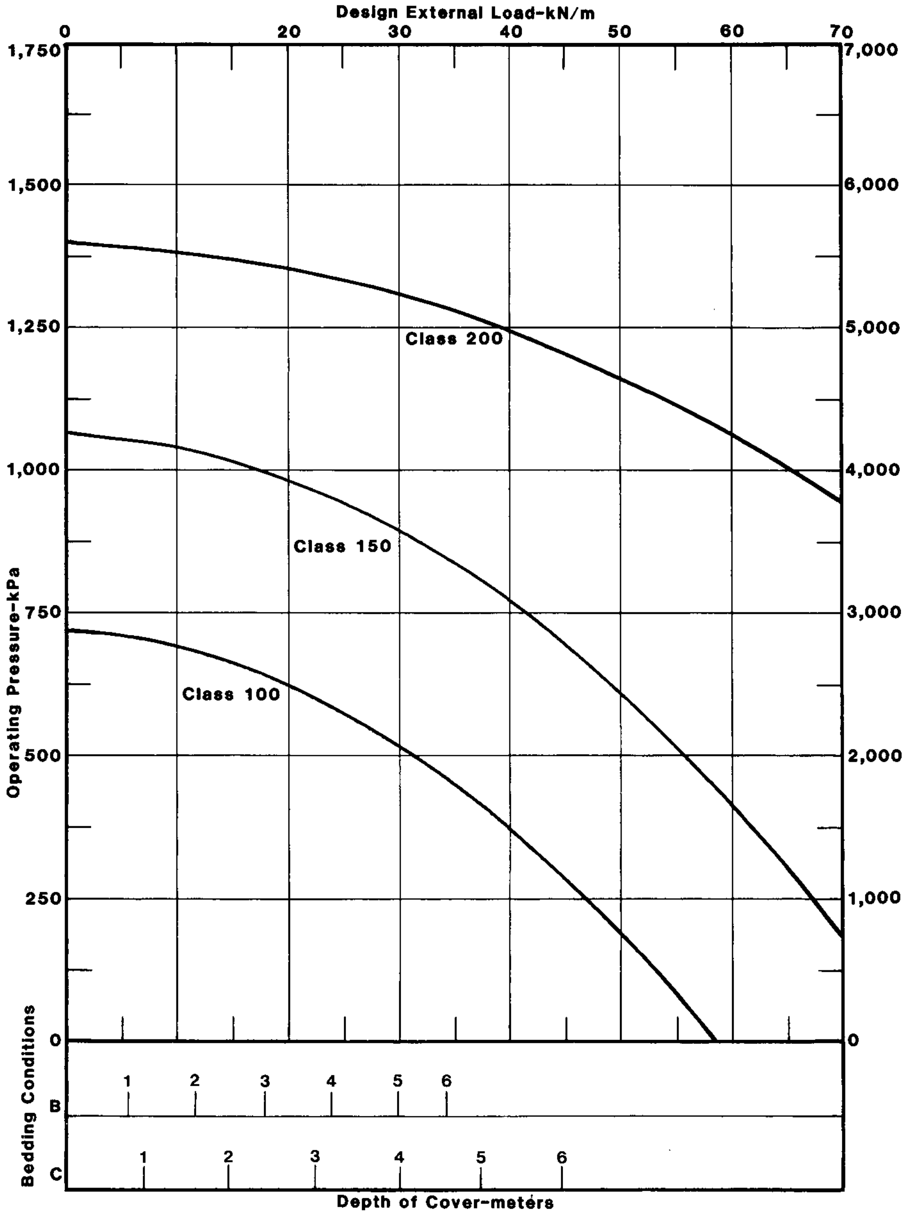


Figure 14A(m). Selection Curves for 100-mm Asbestos-Cement Pipe

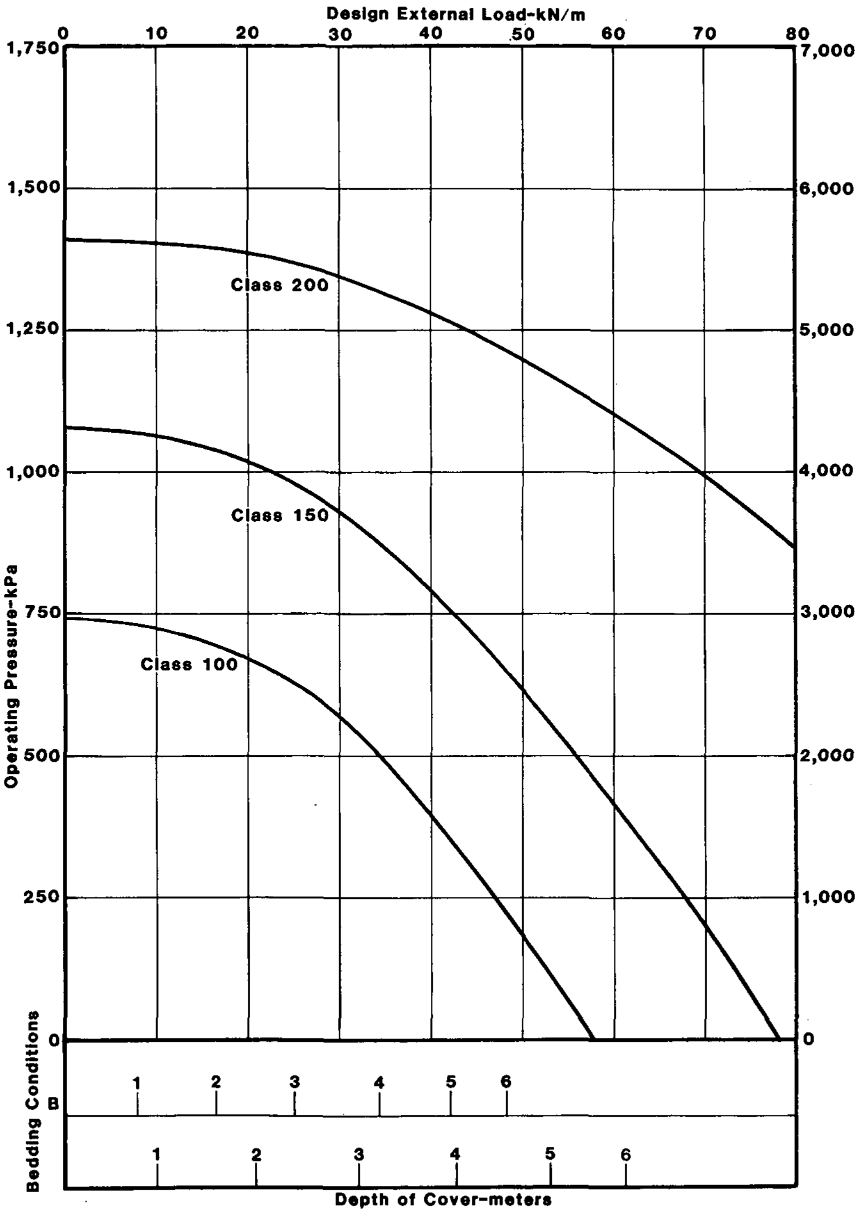


Figure 14B(m). Selection Curves for 150-mm Asbestos-Cement Pipe

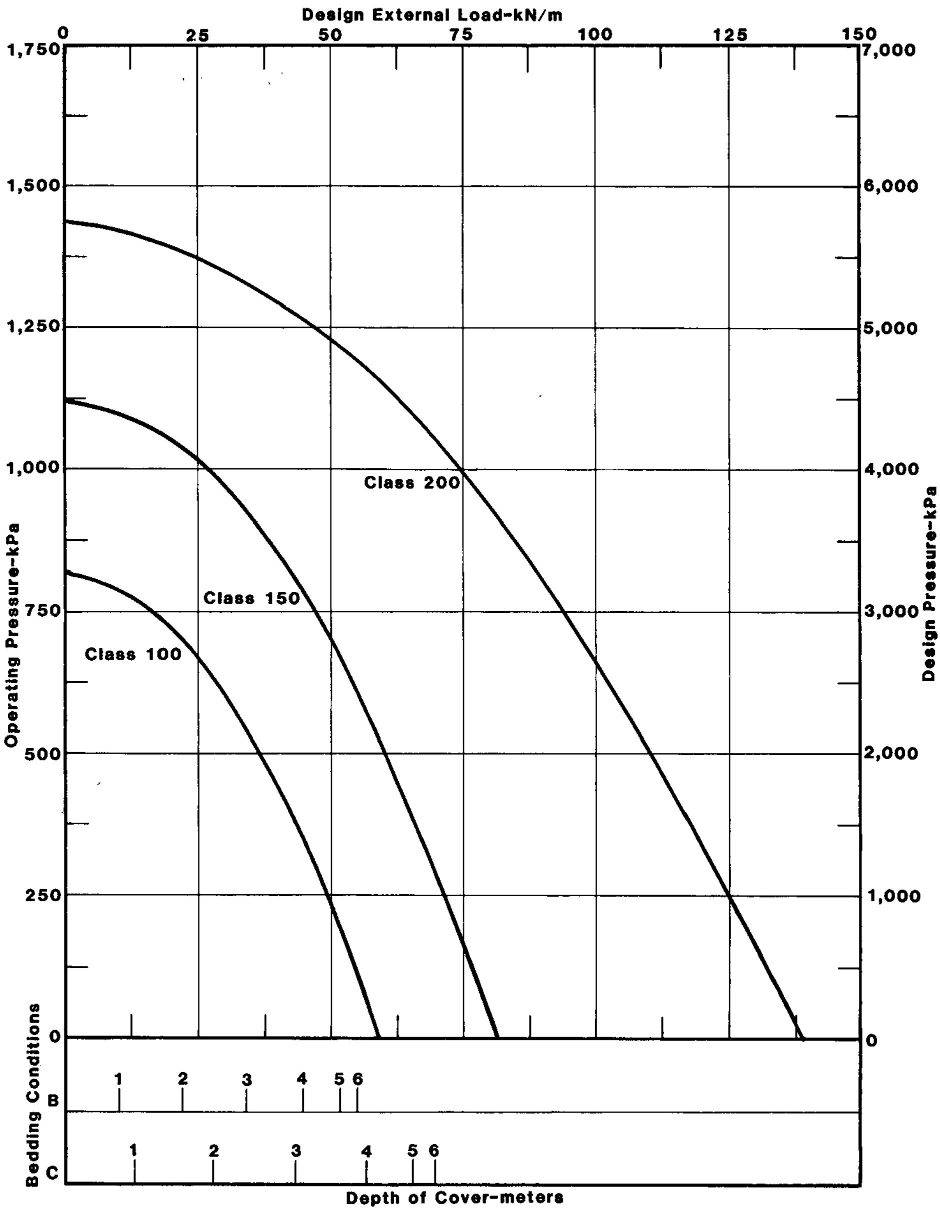


Figure 14C(m). Selection Curves for 200-mm Asbestos-Cement Pipe

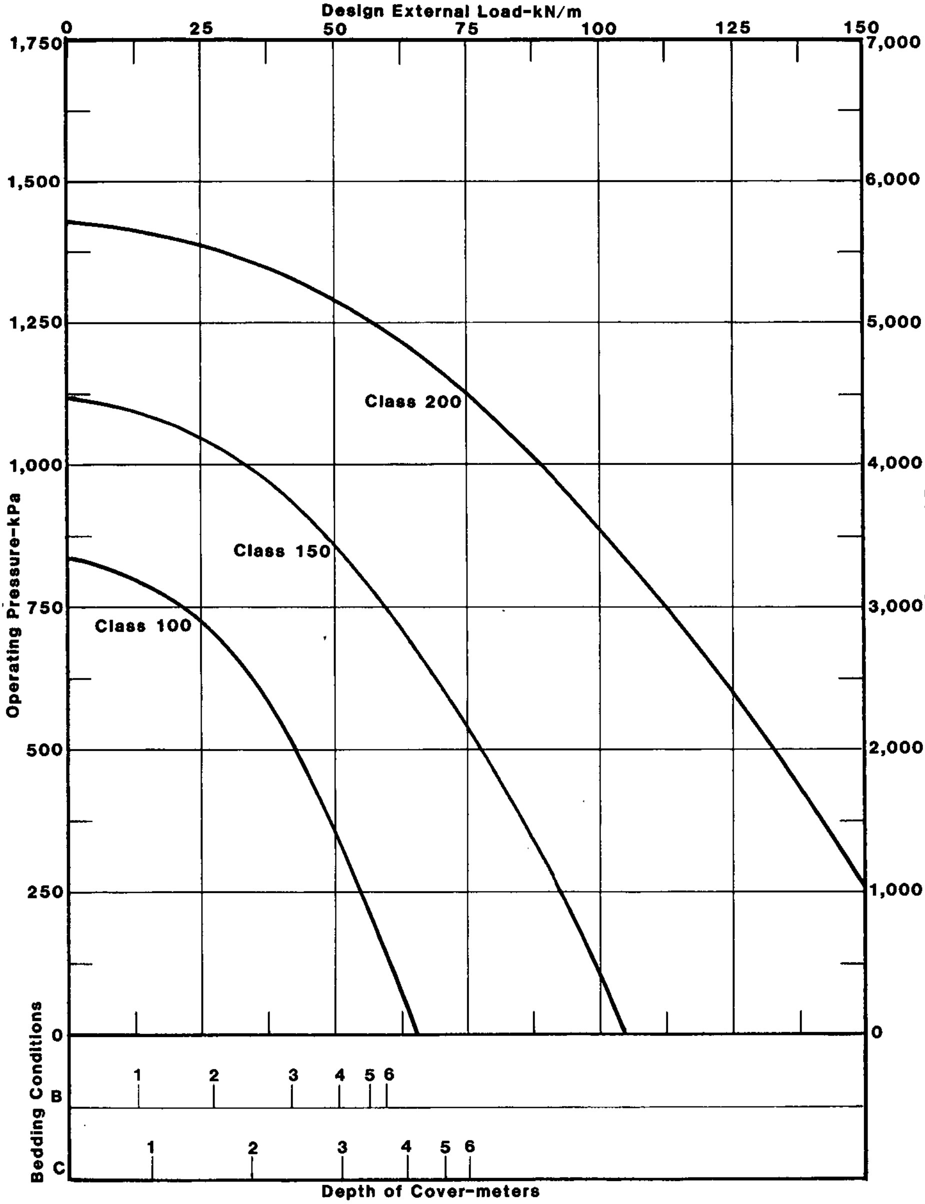


Figure 14D(m). Selection Curves for 250-mm Asbestos-Cement Pipe

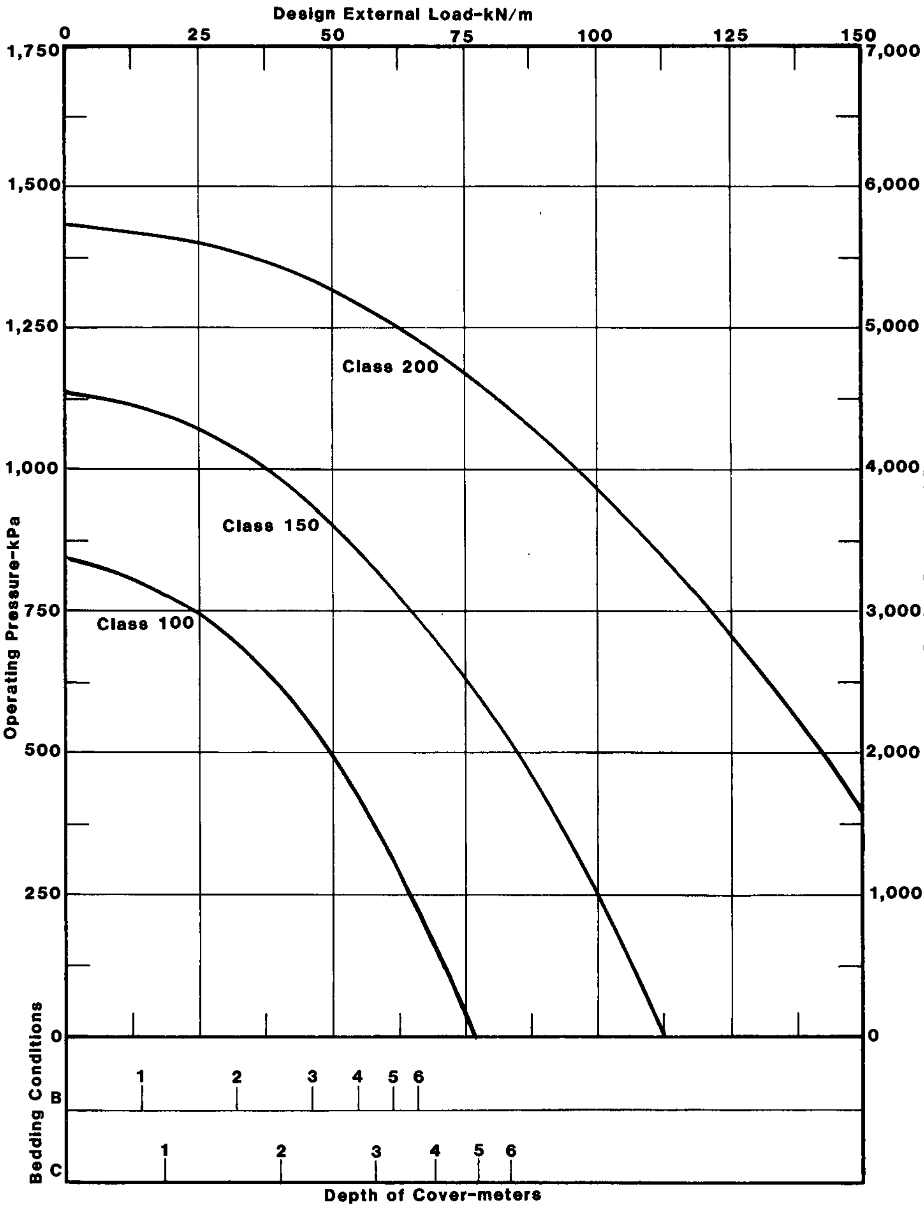


Figure 14E(m). Selection Curves for 300-mm Asbestos-Cement Pipe

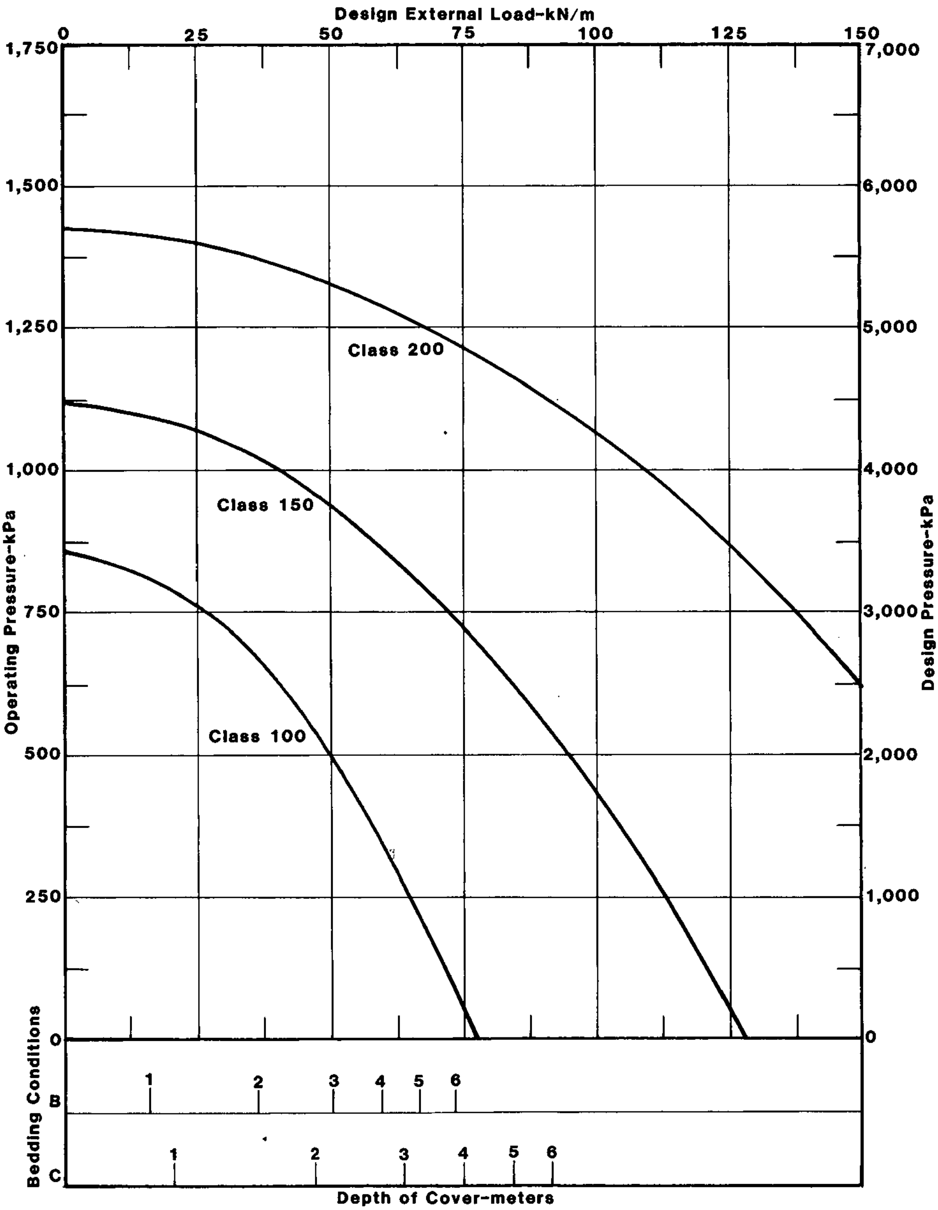


Figure 14F(m). Selection Curves for 350-mm Asbestos-Cement Pipe

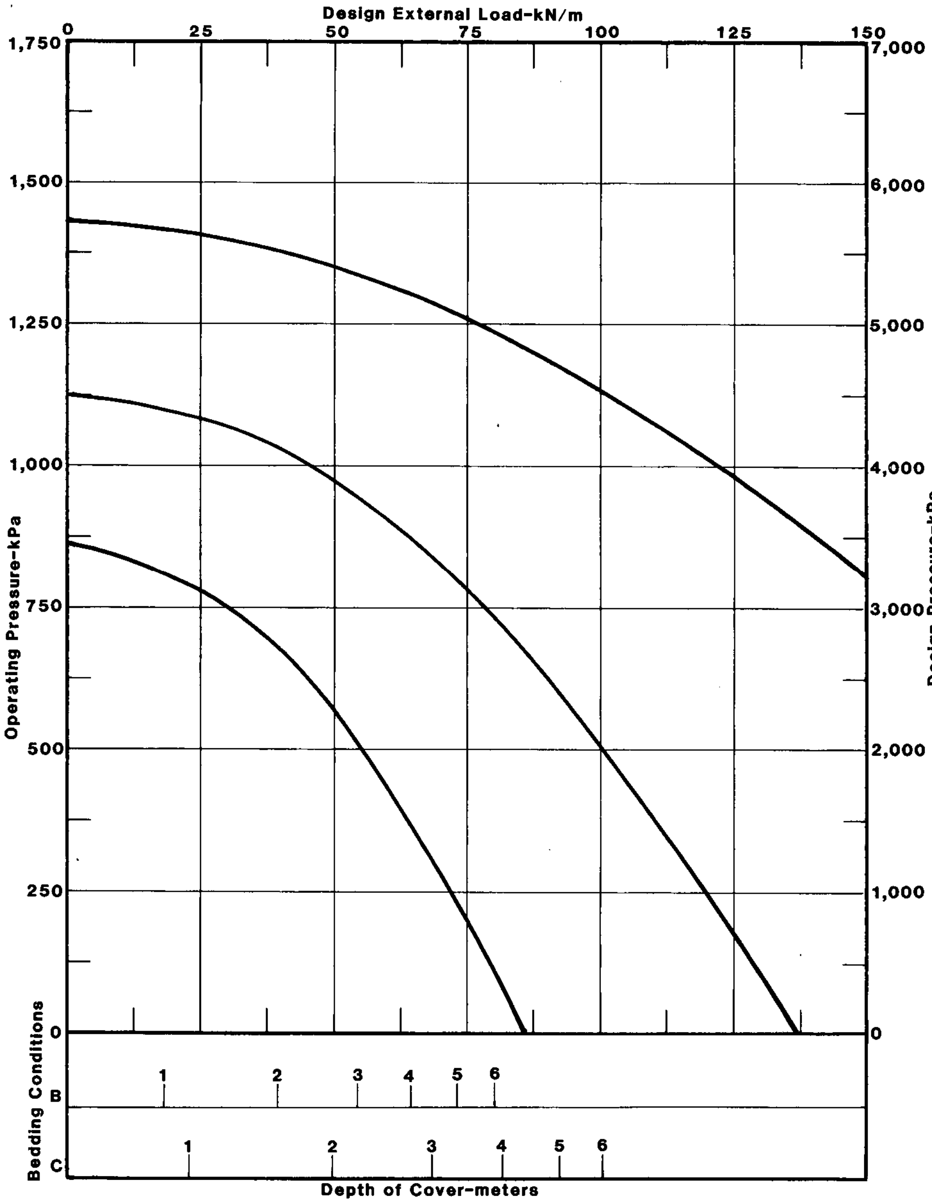


Figure 14G(m). Selection Curves for 400-mm Asbestos-Cement Pipe

Table 5

*Design Internal Pressure and Design External Load**

Nominal Pipe Size	Class 100		Class 150		Class 200	
	Internal Pressure	External Load	Internal Pressure	External Load	Internal Pressure	External Load
in. (mm)	*psi (kPa)*	*lb/lin.ft (kN/m)*	*psi (kPa)*	*lb/lin.ft (kN/m)*	*psi (kPa)*	*lb/lin.ft (kN/m)*
4 (100)	417 (2900)	4100 (60)	616 (4200)	5400 (79)	809 (5600)	8 700 (127)
6 (150)	441 (3000)	4000 (58)	632 (4400)	5400 (79)	815 (5600)	9 000 (136)
8 (200)	472 (3300)	4000 (58)	653 (4500)	5500 (80)	824 (5700)	9 300 (136)
10 (250)	490 (3400)	4400 (64)	650 (4500)	7000 (102)	826 (5700)	11 000 (161)
12 (300)	490 (3400)	5200 (76)	658 (4500)	7600 (111)	830 (5700)	11 800 (172)
14 (350)	500 (3400)	5200 (76)	650 (4500)	8600 (126)	826 (5700)	13 500 (197)
16 (400)	500 (3400)	5800 (85)	654 (4500)	9200 (134)	825 (5700)	15 400 (225)

*It is necessary to apply a load factor to the three-edge bearing loads obtained in the crushing tests in order to correlate them to the field loads.

Table 6

Design External Earth Load

Pipe Size in. (mm)	*H* 2.5 ft (0.76 m)	*H* 5.0 ft (1.52 m)	*H* 8.0 ft (2.44 m)	*H* 12 ft (3.66 m)	*H* 16 ft (4.88 m)	*H* 20 ft (6.10 m)
	Class B Bedding — *W—lb/ft (kN/m)*					
4 (100)	290 (4.23)	610 (8.90)	980 (14.30)	1490 (21.74)	1990 (29.04)	2500 (36.48)
6 (150)	390 (5.69)	840 (12.26)	1380 (20.14)	2090 (30.50)	2800 (40.86)	3360 (49.04)
8 (200)	490 (7.15)	1070 (15.62)	1770 (25.83)	2710 (39.55)	3380 (49.33)	3770 (55.02)
10 (250)	590 (8.61)	1330 (19.41)	2220 (32.40)	3230 (47.14)	3730 (54.44)	4170 (60.86)
12 (300)	670 (9.78)	1550 (22.62)	2610 (38.09)	3550 (51.81)	4120 (60.13)	4620 (67.42)
14 (350)	740 (10.80)	1760 (25.69)	2860 (41.74)	3810 (55.60)	4520 (65.96)	5000 (72.97)
16 (400)	800 (11.68)	1960 (28.60)	2980 (43.49)	4030 (58.81)	4990 (72.82)	5250 (76.62)
	Class C Bedding — *W—lb/ft (kN/m)*					
4 (100)	370 (5.40)	770 (11.24)	1250 (18.24)	1890 (27.58)	2530 (36.92)	3170 (46.26)
6 (150)	500 (7.30)	1060 (15.47)	1740 (25.39)	2650 (38.67)	3550 (51.81)	4250 (62.02)
8 (200)	620 (9.05)	1360 (19.85)	2250 (32.84)	3430 (50.06)	4280 (62.46)	4780 (69.76)
10 (250)	750 (10.95)	1690 (24.66)	2820 (41.15)	4090 (59.69)	4730 (69.03)	5290 (77.20)
12 (300)	850 (12.40)	1970 (28.75)	3310 (48.31)	4500 (65.67)	5220 (76.18)	5850 (85.37)
14 (350)	940 (13.72)	2240 (32.69)	3620 (52.83)	4820 (70.34)	5730 (83.62)	6330 (92.38)
16 (400)	1010 (14.74)	2490 (36.34)	3770 (55.02)	5100 (74.43)	6320 (92.23)	6650 (97.05)

Appendix A

Friction Loss of Head Chart—Coefficient of Flow, *C* = 140

This appendix is for information only and is not a part of AWWA C401.

Derived from the Hazen and Williams formula:

$V = 1.318\, C R^{0.63} S^{0.54}$

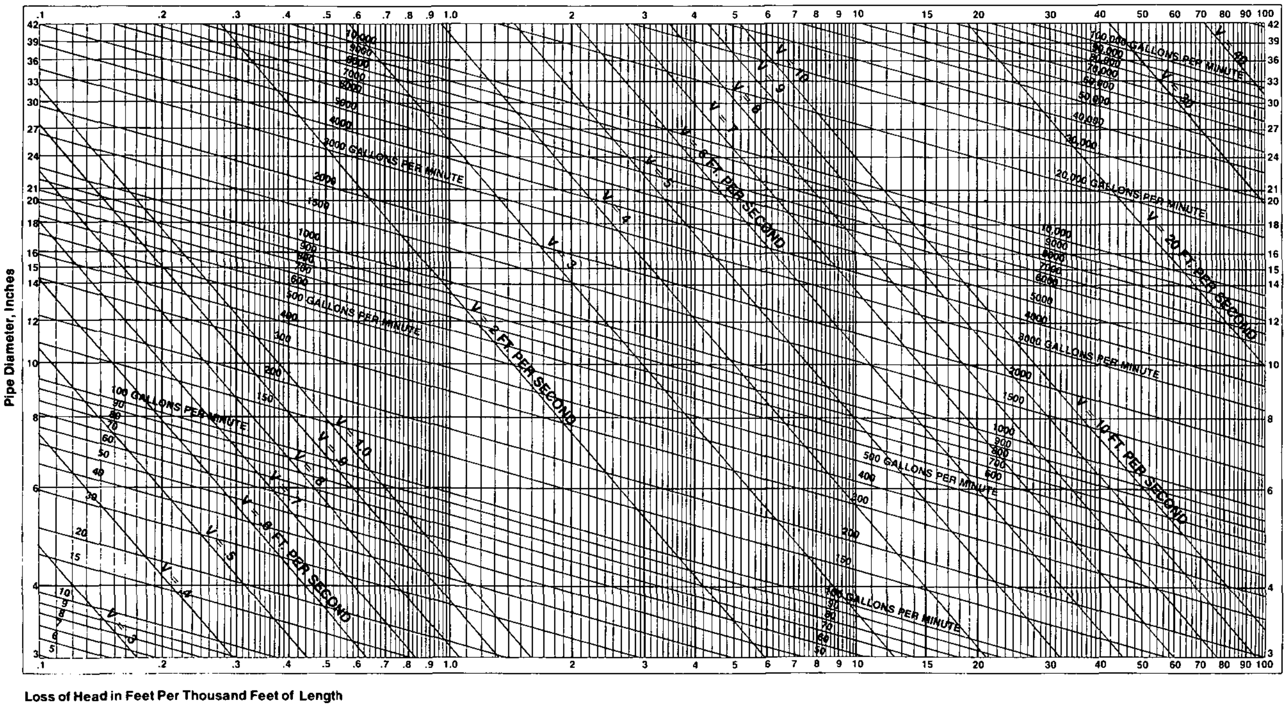
Asbestos-cement distribution and transmission pipe has a coefficient of $C = 140$. Because of asbestos-cement pipe's composition, this initial high flow capacity cannot be reduced by tuberculating water—the chief cause of loss of carrying capacity. This helps maintain the carrying capacity factor in minimizing pumping costs.

NOTE: Loss of head values derived from this chart are for coefficient of flow $C = 140$. They may be converted to loss of head for other coefficients of flow by means of the following multiplying factors:

1.15 for $C = 130$	2.26 for $C = 90$
1.34 for $C = 120$	2.83 for $C = 80$
1.57 for $C = 110$	4.82 for $C = 60$
1.86 for $C = 100$	

NOTE: Diameters derived from this chart are for coefficient of flow $C = 140$. These may be converted to diameters for other coefficients of flow by means of the following multiplying factors:

1.033 for $C = 130$	1.185 for $C = 90$
1.063 for $C = 120$	1.261 for $C = 80$
1.100 for $C = 110$	1.365 for $C = 60$
1.142 for $C = 100$	



Appendix B

Surge Pressure Analysis

This appendix is for information only and is not a part of AWWA C401.

B.1 Water Hammer or Surge

The slowing down or stopping of any moving mass requires a force or forces to counterbalance the kinetic energy that keeps the mass in motion. The faster a mass is decelerated and brought to a halt, the greater the force that is required.

B.1.1 *Forces involved.* It is somewhat of an oversimplification, but water hammer, or surge, can be defined in these terms: the closing of a valve or the stopping of a pump causes a moving column of water in the pipeline to slow down and stop. The forces that bring about this deceleration are exerted radially on the moving water column by the pipeline walls. Conversely, the water exerts added pressure on the pipe, and the hoop stresses in the pipe walls thus increase over the normal operating pressure values. The faster the column of water is brought to a halt, the higher these stresses rise.

B.1.2 *Rate of velocity fluctuation.* The pipe wall stresses are thus developed by, and increase in direct proportion to, the internal pressure that builds up as the column of water decelerates. The slower the deceleration, the less the pressure builds up and the less the pipe wall stresses increase. It is, therefore, of importance to the pipe designer to know how to control the rate of velocity fluctuation, since by controlling this rate he controls the magnitude of the pressure variations during the transitional periods. By such control he can keep the pipe wall stresses during surge to a predetermined value that will allow an economical installation.

B.1.3 *Wave motion.* Water, being liquid, will act in a fairly complex manner when undergoing acceleration or deceleration. Pressure waves are set up, which move along the pipeline at a rate of 2500–4500 ft/sec (760–1370 m/sec), the rate depending on the pipe wall material. The waves will continue until they encounter a boundary condition, such as a reservoir, a closed valve, or a change in pipe diameter, at which point they will reflect back in the opposite direction. The wave motion will oscillate back and forth in the pipe until it is dampened out by the friction effects of the pipe walls.

B.1.4 *Causes.* The two major causes of water hammer or surge are:

1. The closing or opening, fully or partially, of a valve in a pipeline system. The valve may be in the line for one of a number of purposes. It could be a gate valve, float valve, pressure-reducing valve, or serve some other function.
2. The starting up or shutting down of a pump (switch or power failure). It can be seen that both of these occurrences cause changes in the velocity, and consequently in the quantity, of water flowing in the pipeline.

B.1.5 *Effects.* Ignoring the effects of surge in the pipeline can lead to difficulties after the line is in operation. Surge can result in damaged equipment and seriously reduced capacity.

B.2 Water Hammer Analysis

The elastic wave theory for surge analysis has been empirically established to be correct by many experiments, the first of which were performed as early as 1890. Its application to pipeline problems will yield results which are accurate and which may be relied upon for adequate analysis.

B.2.1 *Wave velocity.* Water hammer pressures are a function of the maximum rate of change of flow. When a valve is closed or a pump stops, a pressure wave is propagated along a pipeline. The velocity of the wave is the same as the velocity of sound in water, modified by physical characteristics of the pipeline; it is described by the following equation:

$$a = \frac{V_s}{\sqrt{1 + kd/Ee}} \qquad \text{Eq B1}$$

Where
- a = pressure wave velocity, in feet per second (metres per second)
- k = modulus of compression of water, 300 000 psi (2070 MPa)
- d = internal diameter of pipe, in inches (millimetres)
- E = modulus of elasticity of asbestos-cement pipe, 3 400 000 psi (23 400 MPa)
- e = wall thickness, in inches (millimetres)
- V_s = velocity of sound in water, 4660 ft/sec (1420 m/s)

B.2.2 *Maximum pressure.* If the pressure wave is reflected back from a boundary condition, such as a reservoir, and returns to its initial position after the flow in the line is completely stopped, then maximum water hammer pressure for those conditions will result. Stopping of the flow may be effected by closing a valve or by a pump stoppage. The magnitude of that maximum pressure is given by

$$h = \frac{aV}{g} \qquad \text{Eq B2}$$

Where
- h = surge pressure, in feet of water (metres of water)
- V = velocity of water in the pipeline during normal conditions, in feet per second (metres per second)
- a = pressure wave velocity, in feet per second (metres per second)
- g = acceleration due to gravity, 32.2 ft/sec^2 (9.81 m/s^2)

B.2.3 *Critical time.* The longest elapsed time before final flow stoppage that will still permit this maximum pressure to occur is called the critical time; it is simply the total length that the pressure wave travels in one cycle divided by the velocity of the wave. It is given by the following equation:

$$U = \frac{2L}{a} \qquad \text{Eq B3}$$

Where
- U = critical time, in seconds
- L = distance within the pipeline that the pressure wave moves before it is reflected back by a boundary condition, in feet (metres)
- a = pressure wave velocity, in feet per second (metres per second)

B.3 Valve Closure

A valve in a water line may be of several different varieties, including gate, cone, and globe valves. When closing a valve, the area of the cross section of the pipeline that is progressively cut off is not generally proportional to the reduction in flow. In Figure B1, Graph 1 presents a plot of stem travel versus flow in the line for three types of valves. Note that the first 30–40 percent of stem travel has little effect on the flow in the pipeline.

B.3.1 *Effective time.* As stated previously, water hammer pressure is a function of the maximum rate of change of flow. Therefore, if tangents to the curves in Figure B1 are drawn at the fastest rate of change (or steepest slope), the effective time of closure T_E is obtained. (See the curves in Figure B1 with tangents plotted and values of T_E determined.) This effective time T_E is the time that is used in water hammer calculations. In most cases, it is about one half of the actual valve closing time. This indicates that if the critical time of a certain installed valve is calculated from Eq B3 and found to be *x* seconds, then the actual time for complete valve closure that will cause maximum pressure to occur will be approximately 2*x* seconds.

B.3.2 *Relation to surge control.* In the design of a water system, one of the major considerations in the selection of a pipe is the design internal pressure that the pipe will be required to carry in service. The design internal pressure is the operating pressure plus the water hammer pressure. In order to keep the water hammer or surge pressures at a controlled level, calculations must be made to determine the valve closure times that will be required to stay within the design pressure level.

B.3.3 *Determining effective time.* Figure B1 presents a convenient three-step method for determining effective valve closure times for a given percentage of the maximum pressure (surge pressure when valve is closed in less than the critical time).

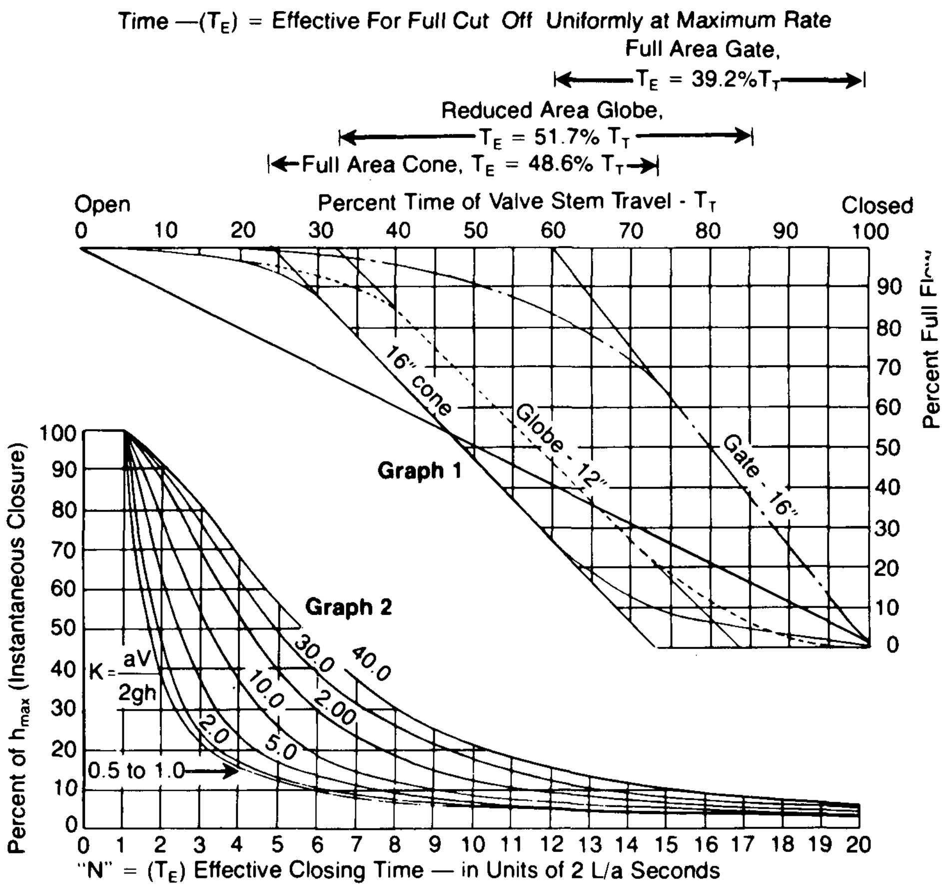


Figure B.1 Time (T_E) = Effective for Full Cut Off Uniformly at Maximum Rate

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1. Determine the pipeline constant K given by

$$K = \frac{aV}{2gh_o} \qquad \text{Eq B4}$$

Where

K = pipeline constant

a = pressure wave velocity, in feet per second (metres per second)

V = velocity of water in the flow line under normal conditions, in feet per second (metres per second)

g = acceleration due to gravity, 32.2 ft/sec^2 (9.81 m/s^2)

h_o = operating pressure in the line under normal conditions, in feet of water (metres of water)

2. Determine the maximum head that might be developed from the surge by using the formula $h_{max} = aV/g$.

3. Determine the percentage of h_{max} and find the corresponding effective closing time shown on the horizontal axis. This is given in units of $2L/a$, which represents the critical time for the pipeline. Note that the time determined is the *effective* closing time, and the *actual* time of valve stem travel is about twice as long. The reason for this is that the first half of the closing of the valve has little effect on the stoppage of the flow. It is the closing of the final half of the valve stem travel that closes off the flow. The second half is the effective closing time. Therefore, two times the effective closing time is the actual time of the valve stem travel.

B.4 Pumped Systems

In relation to water hammer and surge, the most important elements in a system are pumps and valves. In a gravity system, only valves have to be considered. Both pumps and valves must be considered in a pumped system.

B.4.1 *Complexity.* The surge analysis of a pumped system is more complex than in a 100-percent gravity system because

1. In a pumped system, the problem begins in the slowing down of the rising water column when the pump is shut off (because of power failure or otherwise). Consideration must be given to the time required for the pump to stop and for the flow to come to a halt. This involves the inertia of the motor and any flywheel in the assembly. Provisions normally should be made for slow opening and closing of pump control valves on pump systems. In a gravity system, the hydraulic problem consists only of stopping the descending water column.

2. In a pumped system, the pipeline profile is usually irregular, with successive high and low points and variable slopes. These conditions may give rise to water column separation, causing severe surges and operational troubles. Surges from water column separation do not follow a standard pattern and they have been measured at many times the calculated values.

B.4.2 *Alternative layouts.* The design of a pumped system may involve the consideration of alternative layouts to keep surges and the consequent operational difficulties to a minimum. This work should be directed toward reducing the magnitude of surges and toward reducing the risk of water column separation that may be caused by the shutdown of a pump.

B.4.3 *Water column separation.* Water column separation can be serious due to the large magnitude of the surges developed when the water column rejoins. It can occur:

1. At pump locations at the start of a steep main.

2. When the pressure at a high point falls below atmospheric, and air enters the line through air valves that may be located at a high point.

3. When the pressure falls to below the vapor pressure of water.

B.4.4 *Entrapped air.* Water column separation can cause difficulties not only because of the before-mentioned surges set up by the rejoining of the water column, but because of the difficulties in getting air out of the line on subsequent start-up, even with air valves. Entrapped air can cause flow fluctuations and can seriously reduce the capacity of the system.

B.5 Methods of Control

The two types of surge to be controlled are negative surge and positive surge. The type is determined, of course, by whether the surge pressures developed are below or above the normal static level.

B.5.1 *Negative surges.* Negative surges in themselves are usually not dangerous, except when they cause water column separation. If this occurs, extremely high positive surges result when the cavity closes, and this frequently causes serious problems. The control of both negative and positive surges should be given consideration.

B.5.2 *Surge control devices.* Limiting negative and positive surges is accomplished by several types of surge control devices. These devices include:

1. Controlled valves. This is one of the most effective means for controlling positive surges. As explained previously, the rate of opening and closing of a valve can be calculated to allow an acceptable level of surge.

2. Flywheel on pump motor. In the event of a power outage, the inertia of the flywheel will keep the pump running for a period of time, during which it will gradually slow to a stop. This means that the water column in the pipeline will also be brought to a gradual stop, thus reducing the risk of water column separation.

3. Standpipe. This is generally a tank with the surface of the water at atmospheric pressure. It is, therefore, only practical at low heads. At a pump stoppage and consequent reduced pressure, the reserve of water in the tank flows into the pipe and reduces the risk of water column separation. For positive surge control, the tank provides an outlet for the built-up pressure in the system.

4. Air vessel or surge tank. This is an enclosed vessel containing air and water. It functions similarly to a standpipe, with water reentering the line during negative surge and leaving during positive surge. The major difference is that the air in the vessel is under pressure and much higher heads can be employed in the pipe system.

5. One-way surge tank. This is an adaptation of the surge tank. It contains a check valve that permits water to enter the line during negative surge, but will not permit water to leave during positive surge. It is, therefore, only for control of negative surges and is very effective.

6. Reservoir of water. This is similar to the one-way surge tank, but provides some control of positive surge by permitting the slow entrance of water into the reservoir during a positive surge.

7. Suction pipe. This is a bypass around the pump from the suction side. It contains a check valve to prevent backflow into the reservoir. It effectively reduces negative pressure adjacent to the pump.

8. Surge relief valve. This is used for controlling positive and negative surges. The valve opens at a certain pressure and discharges water to relieve a surge—positive or negative. It must be carefully designed and controlled in order to be effective.

9. Nonreturn valve. This is a check, strategically placed in a line, that can bring a small measure of relief to positive pressure. However, unless properly placed, it can lead to higher rather than lower surge.

10. Reversal of pump. At pump stoppage, the column of water reverses itself. If the pump will not run backwards to permit water to flow back through it,

then positive surges will be developed by the sudden stopping of the backflowing column of water. The pump should be designed to run reversed without damage to itself. Design of pumps that can run reversed without damage is a significant problem. Other measures may have to be taken.

B.5.3 *Economic considerations.* From an economic standpoint, it is usually worthwhile to properly evaluate the surge potential in a system under design. The cost of control devices may be balanced against the added strength of pipe, valves, and other equipment that will be needed if surges are not controlled, and the most advantageous conclusion reached. Manufacturers of surge control equipment or consultants in this field should be sought for advice in complex situations.

B.6 Surge Calculation Example

The following example problem illustrates the calculation that may be followed to determine valve closing time for the control of surge within prescribed limits.

Problem: A 24-in. gravity transmission line is to operate at a pressure of 100 psi. Velocity in the line is to be 5 ft/sec. A valve is to be included in the line at a distance of 5000 ft from the reservoir. If positive surge pressure is to be controlled within 50 psi, determine the minimum time for valve closure. Assume that the effective closing time is one half of the actual valve stem travel time. (E for asbestos-cement pipe $= 3.4 \times 10^6$, wall thickness is 1.5 in., k for water $= 3 \times 10^5$.)

Solution:

1. Determine surge wave velocity

$$a = \frac{V_s}{\sqrt{1 + \frac{kd}{Ee}}}$$

$$= \frac{4660}{\sqrt{1 + \frac{3 \times 10^5 \times 24}{3.4 \times 10^6 \times 1.5}}}$$

$$= 3000 \text{ ft/sec.}$$

2. Determine maximum surge pressure if the valve closes within the critical time

$$h = \frac{aV}{g} = \frac{3000 \times 5}{32.2}$$

$$= 465 \text{ ft of water (200 psi)}$$

3. Determine the critical time

$$U = \frac{2L}{a} = \frac{2 \times 5000}{3000} = 3.33 \text{ sec}$$

4. Determine constant K for use in Graph 2 (Figure B1)

$$K = \frac{aV}{2gh_o} = \frac{3000 \times 5}{2 \times 32.2 \times 231} = 1.0$$

5. Determine percent of maximum surge pressure that should not be exceeded in the system

$$\frac{50}{200} \times 100 = 25 \text{ percent}$$

6. Enter Graph 2 (Figure B1) with percent of h_{max} (25 percent). Go horizontally to the curves where $K = 1.0$. Read the effective closing time along the horizontal axis. This value is 2.6 and is given in units of $2L/a$ sec. The effective closing time in seconds would be $2L/a \times 2.6 = 3.33 \times 2.6 = 8.7$ sec. The actual valve stem travel time would be twice this amount, or 17.4 sec. This calculated time (17.4 sec), therefore, represents the fastest allowable time the valve can be closed in order to keep the surge pressure below the desired control level of 50 psi.

B.7 Air in Pipelines

Air in pipelines can cause serious operational difficulties, including reduction in capacity because of reduced cross-sectional area and fluctuation in flow caused by expanding and contracting air in the line. These fluctuations in flow cause sudden movements of the air from one location to another, followed by slugs of water, and this can cause serious surges.

B.7.1 Entrance of air. Air can enter a pipeline in many ways. It may enter at the intake. Entry may be caused by release of air from water due to temperature and pressure variation, or it may be caused by draining the line, or by draining parts of the line during normal shut-down. Negative surges may cause air to enter at air valves. Air should be prevented from entering the line in the first place. This is very important in order to reduce operational difficulties. Suggested solutions for control are as follows:

1. Intake. Correct design procedures, provide low water-level pump cutoff.
2. Release of air. Air is entrained in the water at intake and its release cannot be prevented. However, the quantities are not large and provisions for exhausting can be made by means of air valves. There are various types of air valves with different functions, and the selection of the proper type and location for installation is essential.
3. Draining the line. Air cannot be prevented from entering the line on draining, of course. Large orifice air valves should be provided for exhausting the air during refilling. Draining and then refilling does not often occur; therefore, long filling times may be satisfactory.
4. Drainage during shut down. This can be a serious problem. Open standpipes can be provided for air entry and exhaust. Sweeping air out using high velocities is another method.
5. Negative surges. The best way to prevent air from entering under these conditions is to design out the possibility of water column separation. Large volumes of air may be involved here and can cause serious problems. Any one of the negative surge control devices described in Sec. B.5.2 will normally be adequate.

B.7.2 *Recommendations to combat air entrapment.* Colorado State University has conducted studies to determine the effect of air entrapment in pipelines. The result of the studies proved that suddenly released entrapped air, under apparently static conditions, creates a situation similar to that of classic water hammer. Pressures are generated that may be on the order of 15 times the pipeline test pressure. Any pipeline material is seriously affected by this rapid magnitude of load increase. Hydrostatic failure due to defective pipe may in all probability be traced to suddenly released entrapped air. The initial filling and testing of a pipeline is often the most critical period of its service life. Recommendations to combat air entrapment were made as follows:

1. Pipeline should be laid to grade wherever possible.
2. Automatic continual acting air release valves should be used at all high points.
3. Air should be bled from pipeline slowly.
4. Limit filling velocity in the pipeline to 1 ft/sec (3 m/s) or less.
5. Use $d/D = 1/10$ to $1/100$.

Where

d = diameter of air release valve.

D = pipe diameter.

The results of this study, together with the recommendations, have been found to be most useful to contractors in performing pipeline tests. Such recommendations also have been found to be useful to engineers from the standpoint of designing pipelines to minimize air problems.

Appendix C

Frictional Power Requirements

This appendix is for information only and is not a part of AWWA C401.

The chart shown in Figure C1 permits rapid calculations of the yearly power costs to overcome friction loss of head. This chart is based on continuous pumping operation (24 hours per day and 365 days per year), a power cost of $0.01 per kW·h, and a motor-pump efficiency of 100 percent. For actual operating conditions and local power costs, appropriate factors must be applied to the values shown in the chart. By calculating power costs to overcome friction in two pipe sizes, or for two different types of pipe having different flow coefficients, an annual power cost savings can be determined. Economic justification for going to a larger pipe diameter with lower annual power costs can be determined by establishing the present worth of the annual savings using Table C1*, which is based on the discounted cash flow method. If the present worth of the annual savings based on established interest rates exceeds the added costs for the installation of a different size or type of material, then economic justification exists for the added capital expenditure.

Nomograph values for Figure C1 are based on the following:

Cost per 1000 ft of pipe per year, in dollars

Power cost = $0.01 kW·h

Motor-pump efficiency (combined) = 100 percent

Friction coefficient $C = 140$

Continuous operation.

*This table is reprinted by permission of the Johns-Manville Sales Corporation from their publication, "Discounted Cash Flow Method of Investment Appraisal."

NOTE: Yearly power cost values derived in Figure C1 are for coefficient of flow $C = 140$. They may be converted to yearly power cost values for other coefficients of flow by means of the following multiplying factors:

1.15 for $C = 130$
1.34 for $C = 120$
1.57 for $C = 110$
1.86 for $C = 100$
2.26 for $C = 90$
2.83 for $C = 80$
4.82 for $C = 60$

Diameters derived from Figure C1 are for coefficient of flow $C = 140$. These may be converted to other diameters for other coefficients of flow by means of the following multiplying factors:

1.033 for $C = 130$
1.063 for $C = 120$
1.100 for $C = 110$
1.142 for $C = 100$
1.185 for $C = 90$
1.261 for $C = 80$
1.365 for $C = 60$

Apply the following formula to Table C1.

$$\frac{\left(\frac{1}{r}\right)^N - 1}{r(1 + r)^N}$$

Where

r = rate of yield in percent
N = number of years from present

Derived from the Hazen and Williams formula: $V = 1.318\, CR^{0.63}S^{0.54}$

NOTE: Power cost values derived from this chart are for coefficient of flow $C = 140$. They may be converted to other coefficients of flow by means of the following multiplying factors:

1.15 for $C = 130$	2.26 for $C = 90$
1.34 for $C = 120$	2.83 for $C = 80$
1.57 for $C = 110$	4.82 for $C = 60$
1.86 for $C = 100$	

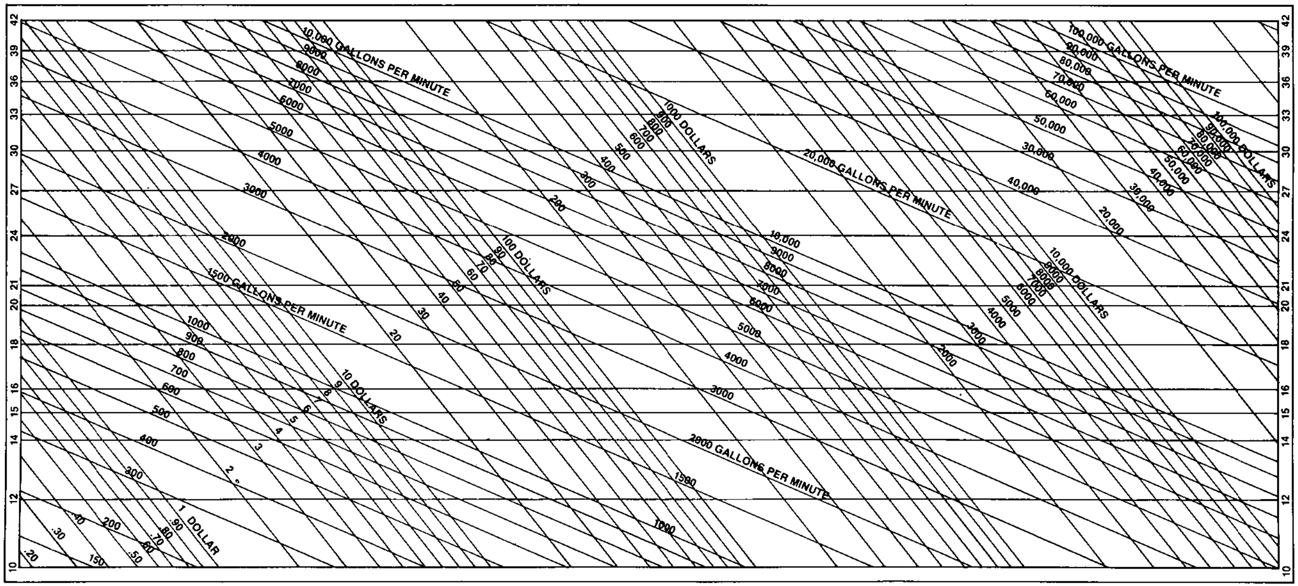
Asbestos-cement pressure pipe has a coefficient of $C = 140$.

EXAMPLE

Given: size of pipe = 6 in. (150 mm), length of line = 3000 ft (914 m), rate of flow = 500 gpm (1893 L/ min), power cost = \$0.02/kW·h, combined efficiency of pump and motor = 50%

Required: Power cost to compensate for friction loss of head for $C = 140$ and $C = 100$.

Solution: On right edge of chart select 6-in. pipe and extend a horizontal line to left until it intersects diagonal line indicating 500 gpm. Using this point and applying it to scale on diagonal lines indicating dollars, the yearly power cost is found to be \$145.00. Total power cost for 3000 ft of 6-in. pipe is $3 \times 145 = 435$ for $C = 140$ and $435 \times 1.86 = 809$ for $C = 100$. Converting to 50% combined efficiency of pump and motor and power cost of \$0.02/kW·h, we find: power cost for $C = 140$ is \$1740.00 and power cost for $C = 100$ is \$3236.00.



NOTE: Power cost—\$0.01/kW·h, combined motor and pump efficiency—100%, per 1000 ft (305 m) of pipe.

Figure C.1 Yearly Power Cost to Compensate for Friction Loss of Head

Example:

When using a 10 percent rate of yield, an income of $1.00 occurring each year for the next five years has a present worth of $3.791; for the next seven years, $4,868; for the next 10 years, $6.145; etc.

The present worth (PW) of a regular pattern of savings in the future is found as follows:

Total years of operation—25
Amount of annual savings—$5000.00
PW factor at 10 percent—9.077
Total present worth (PW)—$45 385.00

When expenditure, cash income, and life are known, and income is the same each year, the PW factor can be computed by dividing expenditure by annual cash income. Yield can then be determined by looking for the factor on the line for known life in Table C1.

TABLE C1

Present Worth of an Income of $1.00 per Year for the Next N *Years*

Years	.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%	Years
1	.995	.990	.985	.980	.976	.971	.966	.962	.957	.952	1
2	1.985	1.970	1.956	1.942	1.927	1.913	1.900	1.886	1.873	1.859	2
3	2.970	2.941	2.912	2.884	2.856	2.829	2.802	2.775	2.749	2.723	3
4	3.950	3.902	3.854	3.808	3.762	3.717	3.673	3.630	3.588	3.546	4
5	4.926	4.853	4.783	4.713	4.646	4.580	4.515	4.452	4.390	4.329	5
6	5.896	5.795	5.697	5.601	5.508	5.417	5.329	5.242	5.158	5.076	6
7	6.862	6.728	6.598	6.472	6.349	6.230	6.115	6.002	5.893	5.786	7
8	7.823	7.652	7.486	7.325	7.170	7.020	6.874	6.733	6.596	6.463	8
9	8.779	8.566	8.361	8.162	7.971	7.786	7.608	7.435	7.269	7.108	9
10	9.730	9.471	9.222	8.983	8.752	8.530	8.317	8.111	7.913	7.722	10
11	10.68	10.37	10.07	9.787	9.514	9.253	9.002	8.760	8.529	8.306	11
12	11.62	11.26	10.91	10.58	10.26	9.954	9.663	9.385	9.119	8.863	12
13	12.56	12.13	11.73	11.35	10.98	10.64	10.30	9.986	9.683	9.394	13
14	13.49	13.00	12.54	12.11	11.69	11.30	10.92	10.56	10.22	9.899	14
15	14.42	13.87	13.34	12.85	12.38	11.94	11.52	11.12	10.74	10.38	15
16	15.34	14.72	14.13	13.58	13.06	12.56	12.09	11.65	11.23	10.84	16
17	16.26	15.56	14.91	14.29	13.71	13.17	12.65	12.17	11.71	11.27	17
18	17.17	16.40	15.67	14.99	14.35	13.75	13.19	12.66	12.16	11.69	18
19	18.08	17.23	16.43	15.68	14.98	14.32	13.71	13.13	12.59	12.09	19
20	18.99	18.05	17.17	16.35	15.59	14.88	14.21	13.59	13.01	12.46	20
21	19.89	18.86	17.90	17.01	16.19	15.42	14.70	14.03	13.41	12.82	21
22	20.78	19.66	18.62	17.66	16.77	15.94	15.17	14.45	13.78	13.16	22
23	21.68	20.46	19.33	18.29	17.33	16.44	15.62	14.86	14.15	13.49	23
24	22.56	21.24	20.03	18.91	17.89	16.94	16.06	15.25	14.50	13.80	24
25	23.45	22.02	20.72	19.52	18.42	17.41	16.48	15.62	14.83	14.09	25
26	24.32	22.80	21.40	20.12	18.95	17.88	16.89	15.98	15.15	14.38	26
27	25.20	23.56	22.07	20.71	19.46	18.33	17.29	16.33	15.45	14.64	27
28	26.07	24.31	22.73	21.28	19.97	18.76	17.67	16.66	15.74	14.90	28
29	26.93	25.07	23.38	21.84	20.45	19.19	18.04	16.98	16.02	15.14	29
30	27.79	25.81	24.02	22.40	20.93	19.60	18.39	17.29	16.29	15.37	30
31	28.65	26.54	24.65	22.94	21.40	20.00	18.74	17.59	16.54	15.59	31
32	29.50	27.27	25.27	23.47	21.85	20.39	19.07	17.87	16.79	15.80	32
33	30.35	27.99	25.88	23.99	22.29	20.77	19.39	18.15	17.02	16.00	33
34	31.20	28.70	26.48	24.50	22.72	21.13	19.70	18.41	17.25	16.19	34
35	32.04	29.41	27.08	25.00	23.15	21.49	20.00	18.67	17.46	16.37	35
36	32.87	30.11	27.66	25.49	23.56	21.83	20.29	18.91	17.67	16.55	36
37	33.70	30.80	28.24	25.97	23.96	22.17	20.57	19.14	17.86	16.71	37
38	34.53	31.49	28.81	26.44	24.35	22.49	20.84	19.37	18.05	16.87	38
39	35.35	32.16	29.37	26.90	24.73	22.81	21.10	19.58	18.23	17.02	39
40	36.17	32.84	29.92	27.36	25.10	23.12	21.36	19.79	18.40	17.16	40
41	36.99	33.50	30.46	27.80	25.47	23.41	21.60	19.99	18.57	17.29	41
42	37.80	34.16	30.99	28.24	25.82	23.70	21.84	20.19	18.72	17.42	42
43	38.61	34.81	31.52	28.66	26.17	23.98	22.06	20.37	18.87	17.55	43
44	39.41	35.46	32.04	29.08	26.50	24.25	22.28	20.55	19.02	17.66	44
45	40.21	36.09	32.55	29.49	26.83	24.52	22.50	20.72	19.16	17.77	45
46	41.00	36.73	33.06	29.89	27.15	24.78	22.70	20.89	19.29	17.88	46
47	41.79	37.35	33.55	30.29	27.47	25.03	22.90	21.04	19.42	17.98	47
48	42.58	37.97	34.04	30.67	27.77	25.27	23.09	21.20	19.54	18.08	48
49	43.36	38.59	34.53	31.05	28.07	25.50	23.28	21.34	19.65	18.17	49
50	44.14	39.20	35.00	31.42	28.36	25.73	23.46	21.48	19.76	18.26	50

TABLE C1 (*continued*)

Years	5.5%	6.0%	6.5%	7.0%	7.5%	8.0%	8.5%	9.0%	9.5%	10.0%	Years
1	.948	.943	.939	.935	.930	.926	.922	.917	.913	.909	1
2	1.846	1.833	1.821	1.808	1.796	1.783	1.771	1.759	1.747	1.736	2
3	2.698	2.673	2.648	2.624	2.601	2.577	2.554	2.531	2.509	2.487	3
4	3.505	3.465	3.426	3.387	3.349	3.312	3.276	3.240	3.204	3.170	4
5	4.270	4.212	4.156	4.100	4.046	3.993	3.941	3.890	3.840	3.791	5
6	4.996	4.917	4.841	4.767	4.694	4.623	4.554	4.486	4.420	4.355	6
7	5.683	5.582	5.485	5.389	5.297	5.206	5.119	5.033	4.950	4.868	7
8	6.335	6.210	6.089	5.971	5.857	5.747	5.639	5.535	5.433	5.335	8
9	6.952	6.802	6.656	6.515	6.379	6.247	6.119	5.995	5.875	5.759	9
10	7.538	7.360	7.189	7.024	6.864	6.710	6.561	6.418	6.279	6.145	10
11	8.093	7.887	7.689	7.499	7.315	7.139	6.969	6.805	6.647	6.495	11
12	8.619	8.384	8.159	7.943	7.735	7.536	7.345	7.161	6.984	6.814	12
13	9.117	8.853	8.600	8.358	8.126	7.904	7.691	7.487	7.291	7.103	13
14	9.590	9.295	9.014	8.745	8.489	8.244	8.010	7.786	7.572	7.367	14
15	10.04	9.712	9.403	9.108	8.827	8.559	8.304	8.061	7.828	7.606	15
16	10.46	10.11	9.768	9.447	9.142	8.851	8.575	8.313	8.062	7.824	16
17	10.87	10.48	10.11	9.763	9.434	9.122	8.825	8.544	8.276	8.022	17
18	11.25	10.83	10.43	10.06	9.706	9.372	9.055	8.756	8.471	8.201	18
19	11.61	11.16	10.74	10.34	9.959	9.604	9.268	8.950	8.650	8.365	19
20	11.95	11.47	11.02	10.59	10.19	9.818	9.463	9.129	8.812	8.514	20
21	12.28	11.76	11.29	10.84	10.41	10.02	9.644	9.292	8.961	8.649	21
22	12.58	12.04	11.54	11.06	10.62	10.20	9.810	9.442	9.097	8.772	22
23	12.88	12.30	11.77	11.27	10.81	10.37	9.963	9.580	9.221	8.883	23
24	13.15	12.55	11.99	11.47	10.98	10.53	10.10	9.707	9.334	8.985	24
25	13.41	12.78	12.20	11.65	11.15	10.68	10.23	9.823	9.438	9.077	25
26	13.66	13.00	12.39	11.83	11.30	10.81	10.35	9.929	9.532	9.161	26
27	13.90	13.21	12.58	11.99	11.44	10.94	10.47	10.03	9.618	9.237	27
28	14.12	13.41	12.75	12.14	11.57	11.05	10.57	10.12	9.697	9.307	28
29	14.33	13.59	12.91	12.28	11.70	11.16	10.66	10.20	9.769	9.370	29
30	14.53	13.77	13.06	12.41	11.81	11.26	10.75	10.27	9.835	9.427	30
31	14.72	13.93	13.20	12.53	11.92	11.35	10.83	10.34	9.895	9.479	31
32	14.90	14.08	13.33	12.65	12.02	11.44	10.90	10.41	9.950	9.526	32
33	15.08	14.23	13.46	12.75	12.11	11.51	10.97	10.46	10.00	9.569	33
34	15.24	14.37	13.58	12.85	12.19	11.59	11.03	10.52	10.05	9.609	34
35	15.39	14.50	13.69	12.95	12.27	11.66	11.09	10.57	10.09	9.644	35
36	15.54	14.62	13.79	13.04	12.35	11.72	11.14	10.61	10.13	9.677	36
37	15.67	14.74	13.89	13.12	12.42	11.78	11.19	10.65	10.16	9.706	37
38	15.81	14.85	13.98	13.19	12.48	11.83	11.24	10.69	10.19	9.733	38
39	15.93	14.95	14.07	13.27	12.54	11.88	11.28	10.73	10.22	9.757	39
40	16.05	15.05	14.15	13.33	12.59	11.93	11.32	10.76	10.25	9.779	40
41	16.16	15.14	14.22	13.39	12.65	11.97	11.35	10.79	10.27	9.799	41
42	16.26	15.23	14.29	13.45	12.69	12.01	11.38	10.81	10.29	9.817	42
43	16.36	15.31	14.36	13.51	12.74	12.04	11.41	10.84	10.31	9.834	43
44	16.46	15.38	14.42	13.56	12.78	12.08	11.44	10.86	10.33	9.849	44
45	16.55	15.46	14.48	13.61	12.82	12.11	11.47	10.88	10.35	9.863	45
46	16.63	15.52	14.54	13.65	12.86	12.14	11.49	10.90	10.36	9.875	46
47	16.71	15.59	14.59	13.69	12.89	12.16	11.51	10.92	10.38	9.887	47
48	16.79	15.65	14.64	13.73	12.92	12.19	11.53	10.93	10.39	9.897	48
49	16.86	15.71	14.68	13.77	12.95	12.21	11.55	10.95	10.40	9.906	49
50	16.93	15.76	14.73	13.80	12.98	12.23	11.57	10.96	10.41	9.915	50

TABLE C1 (*continued*)

Years	10.5%	11.0%	11.5%	12.0%	12.5%	13.0%	13.5%	14.0%	14.5%	15.0%	Years
1	.905	.901	.897	.893	.889	.885	.881	.877	.873	.870	1
2	1.724	1.713	1.701	1.690	1.679	1.668	1.657	1.647	1.636	1.626	2
3	2.465	2.444	2.423	2.402	2.381	2.361	2.341	2.322	2.302	2.283	3
4	3.136	3.102	3.070	3.037	3.006	2.974	2.944	2.914	2.884	2.855	4
5	3.743	3.696	3.650	3.605	3.561	3.517	3.475	3.433	3.392	3.352	5
6	4.292	4.231	4.170	4.111	4.054	3.998	3.943	3.889	3.836	3.784	6
7	4.789	4.712	4.637	4.564	4.492	4.423	4.355	4.288	4.224	4.160	7
8	5.239	5.146	5.056	4.968	4.882	4.799	4.718	4.639	4.562	4.487	8
9	5.646	5.537	5.431	5.328	5.228	5.132	5.038	4.946	4.858	4.772	9
10	6.015	5.889	5.768	5.650	5.536	5.426	5.320	5.216	5.116	5.019	10
11	6.348	6.207	6.070	5.938	5.810	5.687	5.568	5.453	5.341	5.234	11
12	6.650	6.492	6.341	6.194	6.053	5.918	5.787	5.660	5.538	5.421	12
13	6.923	6.750	6.583	6.424	6.270	6.122	5.979	5.842	5.710	5.583	13
14	7.170	6.982	6.801	6.628	6.462	6.302	6.149	6.002	5.861	5.724	14
15	7.394	7.191	6.997	6.811	6.633	6.462	6.299	6.142	5.992	5.847	15
16	7.596	7.379	7.172	6.974	6.785	6.604	6.431	6.265	6.106	5.954	16
17	7.779	7.549	7.329	7.120	6.920	6.729	6.547	6.373	6.206	6.047	17
18	7.945	7.702	7.470	7.250	7.040	6.840	6.649	6.467	6.294	6.128	18
19	8.095	7.839	7.596	7.366	7.147	6.938	6.739	6.550	6.370	6.198	19
20	8.231	7.963	7.710	7.469	7.241	7.025	6.819	6.623	6.437	6.259	20
21	8.354	8.075	7.811	7.562	7.326	7.102	6.889	6.687	6.495	6.312	21
22	8.465	8.176	7.903	7.645	7.401	7.170	6.951	6.743	6.546	6.359	22
23	8.566	8.266	7.984	7.718	7.467	7.230	7.005	6.792	6.590	6.399	23
24	8.657	8.348	8.058	7.784	7.526	7.283	7.053	6.835	6.629	6.434	24
25	8.739	8.422	8.124	7.843	7.579	7.330	7.095	6.873	6.663	6.464	25
26	8.814	8.488	8.183	7.896	7.626	7.372	7.132	6.906	6.693	6.491	26
27	8.881	8.548	8.236	7.943	7.667	7.409	7.165	6.935	6.718	6.514	27
28	8.942	8.602	8.283	7.984	7.704	7.441	7.194	6.961	6.741	6.534	28
29	8.997	8.650	8.326	8.022	7.737	7.470	7.219	6.983	6.761	6.551	29
30	9.047	8.694	8.364	8.055	7.766	7.496	7.242	7.003	6.778	6.566	30
31	9.093	8.733	8.398	8.085	7.792	7.518	7.261	7.020	6.793	6.579	31
32	9.134	8.769	8.429	8.112	7.815	7.538	7.279	7.035	6.806	6.591	32
33	9.171	8.801	8.456	8.135	7.836	7.556	7.294	7.048	6.817	6.600	33
34	9.204	8.829	8.481	8.157	7.854	7.572	7.307	7.060	6.827	6.609	34
35	9.235	8.855	8.503	8.176	7.870	7.586	7.319	7.070	6.836	6.617	35
36	9.262	8.879	8.523	8.192	7.885	7.598	7.330	7.079	6.844	6.623	36
37	9.287	8.900	8.541	8.208	7.898	7.609	7.339	7.087	6.851	6.629	37
38	9.309	8.919	8.557	8.221	7.909	7.618	7.347	7.094	6.856	6.634	38
39	9.330	8.936	8.571	8.233	7.919	7.627	7.354	7.100	6.861	6.638	39
40	9.348	8.951	8.584	8.244	7.928	7.634	7.361	7.105	6.866	6.642	40
41	9.365	8.965	8.595	8.253	7.936	7.641	7.366	7.110	6.870	6.645	41
42	9.380	8.977	8.606	8.262	7.943	7.647	7.371	7.114	6.873	6.648	42
43	9.394	8.989	8.615	8.270	7.949	7.652	7.375	7.117	6.876	6.650	43
44	9.406	8.999	8.623	8.276	7.955	7.657	7.379	7.120	6.879	6.652	44
45	9.417	9.008	8.631	8.283	7.960	7.661	7.383	7.123	6.881	6.654	45
46	9.427	9.016	8.637	8.288	7.965	7.664	7.386	7.126	6.883	6.656	46
47	9.437	9.024	8.643	8.293	7.968	7.668	7.388	7.128	6.885	6.657	47
48	9.445	9.030	8.649	8.297	7.972	7.671	7.390	7.130	6.886	6.659	48
49	9.452	9.036	8.654	8.301	7.975	7.673	7.392	7.131	6.887	6.660	49
50	9.459	9.042	8.658	8.304	7.978	7.675	7.394	7.133	6.889	6.661	50

TABLE C1 (*continued*)

Years	15.5%	16.0%	16.5%	17.0%	17.5%	18.0%	18.5%	19.0%	19.5%	20.0%	Years
1	.866	.862	.858	.855	.851	.847	.844	.840	.837	.833	1
2	1.615	1.605	1.595	1.585	1.575	1.566	1.556	1.547	1.537	1.528	2
3	2.264	2.246	2.228	2.210	2.192	2.174	2.157	2.140	2.123	2.106	3
4	2.826	2.798	2.770	2.743	2.716	2.690	2.664	2.639	2.613	2.589	4
5	3.313	3.274	3.236	3.199	3.163	3.127	3.092	3.058	3.024	2.991	5
6	3.734	3.685	3.636	3.589	3.543	3.498	3.453	3.410	3.367	3.326	6
7	4.099	4.039	3.980	3.922	3.866	3.812	3.758	3.706	3.655	3.605	7
8	4.415	4.344	4.274	4.207	4.142	4.078	4.015	3.954	3.895	3.837	8
9	4.688	4.607	4.527	4.451	4.376	4.303	4.232	4.163	4.096	4.031	9
10	4.925	4.833	4.745	4.659	4.575	4.494	4.415	4.339	4.265	4.192	10
11	5.130	5.029	4.931	4.836	4.745	4.656	4.570	4.486	4.406	4.327	11
12	5.307	5.197	5.091	4.988	4.889	4.793	4.700	4.611	4.523	4.439	12
13	5.461	5.342	5.228	5.118	5.012	4.910	4.810	4.715	4.622	4.533	13
14	5.594	5.468	5.346	5.229	5.117	5.008	4.903	4.802	4.705	4.611	14
15	5.709	5.575	5.447	5.324	5.206	5.092	4.982	4.876	4.774	4.675	15
16	5.808	5.668	5.534	5.405	5.281	5.162	5.048	4.938	4.832	4.730	16
17	5.895	5.749	5.609	5.475	5.346	5.222	5.104	4.990	4.880	4.775	17
18	5.969	5.818	5.673	5.534	5.401	5.273	5.151	5.033	4.921	4.812	18
19	6.034	5.877	5.728	5.584	5.447	5.316	5.191	5.070	4.954	4.843	19
20	6.090	5.929	5.775	5.628	5.487	5.353	5.224	5.101	4.983	4.870	20
21	6.139	5.973	5.815	5.665	5.521	5.384	5.252	5.127	5.007	4.891	21
22	6.181	6.011	5.850	5.696	5.550	5.410	5.276	5.149	5.026	4.909	22
23	6.217	6.044	5.880	5.723	5.574	5.432	5.296	5.167	5.043	4.925	23
24	6.249	6.073	5.905	5.746	5.595	5.451	5.313	5.182	5.057	4.937	24
25	6.276	6.097	5.927	5.766	5.613	5.467	5.328	5.195	5.069	4.948	25
26	6.299	6.118	5.946	5.783	5.628	5.480	5.340	5.206	5.078	4.956	26
27	6.320	6.136	5.962	5.798	5.641	5.492	5.350	5.215	5.086	4.964	27
28	6.337	6.152	5.976	5.810	5.652	5.502	5.359	5.223	5.093	4.970	28
29	6.353	6.166	5.988	5.820	5.661	5.510	5.366	5.229	5.099	4.975	29
30	6.366	6.177	5.999	5.829	5.669	5.517	5.372	5.235	5.104	4.979	30
31	6.378	6.187	6.007	5.837	5.676	5.523	5.377	5.239	5.108	4.982	31
32	6.387	6.196	6.015	5.844	5.681	5.528	5.382	5.243	5.111	4.985	32
33	6.396	6.203	6.021	5.849	5.686	5.532	5.385	5.246	5.114	4.988	33
34	6.404	6.210	6.027	5.854	5.691	5.536	5.389	5.249	5.116	4.990	34
35	6.410	6.215	6.032	5.858	5.694	5.539	5.391	5.251	5.118	4.992	35
36	6.416	6.220	6.036	5.862	5.697	5.541	5.393	5.253	5.120	4.993	36
37	6.420	6.224	6.039	5.865	5.700	5.543	5.395	5.255	5.121	4.994	37
38	6.425	6.228	6.042	5.867	5.702	5.545	5.397	5.256	5.122	4.995	38
39	6.428	6.231	6.045	5.869	5.704	5.547	5.398	5.257	5.123	4.996	39
40	6.431	6.233	6.047	5.871	5.705	5.548	5.399	5.258	5.124	4.997	40
41	6.434	6.236	6.049	5.873	5.707	5.549	5.400	5.259	5.125	4.997	41
42	6.436	6.238	6.051	5.874	5.708	5.550	5.401	5.260	5.125	4.998	42
43	6.438	6.239	6.052	5.875	5.709	5.551	5.402	5.260	5.126	4.998	43
44	6.440	6.241	6.053	5.876	5.710	5.552	5.402	5.261	5.126	4.998	44
45	6.442	6.242	6.054	5.877	5.710	5.552	5.403	5.261	5.127	4.999	45
46	6.443	6.243	6.055	5.878	5.711	5.553	5.403	5.261	5.127	4.999	46
47	6.444	6.244	6.056	5.879	5.711	5.553	5.404	5.262	5.127	4.999	47
48	6.445	6.245	6.057	5.879	5.712	5.554	5.404	5.262	5.127	4.999	48
49	6.446	6.246	6.057	5.880	5.712	5.554	5.404	5.262	5.127	4.999	49
50	6.447	6.246	6.058	5.880	5.712	5.554	5.404	5.262	5.128	4.999	50

TABLE C1 (*continued*)

Years	21%	22%	23%	24%	25%	26%	27%	28%	29%	30%	Years
1	.826	.820	.813	.806	.800	.794	.787	.781	.775	.769	1
2	1.509	1.492	1.474	1.457	1.440	1.424	1.407	1.392	1.376	1.361	2
3	2.074	2.042	2.011	1.981	1.952	1.923	1.896	1.868	1.842	1.816	3
4	2.540	2.494	2.448	2.404	2.362	2.320	2.280	2.241	2.203	2.166	4
5	2.926	2.864	2.803	2.745	2.689	2.635	2.583	2.532	2.483	2.436	5
6	3.245	3.167	3.092	3.020	2.951	2.885	2.821	2.759	2.700	2.643	6
7	3.508	3.416	3.327	3.242	3.161	3.083	3.009	2.937	2.868	2.802	7
8	3.726	3.619	3.518	3.421	3.329	3.241	3.156	3.076	2.999	2.925	8
9	3.905	3.786	3.673	3.566	3.463	3.366	3.273	3.184	3.100	3.019	9
10	4.054	3.923	3.799	3.682	3.571	3.465	3.364	3.269	3.178	3.092	10
11	4.177	4.035	3.902	3.776	3.656	3.543	3.437	3.335	3.239	3.147	11
12	4.278	4.127	3.985	3.851	3.725	3.606	3.493	3.387	3.286	3.190	12
13	4.362	4.203	4.053	3.912	3.780	3.656	3.538	3.427	3.322	3.223	13
14	4.432	4.265	4.108	3.962	3.824	3.695	3.573	3.459	3.351	3.249	14
15	4.489	4.315	4.153	4.001	3.859	3.726	3.601	3.483	3.373	3.268	15
16	4.536	4.357	4.189	4.033	3.887	3.751	3.623	3.503	3.390	3.283	16
17	4.576	4.391	4.219	4.059	3.910	3.771	3.640	3.518	3.403	3.295	17
18	4.608	4.419	4.243	4.080	3.928	3.786	3.654	3.529	3.413	3.304	18
19	4.635	4.442	4.263	4.097	3.942	3.799	3.664	3.539	3.421	3.311	19
20	4.657	4.460	4.279	4.110	3.954	3.808	3.673	3.546	3.427	3.316	20
21	4.675	4.476	4.292	4.121	3.963	3.816	3.679	3.551	3.432	3.320	21
22	4.690	4.488	4.302	4.130	3.970	3.822	3.684	3.556	3.436	3.323	22
23	4.703	4.499	4.311	4.137	3.976	3.827	3.689	3.559	3.438	3.325	23
24	4.713	4.507	4.318	4.143	3.981	3.831	3.692	3.562	3.441	3.327	24
25	4.721	4.514	4.323	4.147	3.985	3.834	3.694	3.564	3.442	3.329	25
26	4.728	4.520	4.328	4.151	3.988	3.837	3.696	3.566	3.444	3.330	26
27	4.734	4.524	4.332	4.154	3.990	3.839	3.698	3.567	3.445	3.331	27
28	4.739	4.528	4.335	4.157	3.992	3.840	3.699	3.568	3.446	3.331	28
29	4.743	4.531	4.337	4.159	3.994	3.841	3.700	3.569	3.446	3.332	29
30	4.746	4.534	4.339	4.160	3.995	3.842	3.701	3.569	3.447	3.332	30
31	4.749	4.536	4.341	4.161	3.996	3.843	3.701	3.570	3.447	3.332	31
32	4.751	4.538	4.342	4.162	3.997	3.844	3.702	3.570	3.447	3.333	32
33	4.753	4.539	4.343	4.163	3.997	3.844	3.702	3.570	3.448	3.333	33
34	4.755	4.540	4.344	4.164	3.998	3.845	3.703	3.571	3.448	3.333	34
35	4.756	4.541	4.345	4.164	3.998	3.845	3.703	3.571	3.448	3.333	35
36	4.757	4.542	4.345	4.165	3.999	3.845	3.703	3.571	3.448	3.333	36
37	4.758	4.543	4.346	4.165	3.999	3.845	3.703	3.571	3.448	3.333	37
38	4.759	4.543	4.346	4.165	3.999	3.846	3.703	3.571	3.448	3.333	38
39	4.759	4.544	4.346	4.166	3.999	3.846	3.703	3.571	3.448	3.333	39
40	4.760	4.544	4.347	4.166	3.999	3.846	3.703	3.571	3.448	3.333	40
41	4.760	4.544	4.347	4.166	4.000	3.846	3.703	3.571	3.448	3.333	41
42	4.760	4.544	4.347	4.166	4.000	3.846	3.704	3.571	3.448	3.333	42
43	4.761	4.545	4.347	4.166	4.000	3.846	3.704	3.571	3.448	3.333	43
44	4.761	4.545	4.347	4.166	4.000	3.846	3.704	3.571	3.448	3.333	44
45	4.761	4.545	4.347	4.166	4.000	3.846	3.704	3.571	3.448	3.333	45
46	4.761	4.545	4.348	4.166	4.000	3.846	3.704	3.571	3.448	3.333	46
47	4.761	4.545	4.348	4.166	4.000	3.846	3.704	3.571	3.448	3.333	47
48	4.761	4.545	4.348	4.167	4.000	3.846	3.704	3.571	3.448	3.333	48
49	4.761	4.545	4.348	4.167	4.000	3.846	3.704	3.571	3.448	3.333	49
50	4.762	4.545	4.348	4.167	4.000	3.846	3.704	3.571	3.448	3.333	50

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