FOR OFFICIAL USE ONLY

DESIGN DATA SHEET
DEPARTMENT OF THE NAVY
NAVAL SHIP ENGINEERING CENTER

1 October 1972
DDS 221-1
Supersedes DDS9520-1 dated 1 August 1969, w/Rev. dated 1 June 1971

DATA FOR ESTIMATING PRESSURE LOSSES IN ENGINE AND BOILER INLET AND EXHAUST SYSTEMS

Contents

A. References

1. "The Dynamics and Thermodynamics of Compressible Fluid Flow," Vol. I, Shapiro, A. H., Ronald Press, New York, Ch. 7, 1953.

2. "Subsonic Flow in a Duct of Constant Cross-Sectional Area," Smith, A. J. W. Journal Royal Aeronautical Society, Vol. 68, p. 117, Feb. 1966.

3. "A Generalized Approach to One-Dimensional Gas Dynamics," Benedict, R. P. and Steltz, W. G., Transactions ASME, Vol. 64, Journal of Engineering for Power, pp. 49-68, 1962.

4. "Testing of Gas Turbine High Velocity Duct Systems," Kelnhofer, W. J. and Smith, R. A., The Catholic University of America, Report for period 1 September 1964 to 31 August 1966, Contract NObs 92176, submitted to Naval Ship Engineering Center, Code 6436, 31 August 1966. AD 640 070

5. "Gas Tables," Keenan, J. H. and Kaye, J., Wiley & Sons, New York, 1948.
6. "Design of Power Plant Installations, Pressure Loss Characteristics of Duct Components," Henry, J. R., NACA ARR No. L4F26, 1944.
7. "The Flow and Pressure Losses in Smooth Pipe Bends of Constant Cross Section," Smith, A. J. W., Journal of the Royal Aeronautical Society, Vol. 67, p. 438, July 1963.
8. "A Study of the High-Speed Performance Characteristics of 90° Bends in Circular Ducts," Higginbotham, J. T., Wood, C. C., and Valentine, E. F., NACA TN 3696, June 1956.
9. "Review of Incompressible Diffuser Flow," Cockrell, D. J. and Markland, E., Aircraft Engineering, Vol. 35, p. 286, Oct. 1963.
10. "Performance and Design of Straight Two-Dimensional Diffusers," Reneau, L. R., Johnston, J. P. and Kline, S. J., ASME paper 66-FE-10, presented at ASME-EIC Fluids Engineering Conference, Denver, Colorado, April 1966.
11. "Performance Characteristics of Plane-Wall Two-Dimensional Diffusers," Reid, E. G., NACA TN 2888, 1953.
12. "An Experimental Investigation of Incompressible Flow in Conical Diffusers," McDonald, A. T. and Fox, R. W., ASME Paper 65-FE-25, presented at Applied Mechanics and Fluids Engineering Conference, Washington, D. C., June 7-9, 1965.
13. "The Effect of Tailpipe Addition to Straight-Walled Diffuser Performance with Fully Developed Inlet Conditions," C. T. Derick, Wm. J. Kelnhofer Mechanical Engineering Department, The Catholic University of America, Washington, D. C., August 1966.
14. "Vane Systems for Very-Wide-Angle Subsonic Diffusers," Feil, O. G., ASME Paper 64-FE-4, presented at Fluids Engineering Conference, Philadelphia, Pa., May 18-21, 1964.
15. "Splitter Effect in Conical Diffusers," Yang, T. T., Bulletin 103, Engineering Experiment Station, Clemson University, Clemson, South Carolina, 1965.
16. "An Investigation of Screens for Removing Distortions in Ducted Flow at High Subsonic Speed," Wood, C. C. and Knip, G. Jr., NACA RM L57G07, 1957.
17. "Losses in Flow Normal to Plane Screens," Cornell, W. G., Transactions ASME, p. 791, May 1958.

18. "Fan Engineering," edited by R. Jorgensen, Buffalo Forge Company, Buffalo, New York, 1961.

19. "Flow Losses in Abrupt Enlargements and Contractions," Benedict, R. P., Carlucci, N. A. and Smetz, S. D., ASME paper 65-WA/PTC-1, presented at the Winter Annual Meeting ASME, Chicago, Ill., November 1965.

20. "Fluid Flow Through Screens of Low Solidity," Morgan, P. G., Journal of the Royal Aeronautical Society, Vol. 66, page 54, January 1962.

21. "Fluid-Dynamic Drag," Hoerner, S. F., 1958.

B. Scope

This design data sheet is intended for use in estimating total and static pressure losses in the intake and exhaust duct systems of steam, diesel and gas turbine power plants where the Mach number is less than 0.4 throughout the system.

C. Definitions

1. Density. (#/ft^3) - The density of the gas is obtained from the state equation of a perfect gas.

$$\rho = \frac{p}{R_g T} = \frac{p}{53.3\,T}$$

2. Viscosity. The absolute (dynamic) viscosity of air as a function of temperature is given in Table 1. The data of Table 1 are selected from Reference 5.

3. Mass Flow Rate. The mass flow rate in #/sec is

$$m = \rho A V$$

4. Mach Number. The Mach number is defined as

$$M = \frac{V}{(kgR_g T)^{0.5}} = \frac{V}{49.02\,T^{0.5}} \qquad \text{(for } k = 1.4\text{)}$$

The denominator of this expression is known as the acoustic or sonic velocity, a, and is tabulated as a function of temperature in Table 1.

5. Dynamic pressure. The dynamic pressure or velocity pressure is defined as

$$q = \frac{\rho V^2}{2g} = \frac{\rho V^2}{64.4}$$

6. Total or Stagnation Properties,

   a. The stagnation pressure for incompressible flow is defined as $p_o = p + q$. For compressible flow the ratio p/p_o as a function of the Mach number is given in Table 2.

   b. The stagnation temperature T_o is defined as

$$T_o = T + \frac{V^2}{2 g_c c_p J} = T + .00001995 \frac{V^2}{c_p}$$

Where c_p is tabulated in Table 1 as a function of temperature. The ratio T/T_o as a function of the Mach number is given in Table 2.

7. Reynolds Number. The Reynolds number is defined as

$$Re = \rho \frac{VDh}{\mu}$$

8. Friction factor. Friction factor versus Reynolds number is presented in Figure 3. Typical values of absolute roughness, ϵ, are tabulated below.

Drawn tubing	0.000005
Commercial steel	0.00015
Wrought iron	0.00015
Galvanized sheet	0.0005
Wood stave	0.0006 - 0.003
Cast iron	0.00085
Concrete	0.001 - .01
Riveted steel	0.003 - .03

D. Symbols

The following symbols are used in this design data sheet.

List of Symbols

A - cross-sectional area of flow, ft.^{2}

Ao - area of orifice, ft.^{2}

Ar - area ratio of diffuser

C_p - diffuser pressure recovery coefficient

C_f - correction factor to incompressible friction pressure loss for compressibility effects

C_{L_m} = correction for upstream conditions

C_{L_d} = correction for downstream conditions

C_{Re} = correction for Reynolds number

$C_{b/w}$ = correction for aspect ratio

C_M = correction for effects of compressibility

C_s = correction for effects of vanes or splitters

$C_{\Delta A}$ = correction for effects of changing cross-sectional area

C_i = correction for the effects of non-fully-developed inlet flow

D - diameter of circular duct, ft.

D_h - hydraulic diameter = $4\ A/P$, ft.

E - width of obstruction, ft.

J - mechanical equivalent of heat = 778 ft. lbs/BTU

K - component pressure loss coefficient

L - Length of duct, ft.

L_d - Downstream duct length, ft.

L_m - Upstream duct length, ft.

M - Mach number = $V/a = V/(kgR_g T)^{0.5}$

N - axial length of diffuser or section of contracting area, ft.

P - wetted perimeter of duct, ft.

Re - Reynolds number = $\rho D_h V/\mu$

R_g - perfect gas constant for air = 53.3 $\frac{\text{ft.}}{^{o}R}$

R - elbow centerline radius, ft.

S - screen solidity = (blocked area)/A

T - absolute static temperature, ^{o}Rankine

T_o - absolute total temperature, ^{o}Rankine

V - velocity, ft/sec

a - acoustic velocity $[= kgR_g T]^{0.5}$ ft/sec

b - height of rectangular duct, ft.

c_p - specific heat (constant pressure), BTU/lb-^{o}R

c_v - specific heat (constant volume), BTU/lb-^{o}R

d - diameter of screen element, ft.

f - friction factor

g - acceleration of gravity = 32.2 ft/sec^2

k - ratio of specific heats = c_p/c_v

$\dot{m}$ - mass flow rate, lb/sec

n - station number, also function of relative radius

p - static pressure, lb/ft^2

p_o - total pressure, lb/ft^2

q - dynamic pressure, lb/ft^2

r_a - inside radius of elbow, ft.

v - specific volume, ft^3/lb

w - width of rectangular elbow in plane of bend, ft.

ϵ - absolute roughness of surface, ft.

φ - semi-vertex angle of diffuser or contraction, degrees

θ - turning angle of elbow or bend, degrees

μ - absolute (dynamic) viscosity, lb/ft-sec

ρ - density, lb/ft^3

Subscripts

1 or i - indicates inlet of a flow component

2 or e - indicates exit of a flow component

x - indicates larger end of converging or diverging flow component

y - indicates smaller end of converging or diverging flow component

E. General Design

1. The general procedure for performing the calculations is described in 9520-1-f, Detail Design and 9520-1-g, Method of System Calculation, of the report. The specific step by step calculation details are enumerated on worksheets contained in Appendix I. These worksheets are included for the dual purpose of clarifying and facilitating the computational procedure.

2. The data and procedures contained in this report are intended for use in systems where the Mach number is not greater than 0.4. For situations where higher Mach numbers occur, consult References 1, 2, and 3. Reference 4 contains an extensive list of general references for flow losses in duct systems. Reference 21 is a comprehensive source of practical data on Aerodynamic Drag and Hydrodynamic Resistance.

3. The chief distinction between the problem of calculating compressible and incompressible flow losses is the variation in density introduced by the pressure and temperature change. However, for low Mach numbers, a multiplicative correction to the results of incompressible flow is sufficient.

4. As a fluid flows through a duct system, pressure losses occur because of turbulence caused by changing the direction of flow or abruptly changing the ducting area, by friction between the fluid and the duct, or by a combination of both. In all cases though, the total head of the fluid, the sum of the

dynamic pressure and the static pressure, must decrease in the direction of flow as illustrated in Figures 1 and 2. The distinction between static and total pressure is important. Static pressure is conventionally used as the basis for system design, but the actual mechanical energy supplied by the system is determined by the total pressure. The change in total pressure occuring in a duct system is a measure of the duct efficiency.

5. Pressure loss calculations can be made based on total or static pressure loss. The difference is indicated on Figures 1 and 2 for typical duct systems. For incompressible flow one can write a pressure equation any two points in the duct system:

Exit total pressure + Losses = Entrance total pressure

$$q_1 + p_1 = q_2 + p_2 + (\text{Loss})_{1-2}$$

$$(\text{Total pressure loss}) = (\text{Loss})_{1-2} = (q_1 + p_1) - (q_2 + p_2)$$

$$(\text{Static pressure loss}) = (p_1 - p_2) = (q_2 - q_1) + (\text{Loss})_{1-2}$$

6. The properties of air are generally satisfactory for predicting the behavior of exhaust gases from steam, diesel and gas turbine power plants. This is particularly so for gas turbine exhaust gases, where approximately 80 percent of the originally available oxygen is still present. The values of the perfect gas constant (R_g) and the dynamic viscosity (μ) for typical diesel and boiler exhaust gases are approximately five percent lower than the values for air. Where situations warrant, appropriate values of R_g and μ should be used.

7. The pressure loss due to wall friction is reduced by heat transfer from the exterior surfaces of the duct system. The amount of pressure loss will be influenced by the rate of heat transfer, gas velocity, and temperature. Reductions in wall friction causing pressure losses of 10-25 percent are possible. The loss data presented in this report for straight ducting and elbows are for adiabatic (insulated) flow conditions. If it is desired to evaluate this effect References 1 and 4 should be consulted. From a practical point of view, this phenomenon can be neglected in those ducting systems where the pressure loss attributable to the straight duct sections is small. In those components where the pressure losses are primarily dynamic in nature, for example, elbows, the friction loss reduction for these components will be relatively small.

8. The data presented in this report were derived from the work of a number of independent investigators. Even in cases where all test conditions were known, it was not always possible to obtain exact correlation between

different investigators. The loss data for duct components reflects aerodynamically clean internal surfaces. Friction factors for ducting accounts only for drag caused by surface roughness. Friction loss in insulated ducts is greater than in uninsulated duct systems and all the loss data presented herein were not obtained under adiabatic (insulated) flow conditions. The agreement between estimated pressure drops and the actual pressure drops will, therefore, be dependent upon the appropriate application of the loss data contained in this report.

F. Detail Design

1. Pressure Loss in Straight Ducting.

a. The pressure loss, Δp, for compressible flow in straight ducting is found by correcting the pressure loss found for incompressible flow in the same ducting. The pressure loss for incompressible flow is determined by the Darcy-Weisbach formula. Thus,

$$\Delta p_{incomp} = f \times \frac{L}{D_h} \times q$$

Figure 3 gives f as a function of Re and ϵ/D

The pressure loss for incompressible flow is then determined by use of a correction factor C_f, where

$$\Delta p_{comp} = C_f \times \Delta p_{incomp}$$

C_f is given in Figure 4 as a function of friction factor, Mach number, and length of duct. The basis for C_f is discussed in Reference 4.

b. A detailed treatment of the procedure for determining compressible pressure losses may be found in References 2, 3, and 4.

c. The calculation sequence for straight ducts is detailed in Appendix I.

2. Elbows

a. The pressure loss due to flow through an elbow is dependent on many flow parameters and geometrical considerations, for example, turning angle, aspect ratio, vanes. The effective loss coefficient, K_{eff}, includes the total effect of these variables. K_{eff} is determined by correcting a loss coefficient, K, which is accurate for a standard set of conditions. Thus,

$$K_{eff} = K \times \left(C_{L_M} \times C_{L_d} \times C_{Re} \times C_M \times C_{b/w} \times C_s \times C_{\Delta A} \times C_i\right)$$

Where K = loss coefficient for aspect ratio of unity, fully-developed incompressible flow, Reynolds number of 1×10^5, with no vanes nor with any effects of the upstream or downstream conditions (See Figure 5). The correction for aspect ratio applies only to rectangular ducts.

K = standard loss coefficient for a constant flow area elbow (Figure 5)

C_{L_m} = correction for upstream conditions (Figure 6)

C_{L_d} = correction for downstream conditions (Figures 7a and 7b)

C_{Re} = correction for Reynolds number (Figure 8)

$C_{b/w}$ = correction for aspect ratio (Figure 9)

C_M = correction for effects of compressibility (Figure 10)

C_{SA} = correction for effects of changing cross-sectional area (Figure 11)

$C_{\Delta A}$ = correction for effects of changing cross-sectional area (Figure 12)

C_i = correction for effects of non-fully-developed flow into elbow (see below)

b. If the elbow is an entrance below, it behaves somewhat differently than that discussed above, which is for the case of fully-developed flow, i.e., an upstream duct length of approximately 40-50 duct diameters. For such an elbow, the correction for the effects of non-fully-developed flow is incorporated into the elbow loss coefficient by a factor C_i. A value of 1.3 is assumed for all elbows, Reference 18. This loss is in addition to entrance losses discussed in Entrance Sections, following.

c. The data of Figure 5 do not extend into the range of very small bend angles ($\theta < 15^\circ$). For such an elbow a linear interpolation can be made. That is,

$$K(\theta < 15^\circ) = K(\theta = 15^\circ)\frac{\theta}{15}$$

d. It is sometimes required to simultaneously achieve a change in flow area and a turning of the flow. This may be accomplished by a diffusing or accelerating elbow, that is, one in which the flow cross-section is changing. The loss coefficient for such an elbow can be found by utilizing the data of Figures 5 and 12 (see Reference 6). For non-rectangular ducts enter Figure 12 with an area ratio based on hydraulic diameter. In addition to the loss in pressure associated with friction and separation in an elbow, there is a pressure change due to the variation of cross-sectional area. This term is expressible by the continuity and Bernoulli equations as

$$\Delta p \text{ (Reduction)} = q_1 \left[\left(\frac{A_1}{A_2} \right)^2 - 1 \right]$$

e. These data on elbow losses are taken from References 4, 7 and 8.

f. The calculation sequence for elbows is detailed in Appendix I.

3. Diffusers - (gradual enlargement)

a. In terms of static pressure the diffuser results in a recovery or increase in static pressure. The recovery of pressure realized by a diffuser is predicted by a coefficient C_p, defined

$$C_p = \frac{\Delta p}{q_1}$$

where q_1 is the inlet dynamic pressure and Δp is the increase in static pressure obtained through the diffuser. Such a coefficient is found in Figure 13a and 13b by entering with the total expansion angle, 2ϕ, and the length parameter N/w (inlet) for the two-dimensional plane-walled diffuser or the length parameter N/D (inlet) for the conical diffuser. This recovery coefficient is for fully-developed flow and no downstream length of pipe. If a downstream length is added to the diffuser the recovery is increased. The increase is indicated by a correction factor in Figure 14. The data presented in Figures 13a and 13b are based on References 9, 10, 11, and 12. The data of Figure 14 are based on Reference 13.

b. Conditions of fully developed flow generally require upstream ducting lengths in excess of 40 pipe diameters. As the inlet length is reduced the diffuser pressure recovery progressively degenerates. At an inlet length which is a function of diffuser angle and Reynolds number this adverse trend reverses until at some lower value of duct length a situation will be reached when further reductions in duct length will have a beneficial effect on diffuser performance. An indication of the magnitude of this effect can be found in References 9 and 10.

As a guide to determining whether this effect is significant the following information extracted from Reference 9 is provided.

ΔCp

Diffuser Angle	L/D = 40	L/D = 30	L/D = 20	L/D = 5
5°	0.0	-0.005	0.005	0.0875
20°	0.0	-0.02	-0.075	-0.025

c. Maximum pressure recovery in a vaneless diffuser requires a small angle of divergence. As the divergence angle increases, separation and flow fluctuations will occur. If space limitations are such that the design would necessitate a diffuser operating above the line of optimum Cp (see line m-m of Figure 13a), the included angle of the diffuser should be increased to 60-75 degrees and vanes installed. References 14 and 15 provide design parameters for use in designing a vaned diffuser.

d. A correction for compressibility effects is given in Figure 15. The correction should be applied to the pressure recovery coefficient obtained from Figures 13a and 13b.

e. In the general case of area enlargement which is neither a conical nor plane-walled diffuser, and "Apparent" angle, 2φ, should be used as described below and presented graphically by Figure 18.

$$2\varphi = 2\,\mathrm{Tan}^{-1}\left[\frac{1}{2N}\left(A_y^{\frac{1}{2}} - A_x^{\frac{1}{2}}\right)\right]$$

Cp is then determined from Figure 13a. If the area enlargement is asymmetric, the recovery of pressure may be reduced by the more severe adverse pressure gradient in the asymmetric diffuser. Quantitative data are lacking in this area but based on limited test data in Reference 11 it appears that this effect is negligible for area ratios less than optimum. On this basis, values of Cp, as determined from Figure 13a, are below the optimum area ratio (line m-m), no correction for asymmetry is required. However, as the optimum area ratio is exceeded, plane-wall asymmetric diffusers rapidly exhibit a progressively lower value of Cp than obtained from Figure 13b.

f. The calculation sequence for diffusers is detailed in Appendix I.

4. Screens

a. The pressure loss across a screen placed normal to the flow is given by a coefficient K_s,

$$K_s = \frac{\Delta p}{q} = \frac{\Delta p}{\frac{V^2}{2g}} = \frac{\Delta p}{V^2/64.4}$$

where Δp is the pressure loss across the screen and V is the velocity in the plane of the screen elements. This coefficient is dependent on Reynolds number and the screen solidity, S, where

$$S = \frac{\text{Blocked Area}}{\text{Total Cross-Sectional Area}}$$

b. The coefficient K_s is found in Figures 16a and 16b, and a correction for compressibility effects is given in Figure 17. The above data are based on References 16, 17, and 20.

c. The calculation sequence for screens is detailed in Appendix I.

5. Gradual Contraction - Nozzles

a. The pressure loss across a nozzle or duct of gradual contraction is attributable to friction, reduction in flow cross-sectional area, and flow separation at the section of minimum area.

b. The loss attributable to friction may be calculated similarly to a straight duct, using an average dynamic pressure (average of inlet and exit values). The flow separation loss is not significant for any configuration with well rounded joints and small included angles and can be assumed to be zero. Even for sharp edged contractions, the separation loss is small enough to be neglected unless the "Apparent" contraction angle exceeds 30 degrees. For an angle greater than 30 degrees, calculate the flow separation loss by treating the contraction as a sudden contraction (see 8 following), which will be conservative.

c. The calculation sequence for gradual contraction is detailed in Appendix I.

6. Entrance Sections.

a. The pressure loss occurring at the entrance of a duct system should be computed by multiplying the entrance dynamic pressure by K_i. Thus

$$\Delta p = K_i q$$

where values of K_i are listed in Table 3.

b. The calculation sequence for entrance sections is detailed in Appendix I.

7. Sudden Enlargement

a. The loss of pressure associated with a sudden enlargement is

$$\Delta p = p_1 - p_2 = q_2 - q_1 + K_{q_1} = \left\{ K - \left[1 - \left(\frac{A_1}{A_2} \right)^2 \right] \right\} q_1$$

where $K = \left(1 - \frac{A_1}{A_2} \right)^2$

b. In terms of static pressure a sudden enlargement will result in an increase in static pressure.

c. A correction factor for Mach number effects is presented in Figure 19. These data are taken from Reference 19.

d. The calculation sequence for sudden enlargement is detailed in Appendix I.

8. Sudden Contraction.

a. The loss in pressure associated with a sudden contraction is

$$\Delta p = p_1 - p_2 = q_2 - q_1 + K_{q_2}$$

$$= \left\{ K + \left[1 - \left(\frac{A_2}{A_1} \right)^2 \right] \right\} q_2$$

where K is given as a function of D_{h_2}/D_{h_1} by Figure 20 and is based on the dynamic pressure at station 2.

b. In terms of static pressure a sudden contraction will result in a decrease in static pressure.

c. A correction factor for Mach number is presented in Figure 21. These data are taken from Reference 19.

d. The calculation sequence for sudden contraction is detailed in Appendix I.

9. Inlet Louvers

a. Although inlet louvers are often used, little pressure loss data are available. If loss data from previous installations are not available, the following method is suggested. The value of q in the following equation is based on the louver inlet free area. This approach assumes the louver loss to be composed of a sharp edge entrance loss plus the loss for a miter elbow exhausting to atmosphere.

$$\Delta p = K \times q$$

where

$$K = K_1 + K_2$$

$$K_1 = 0.5 \text{ (Sharp edge entrance section, Table 3)}$$

$$K_2 = K \times C_i \times C_{L_d} \times C_{b/w}$$

The appropriate values for K and $C_{b/w}$ can be obtained from Figures 5 and 9. Assume the following values for C_i and C_{L_d}

$$C_i = 1.3 \text{ (From paragraph 2b)}$$

$$C_{L_d} = 2.8 \text{ (From figure 7a)}$$

b. The calculation sequence for inlet louvers is detailed in Appendix I.

10. Obstructions and Blockages.

Losses resulting from partial blockages in ducts which are similar to orifices may be estimated using values of K obtained from Figure 23. Losses due to obstructions in ducts such as structure or pipes may be estimated using the value of K obtained from Figure 22. The losses are found from

$$\Delta p = Kq$$

E. Method of System Calculation

The method of calculating pressure loss used in this report is based on a calculation of static pressure change rather than irreversible static pressure loss. The static pressure change for each component of the system is summed to determine the overall static pressure change for the system. The sign convention is positive for decrease and negative for static pressure increases. Indicating n for the entrance and n + 1 for the exit, this gives for any component.

$$p_n = p_{n+1} + \text{Loss}_{n-(n+1)}$$

Summing these equations over the n components and straight duct lengths of the system under consideration, and denoting station 1, the entrance to the system by i, and denoting station n + 1, the exit from the system by e, one obtains

$$p_i = p_e + \text{Loss}_{1-2} + \text{---------}\Delta\ \text{Loss}_{n-(n+1)}$$

the Δ Loss terms being evaluated for each component.

Finally then,

$$p_i - p_e = \text{static pressure loss} = \Sigma\, \Delta\ \text{Loss}_{n-(n+1)}$$

The total pressure change is determined by use of the following equation:

$$\begin{aligned} p_{o_i} - p_{o_e} &= \text{total pressure loss} \\ &= p_i + q_i - p_e - q_e \\ &= \Delta p + q_i - q_e \end{aligned}$$

where Δp is the static pressure loss.

The calculations are based on an average system density based on a mean system pressure (for example, average of inlet and exit pressure). If the system static pressure loss and/or desired accuracy require, a series of average densities may be assumed, for example, one for each component. As a guide, for a system pressure loss of eight inches H_2O or less, use of the average density will produce an error of less than one percent.[2]

In determining the total pressure drop, the dynamic head based on actual conditions at entrance and exit should be used rather than the head based on the assumed average system pressure. If the difference between actual and assumed are significant, the actual dynamic pressure can be calculated using the following relationship

$$\text{for inlet or exit } q_{(\text{actual})} = q_{(\text{assumed})} \times \frac{p_{(\text{assumed})}}{p_{(\text{actual})}}$$

If the assumed average density is significantly greater than the average density based on the calculation the effect of this difference can be approximated by

$$\Delta p_{(\text{actual})} = \Delta p_{(\text{calculated})} \times \frac{p_{\text{ave (assumed)}}}{p_{\text{ave (calculated)}}}$$

The gas temperature assumed in the calculations will depend on the accuracy desired. Pressure loss is directly proportional to gas temperature.

TABLE 1

PROPERTIES OF AIR

T ° R	$\mu \times 10^7$ lb/sec-ft	a ft/sec	c_p Btu/#m-° R
500	118	1096	0.2396
550	126	1150	0.2399
600	135	1200	0.2403
650	143	1249	0.2409
700	151	1295	0.2416
750	158	1340	0.2424
800	166	1383	0.2434
850	173	1425	0.2444
900	179	1464	0.2458
950	186	1500	0.2471
1000	192	1539	0.2486
1050	199	1573	0.2501
1100	205	1611	0.2516
1150	212	1644	0.2531
1200	218	1679	0.2547
1250	224	1712	0.2563
1300	230	1743	0.2579
1350	236	1774	0.2594
1400	242	1805	0.2611
1450	248	1836	0.2625
1500	253	1865	0.2642
1550	259	1893	0.2656
1600	264	1922	0.2671

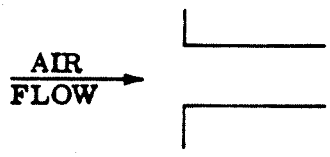
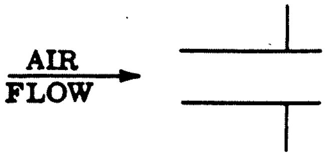
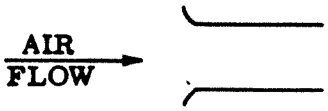
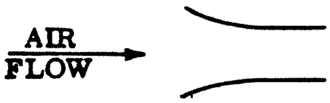
TABLE 2

PROPERTIES OF AIR
(k = 1.4)

M	p/p_o	T/T_o
0.10	0.99303	0.99800
0.11	0.99157	0.99758
0.12	0.98998	0.99714
0.13	0.98826	0.99664
0.14	0.98640	0.99610
0.15	0.98441	0.99552
0.16	0.98228	0.99490
0.17	0.98003	0.99425
0.18	0.97765	0.99356
0.19	0.97514	0.99283
0.20	0.97250	0.99206
0.21	0.96973	0.99125
0.22	0.96685	0.99041
0.23	0.96383	0.98953
0.24	0.96070	0.98861
0.25	0.95745	0.98765
0.26	0.95408	0.98666
0.27	0.95060	0.98563
0.28	0.94700	0.98456
0.29	0.94329	0.98346
0.30	0.93947	0.98232
0.31	0.93554	0.98114
0.32	0.93150	0.97993
0.33	0.92736	0.97868
0.34	0.92312	0.97740
0.35	0.91877	0.97608
0.36	0.91433	0.97473
0.37	0.90979	0.97335
0.38	0.90516	0.97193
0.39	0.90044	0.97048
0.40	0.89562	0.96899

TABLE 3

HEAD LOSS COEFFICIENTS FOR DUCT ENTRANCES

TYPE OF ENTRANCE	Ki
	0.50
	0.85
	0.25
	0.05

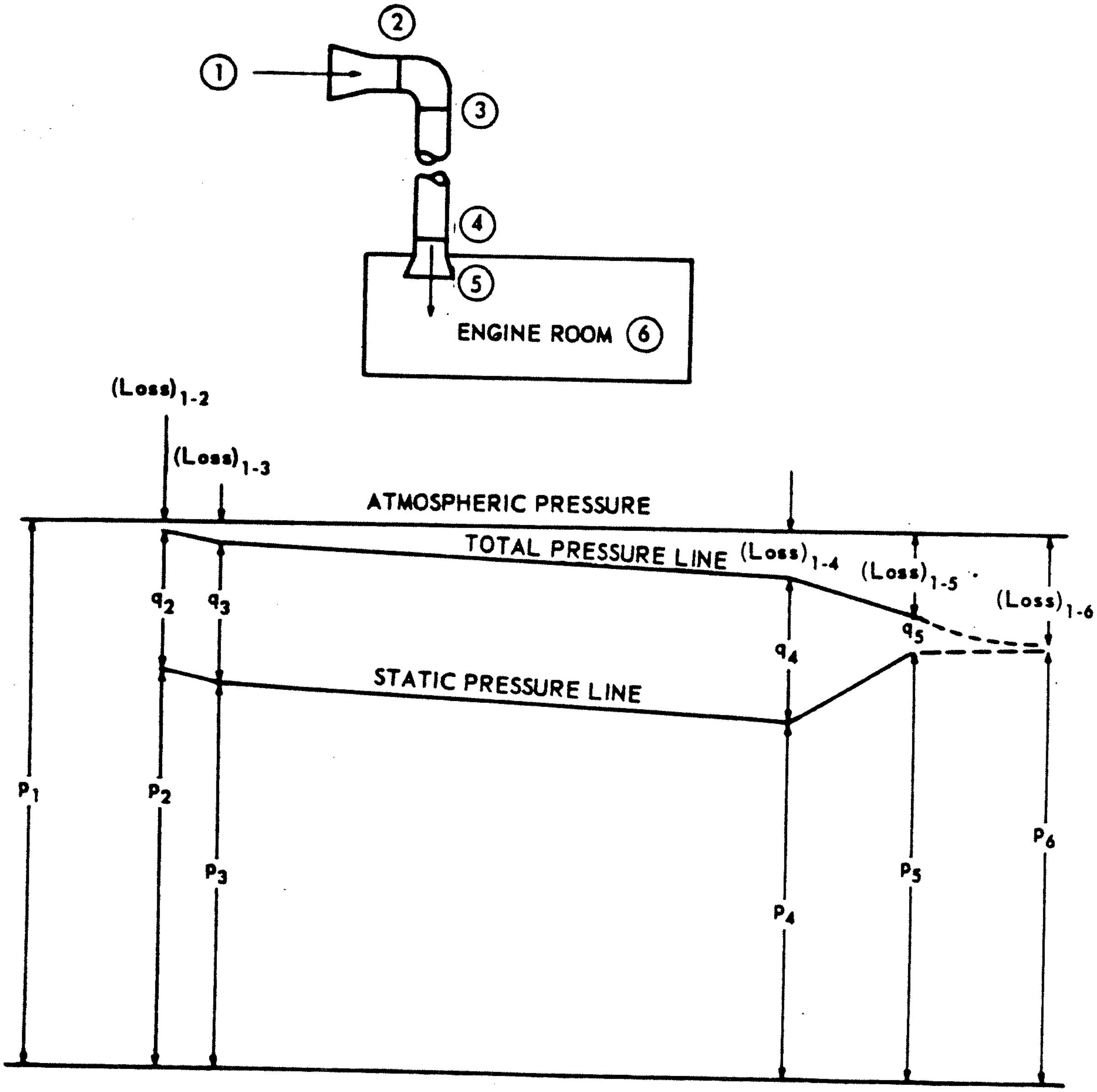

①
②
③
④
⑤
ENGINE ROOM ⑥
(Loss)1-2
(Loss)1-3
ATMOSPHERIC PRESSURE
TOTAL PRESSURE LINE
(Loss)1-4
(Loss)1-5
(Loss)1-6
q2
q3
q4
q5
STATIC PRESSURE LINE
P1
P2
P3
P4
P5
P6

FIGURE 1

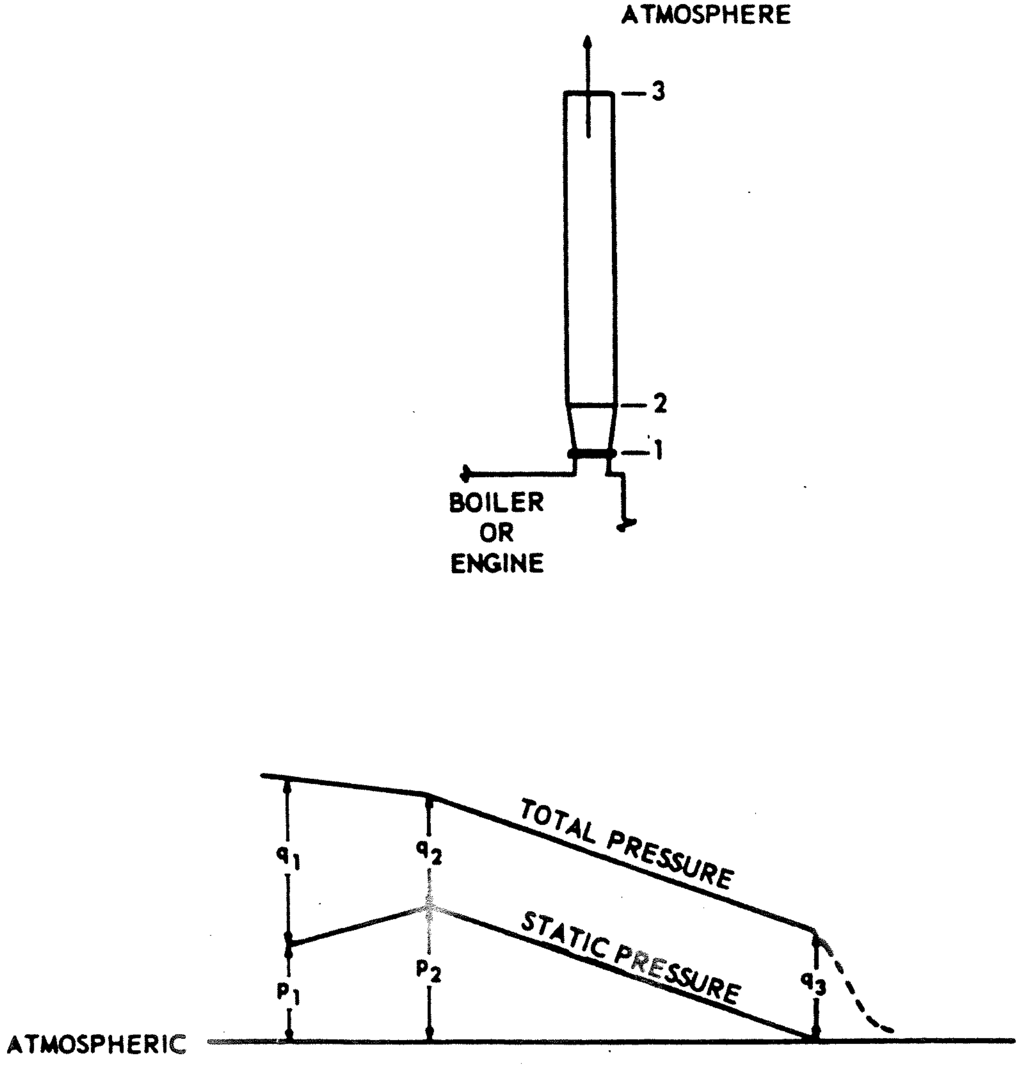

ATMOSPHERE
3
2
1
BOILER
OR
ENGINE
TOTAL PRESSURE
STATIC PRESSURE
q_1
q_2
q_3
p_1
p_2
ATMOSPHERIC

FIGURE 2

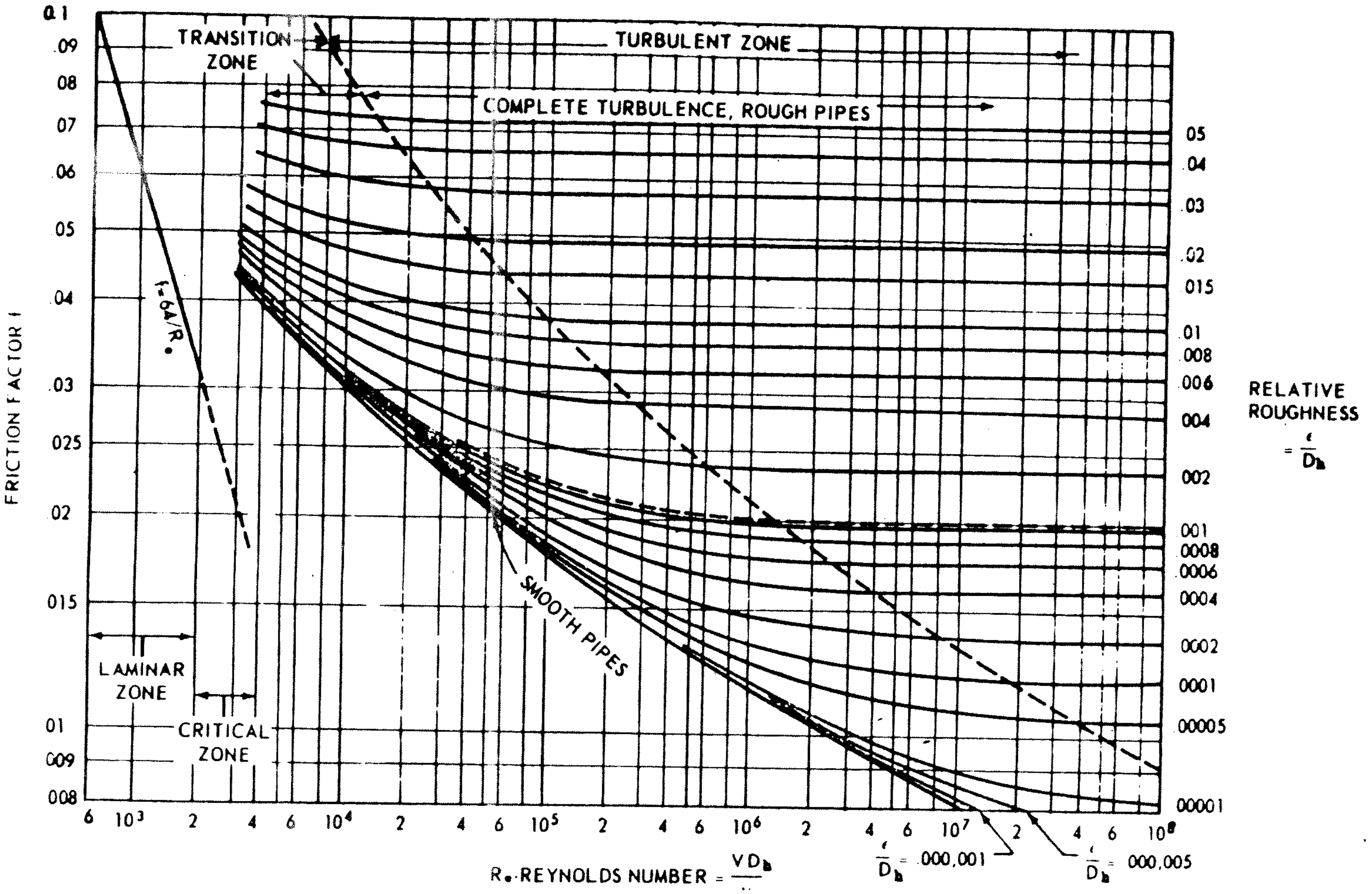


FIGURE 3

Ref: Friction Factors for Pipe Flow, L. Moody
Transactions A.S.M.E., Vol. 66, 1944, p. 671

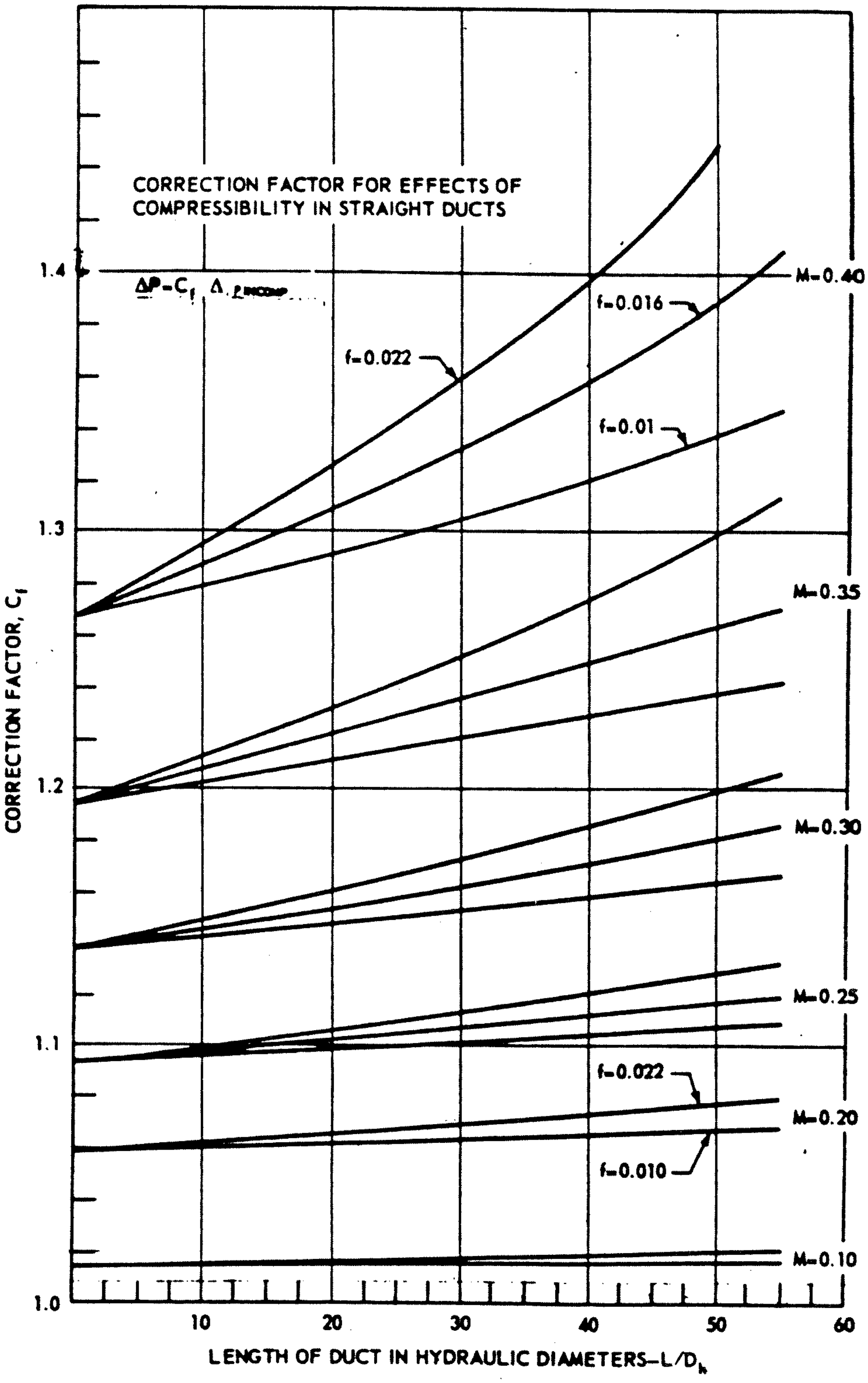

CORRECTION FACTOR FOR EFFECTS OF COMPRESSIBILITY IN STRAIGHT DUCTS
ΔP = C_f Δ P_INCOMP
f = 0.022
f = 0.016
f = 0.01
M = 0.40
M = 0.35
M = 0.30
M = 0.25
f = 0.022
M = 0.20
f = 0.010
M = 0.10
CORRECTION FACTOR, C_f
1.0
1.1
1.2
1.3
1.4
10
20
30
40
50
60
LENGTH OF DUCT IN HYDRAULIC DIAMETERS—L/D_h

FIGURE 4

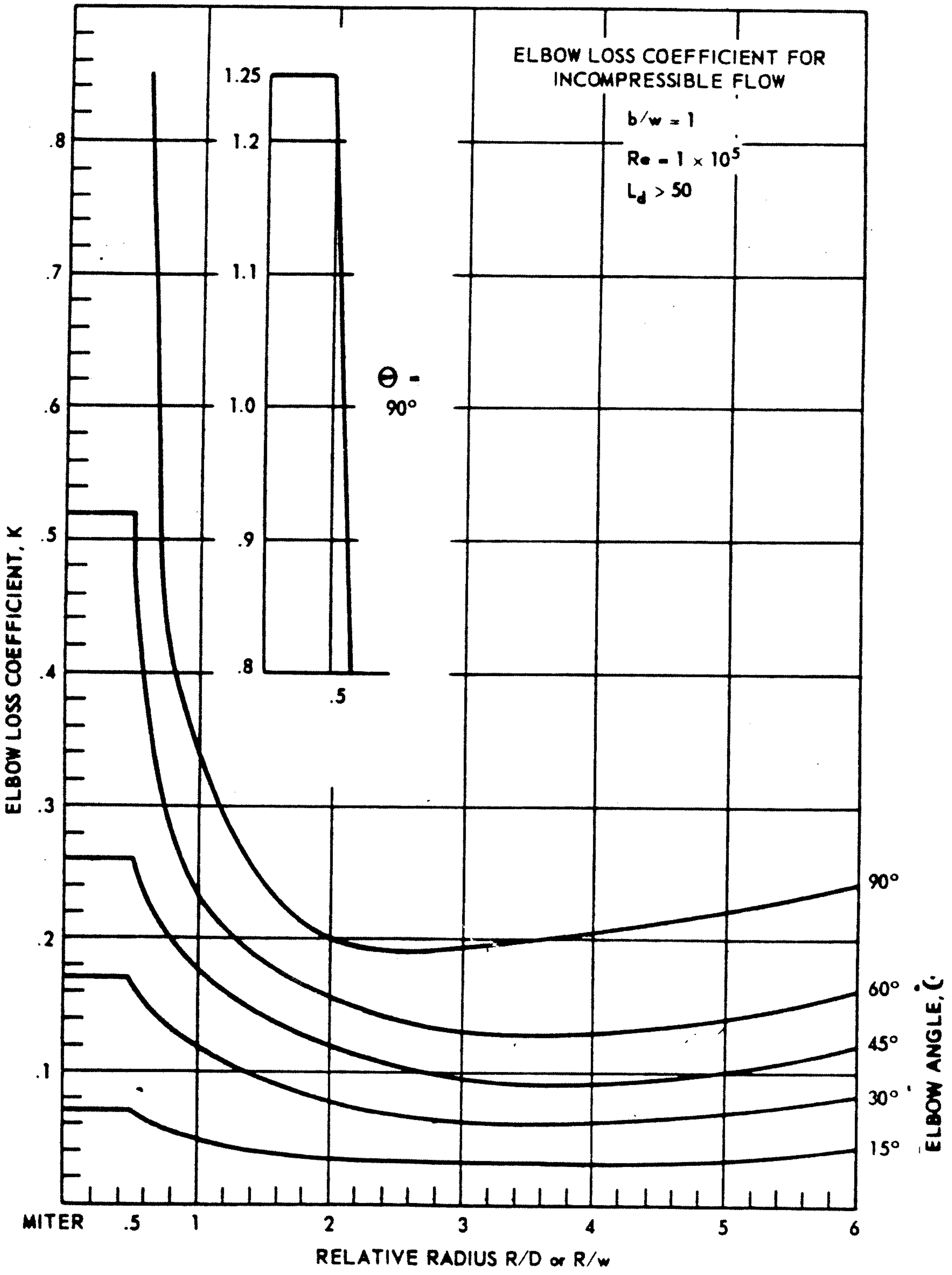

ELBOW LOSS COEFFICIENT FOR INCOMPRESSIBLE FLOW
b/w = 1
Re = 1 × 10^5
L_d > 50
Θ = 90°
1.25
1.2
1.1
1.0
.9
.8
.5
.8
.7
.6
.5
.4
.3
.2
.1
ELBOW LOSS COEFFICIENT, K
90°
60°
45°
30°
15°
ELBOW ANGLE, θ
MITER
.5
1
2
3
4
5
6
RELATIVE RADIUS R/D or R/w

FIGURE 5

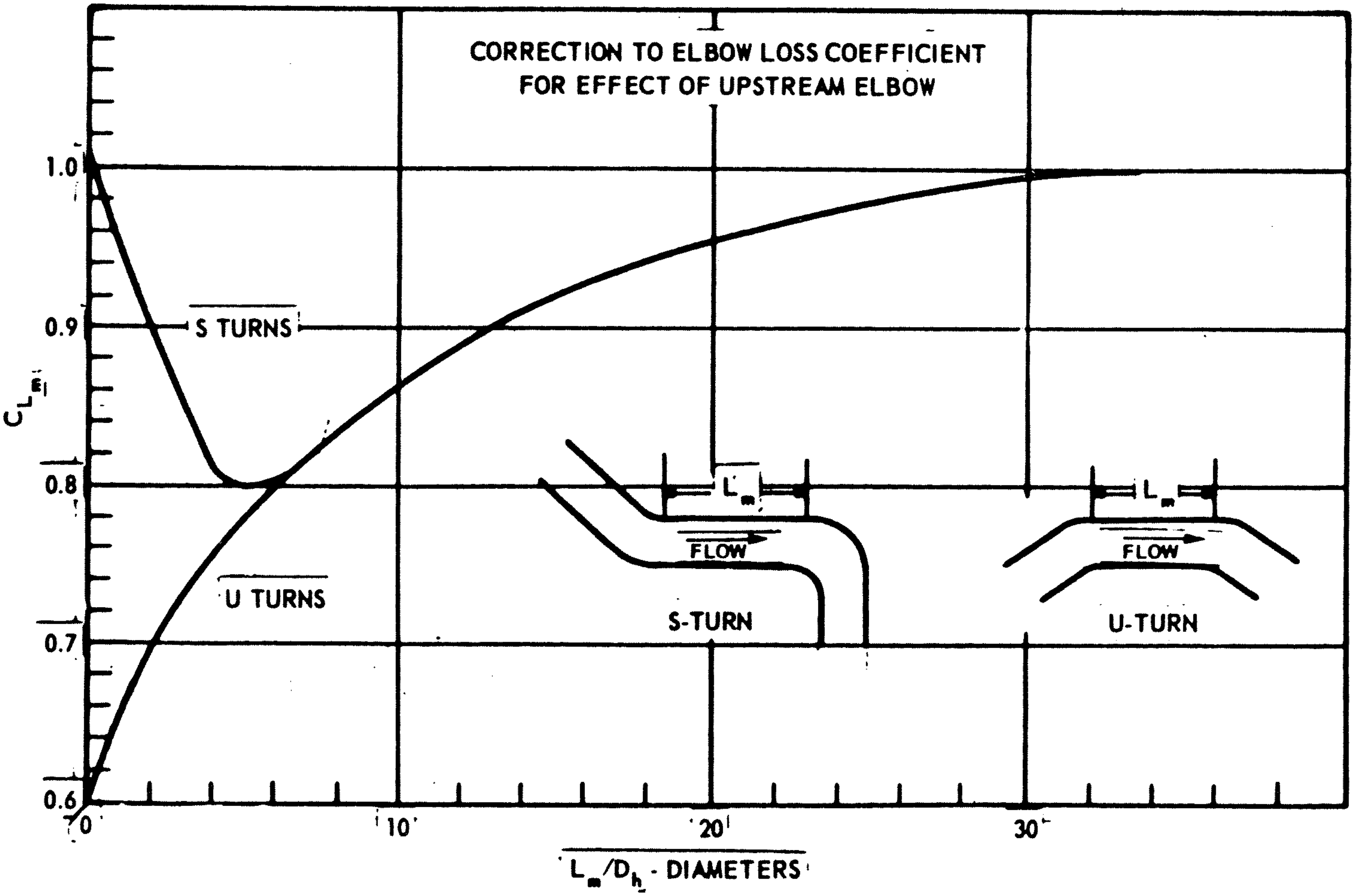

CORRECTION TO ELBOW LOSS COEFFICIENT
FOR EFFECT OF UPSTREAM ELBOW
1.0
0.9
0.8
0.7
0.6
$C_{L_{m1}}$
S TURNS
U TURNS
L_m
FLOW
S-TURN
U-TURN
0
10
20
30
L_m/D_h - DIAMETERS

FIGURE 6

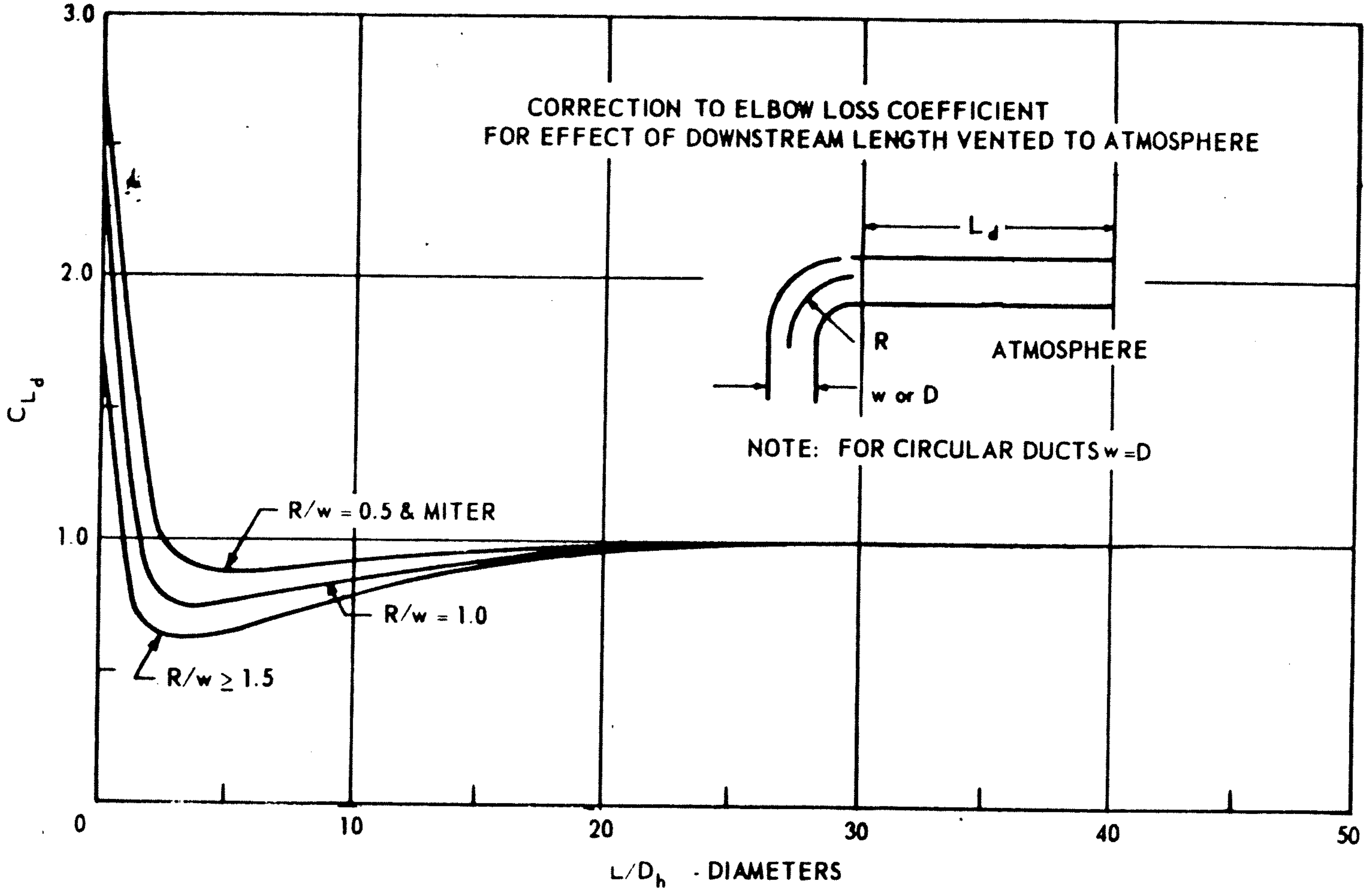

CORRECTION TO ELBOW LOSS COEFFICIENT
FOR EFFECT OF DOWNSTREAM LENGTH VENTED TO ATMOSPHERE
L_d
R
ATMOSPHERE
w or D
NOTE: FOR CIRCULAR DUCTS w = D
R/w = 0.5 & MITER
R/w = 1.0
R/w ≥ 1.5
C_{L_d}
3.0
2.0
1.0
0
10
20
30
40
50
L/D_h - DIAMETERS

FIGURE 7a

CORRECTION TO ELBOW LOSS COEFFICIENT FOR EFFECT OF DOWNSTREAM LENGTH WITH ANOTHER COMPONENT ADDED

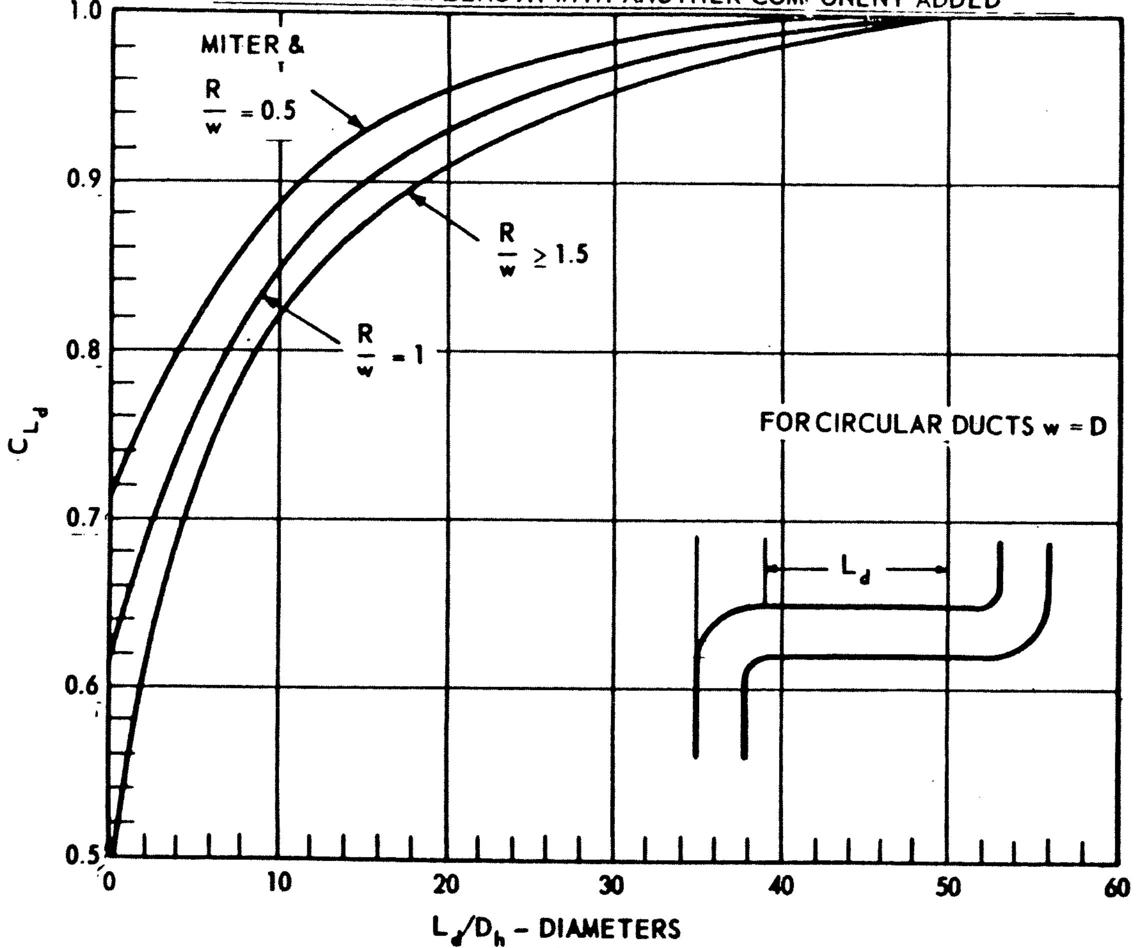


FIGURE 7b

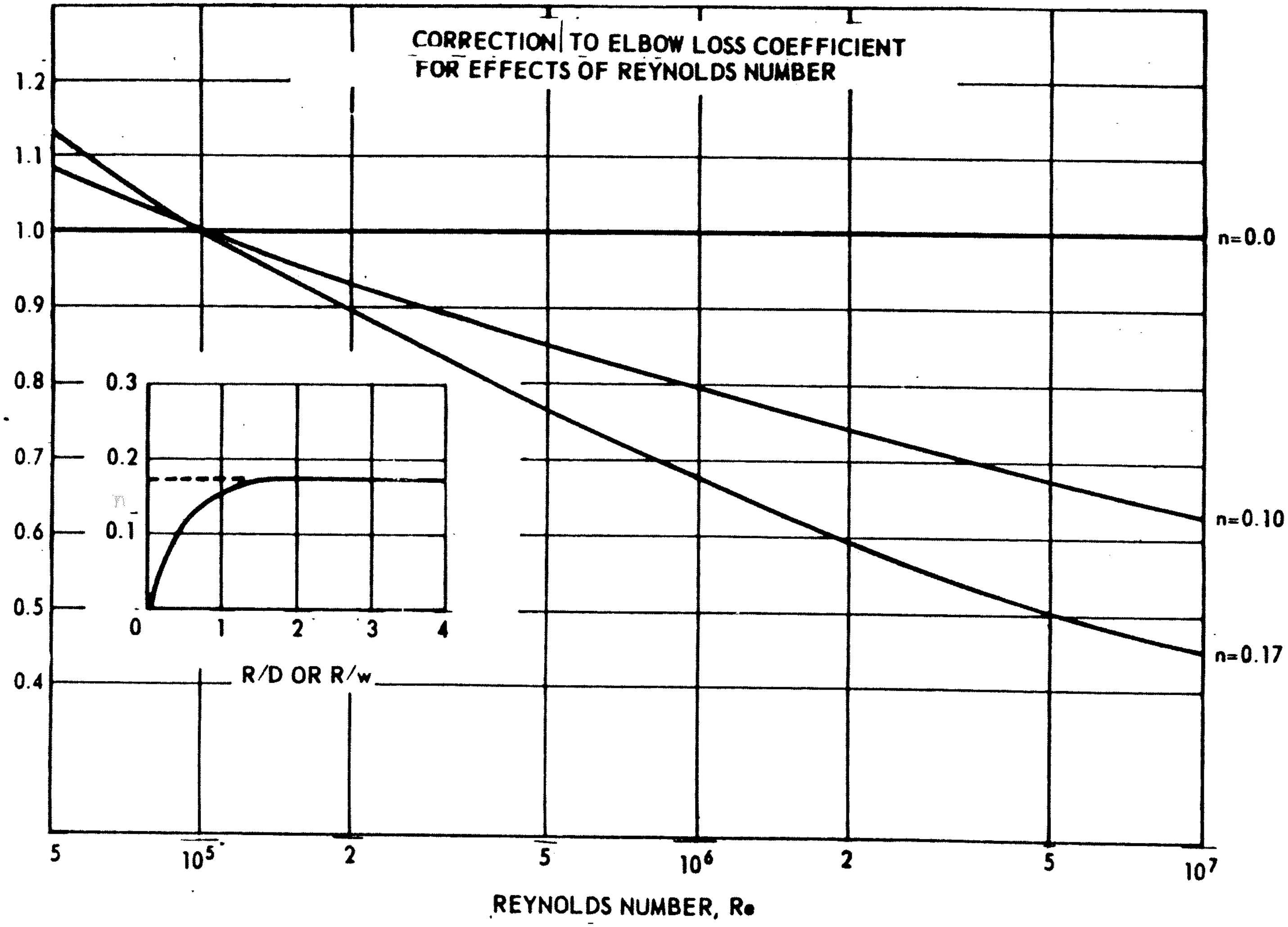

CORRECTION TO ELBOW LOSS COEFFICIENT
FOR EFFECTS OF REYNOLDS NUMBER
C_{Re}
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
n=0.0
n=0.10
n=0.17
0.3
0.2
0.1
0
1
2
3
4
R/D OR R/w
5
10^5
2
5
10^6
2
5
10^7
REYNOLDS NUMBER, Re

FIGURE 8

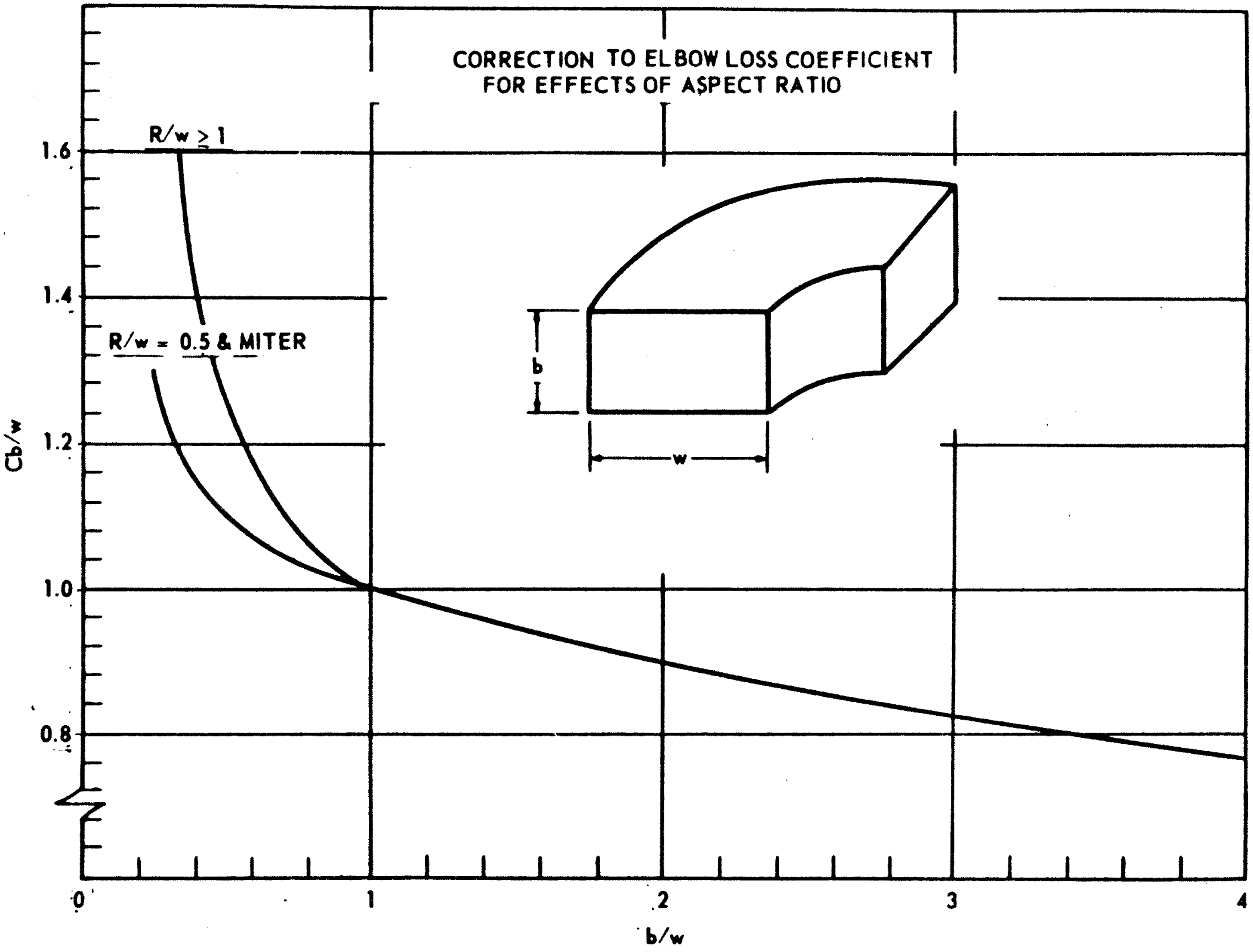

CORRECTION TO ELBOW LOSS COEFFICIENT
FOR EFFECTS OF ASPECT RATIO
R/w ≥ 1
R/w = 0.5 & MITER
b
w
Cb/w
1.6
1.4
1.2
1.0
0.8
0
1
2
3
4
b/w

FIGURE 9

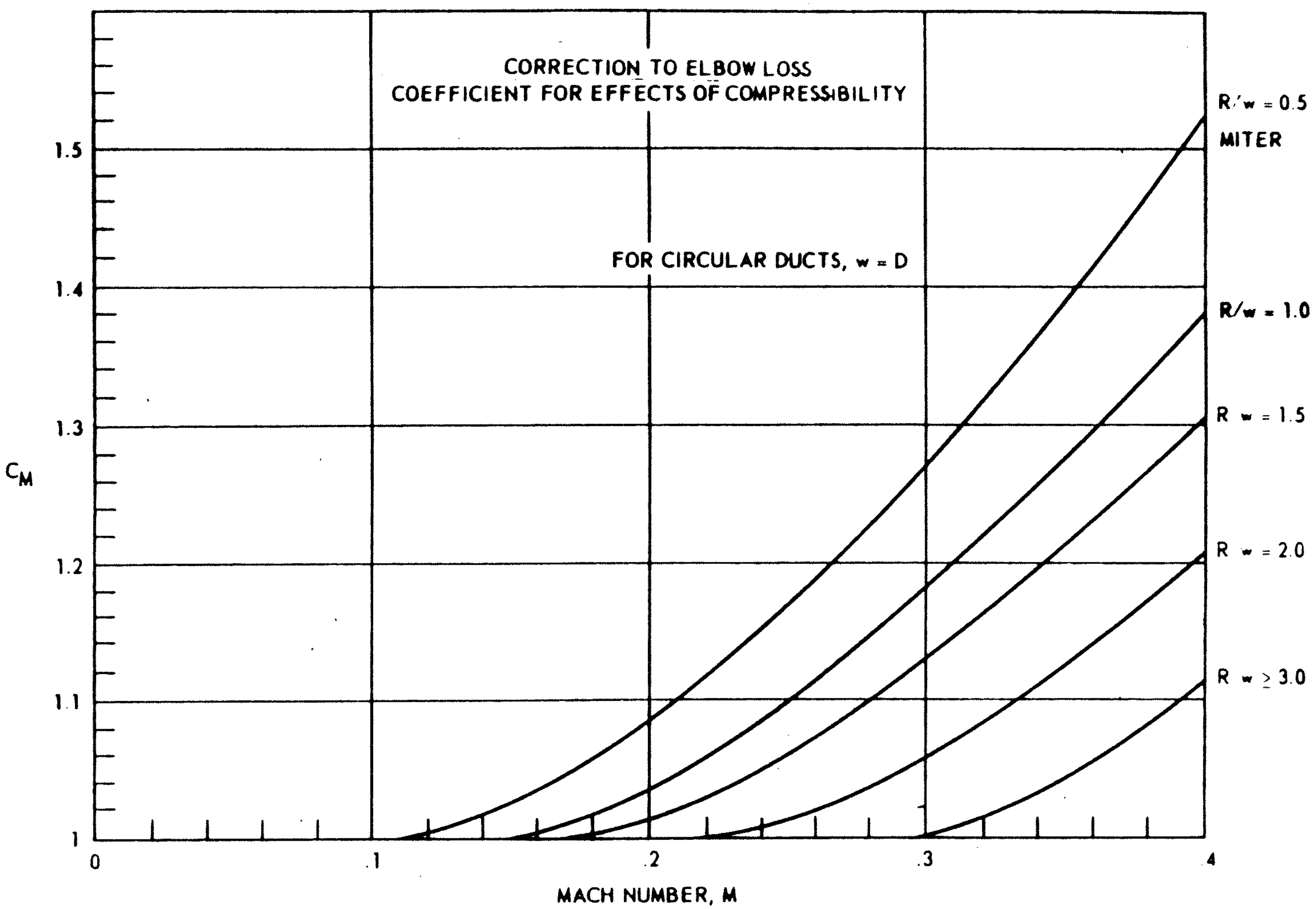

CORRECTION TO ELBOW LOSS
COEFFICIENT FOR EFFECTS OF COMPRESSIBILITY
FOR CIRCULAR DUCTS, w = D
R/w = 0.5
MITER
R/w = 1.0
R/w = 1.5
R/w = 2.0
R/w ≥ 3.0
C_M
1.5
1.4
1.3
1.2
1.1
1
0
.1
.2
.3
.4
MACH NUMBER, M

FIGURE 10

CORRECTION TO ELBOW LOSS COEFFICIENT FOR EFFECTS OF VANES OR SPLITTERS

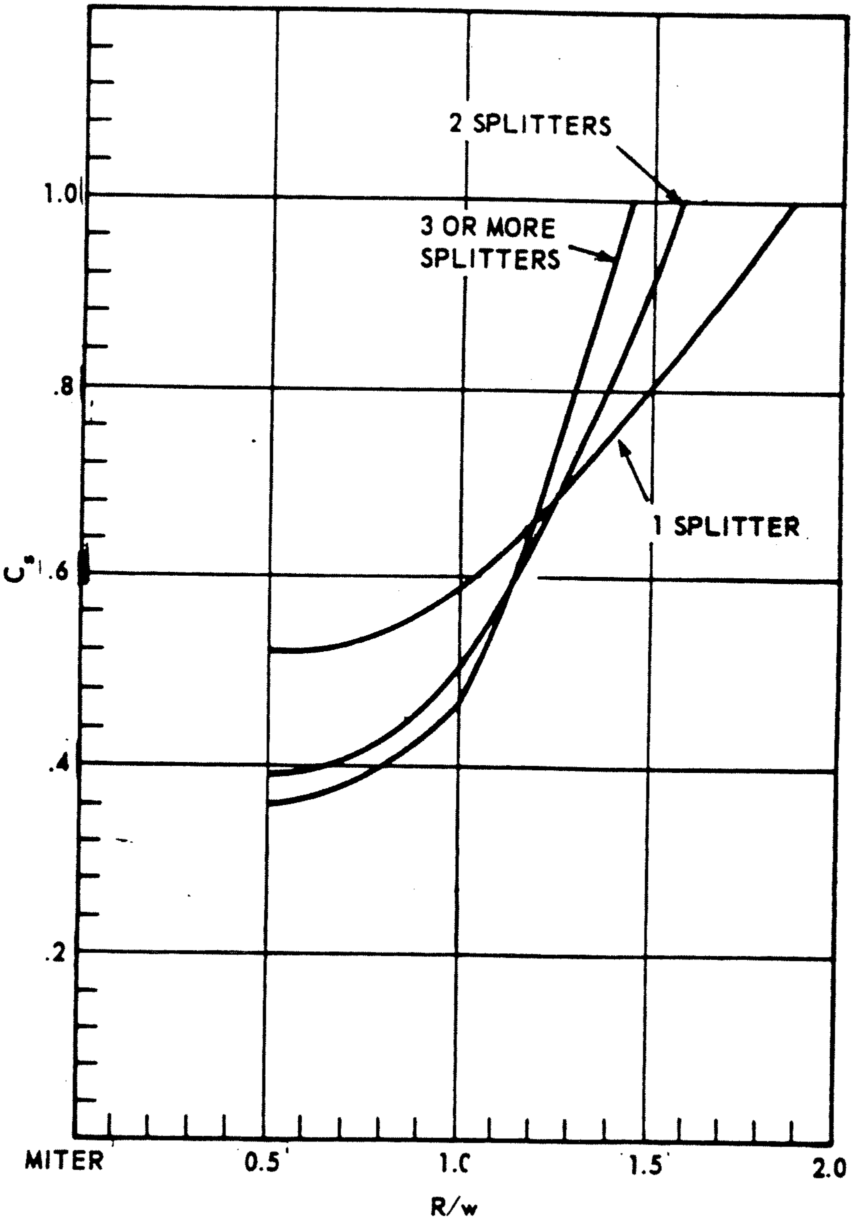


FIGURE 11

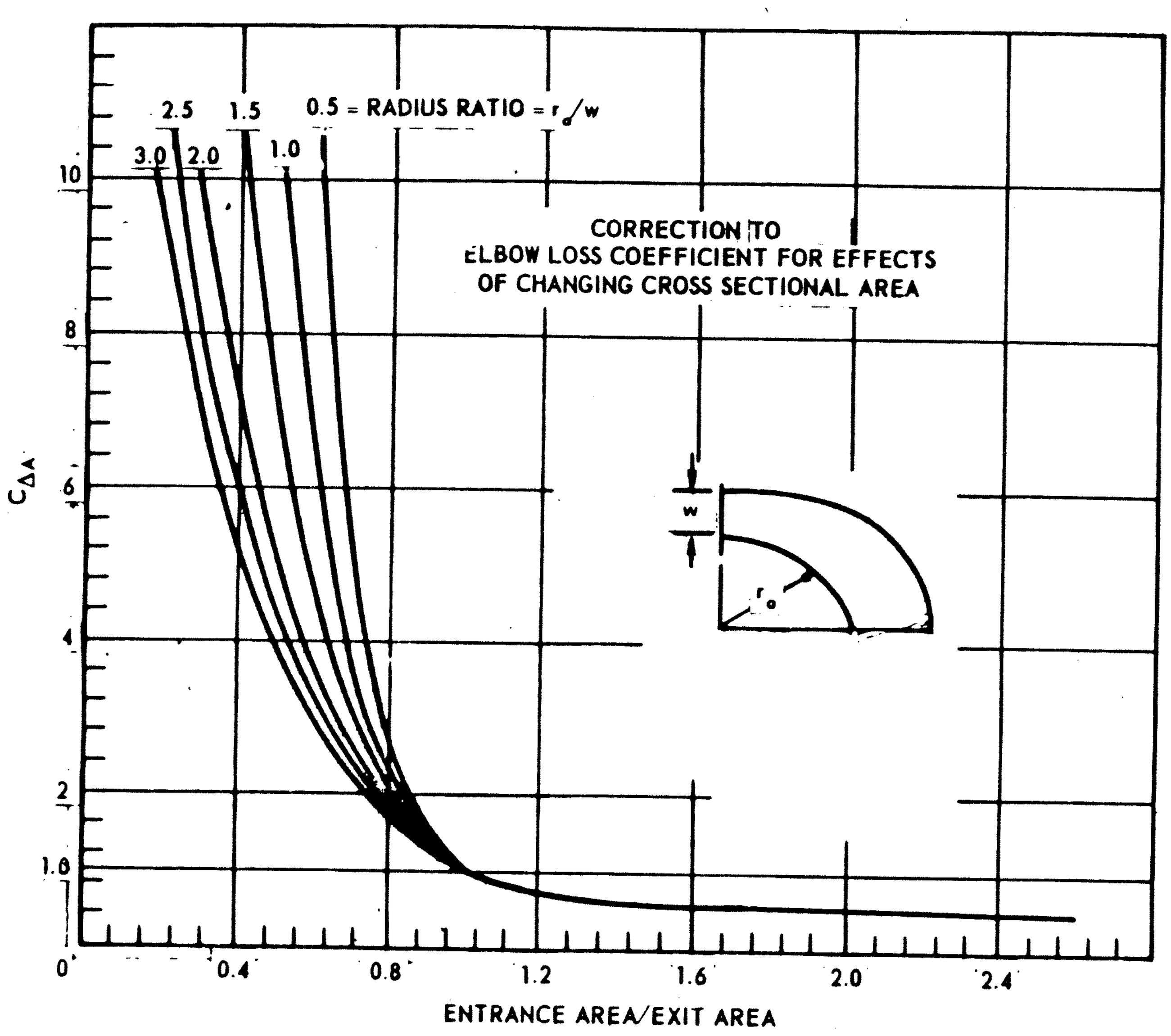

CORRECTION TO
ELBOW LOSS COEFFICIENT FOR EFFECTS
OF CHANGING CROSS SECTIONAL AREA
2.5
1.5
0.5 = RADIUS RATIO = r_o/w
3.0
2.0
1.0
$C_{\Delta A}$
10
8
6
4
2
1.0
0
0.4
0.8
1.2
1.6
2.0
2.4
ENTRANCE AREA/EXIT AREA
w
r_o

FIGURE 12

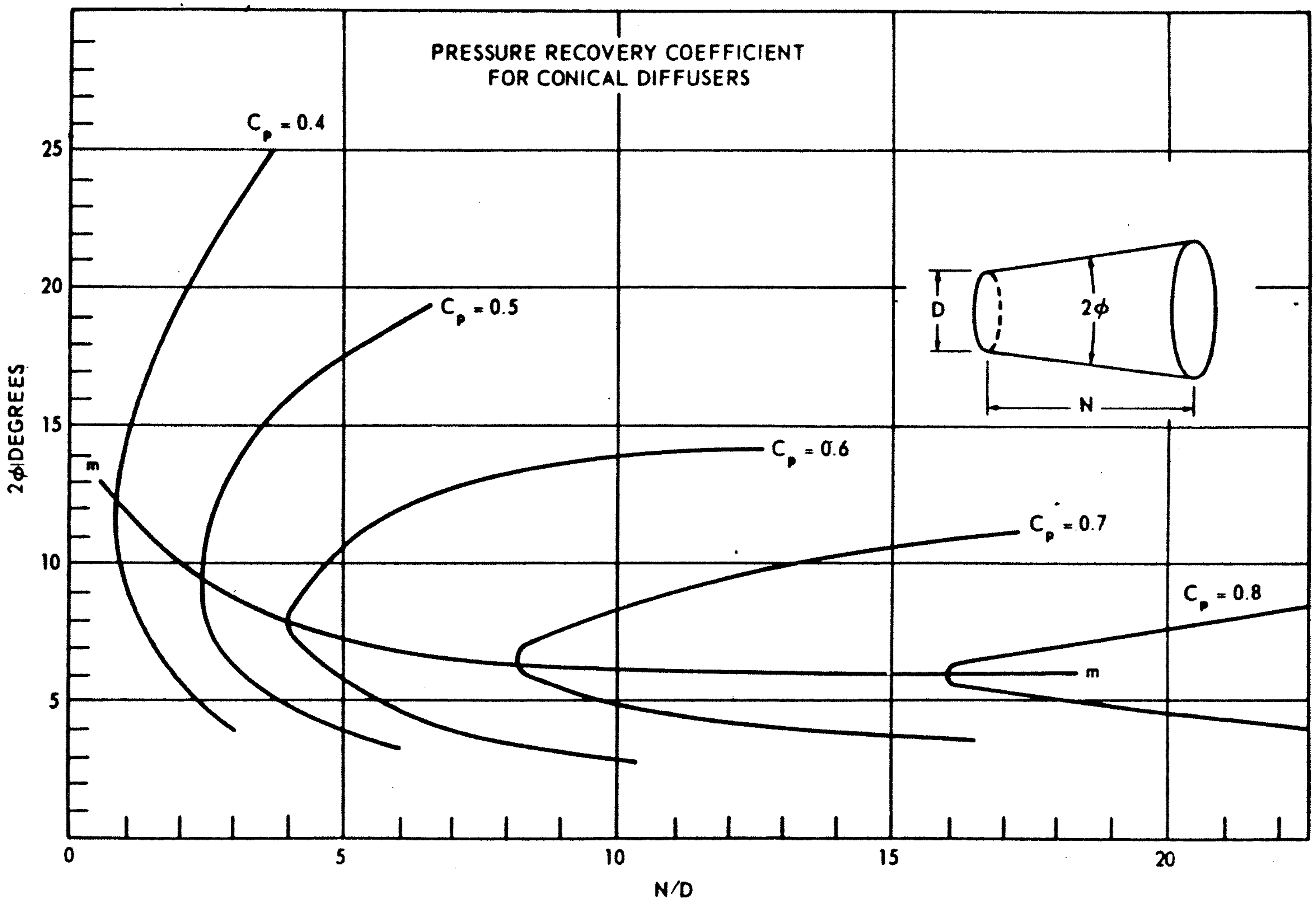

PRESSURE RECOVERY COEFFICIENT
FOR CONICAL DIFFUSERS
$C_p = 0.4$
$C_p = 0.5$
$C_p = 0.6$
$C_p = 0.7$
$C_p = 0.8$
m
m
D
2φ
N
2φ DEGREES
25
20
15
10
5
0
5
10
15
20
N/D

FIGURE 13a

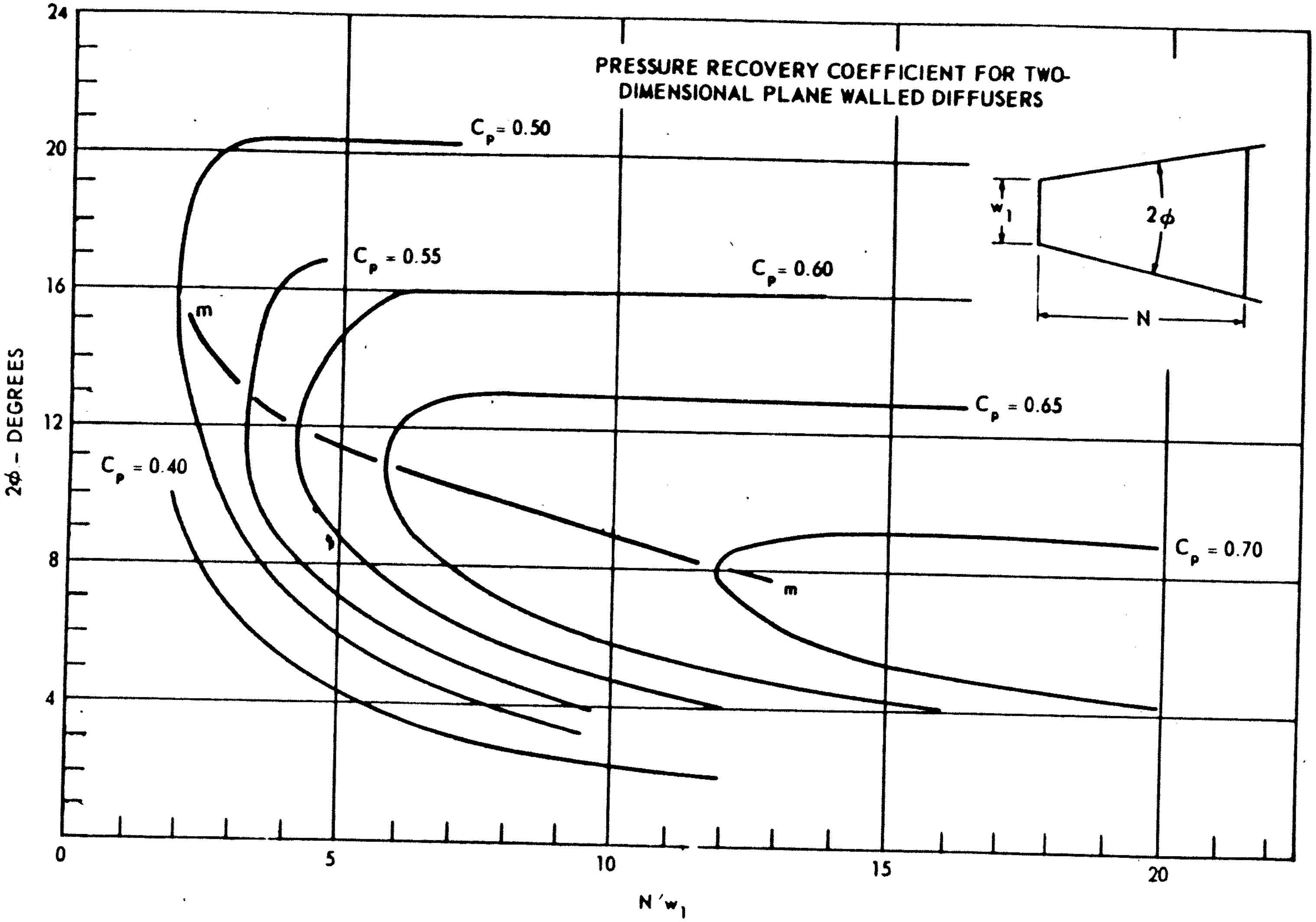

PRESSURE RECOVERY COEFFICIENT FOR TWO-DIMENSIONAL PLANE WALLED DIFFUSERS
C_p = 0.50
C_p = 0.55
C_p = 0.60
C_p = 0.65
C_p = 0.70
C_p = 0.40
m
m
2ϕ - DEGREES
24
20
16
12
8
4
0
5
10
15
20
$N'w_1$
w_1
2ϕ
N

FIGURE 13b

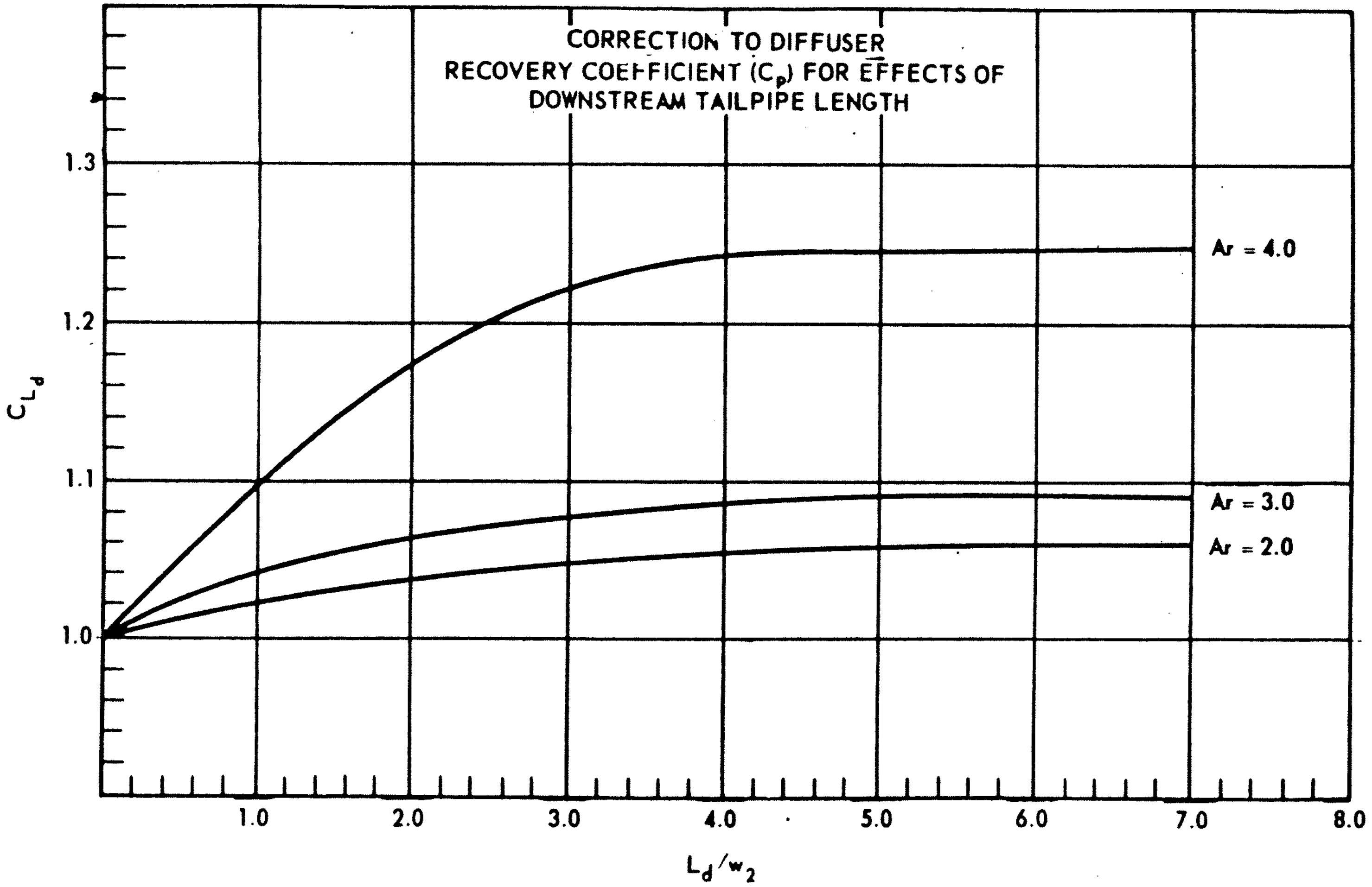
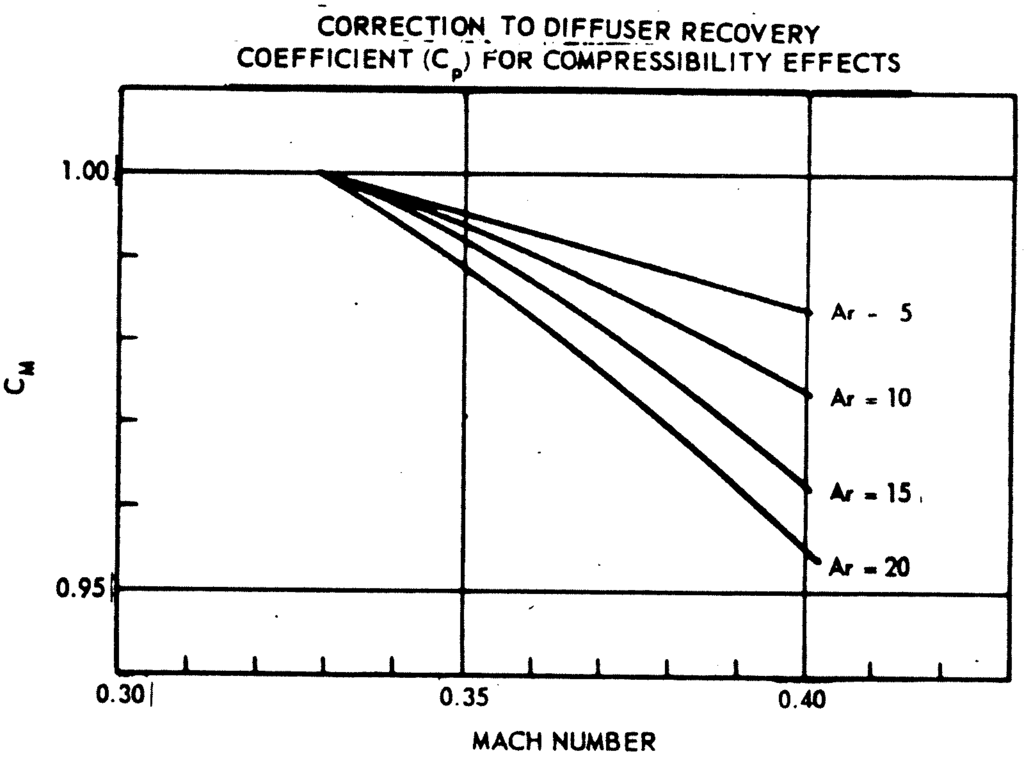

CORRECTION TO DIFFUSER
RECOVERY COEFFICIENT (C_p) FOR EFFECTS OF
DOWNSTREAM TAILPIPE LENGTH
C_{L_d}
1.3
1.2
1.1
1.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
L_d/w_2
Ar = 4.0
Ar = 3.0
Ar = 2.0

FIGURE 14



CORRECTION TO DIFFUSER RECOVERY COEFFICIENT (C_p) FOR COMPRESSIBILITY EFFECTS

FIGURE 15

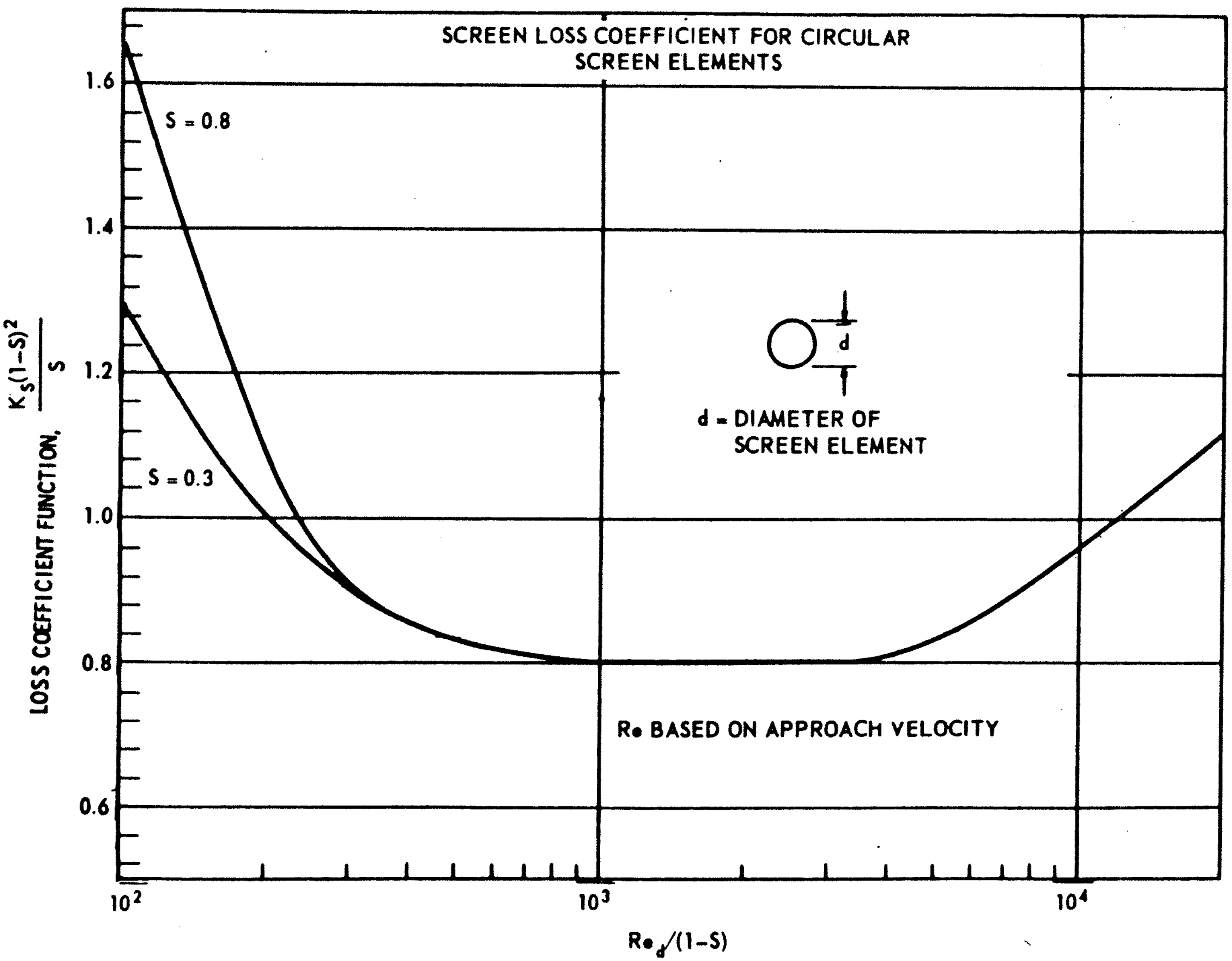

SCREEN LOSS COEFFICIENT FOR CIRCULAR SCREEN ELEMENTS
S = 0.8
S = 0.3
d
d = DIAMETER OF SCREEN ELEMENT
Re BASED ON APPROACH VELOCITY
LOSS COEFFICIENT FUNCTION, $\frac{K_S(1-S)^2}{S}$
1.6
1.4
1.2
1.0
0.8
0.6
10^2
10^3
10^4
$Re_d/(1-S)$

FIGURE 16a

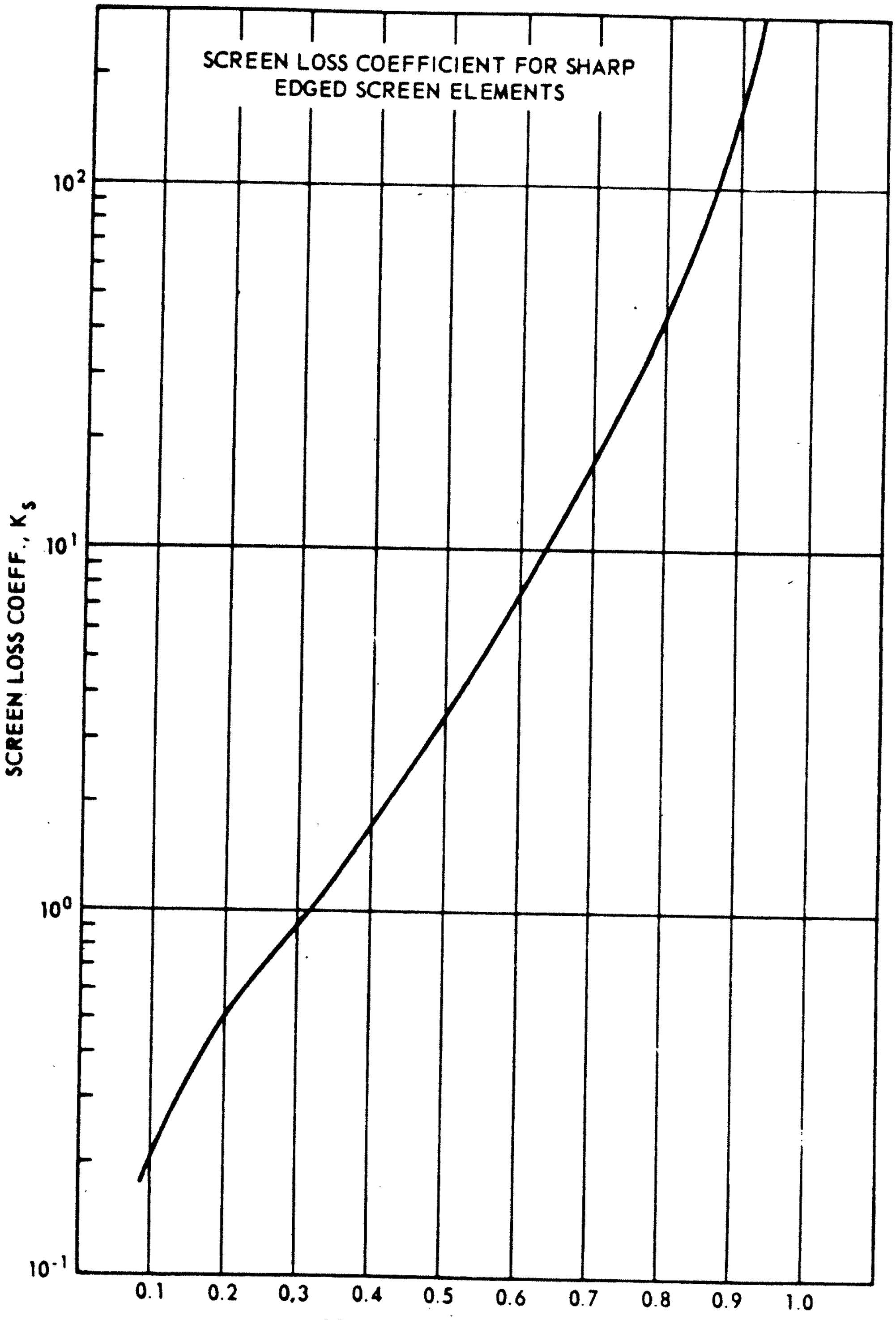

SCREEN LOSS COEFFICIENT FOR SHARP EDGED SCREEN ELEMENTS
SCREEN LOSS COEFF., K_S
10²
10¹
10⁰
10⁻¹
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SCREEN SOLIDITY, S

FIGURE 16b

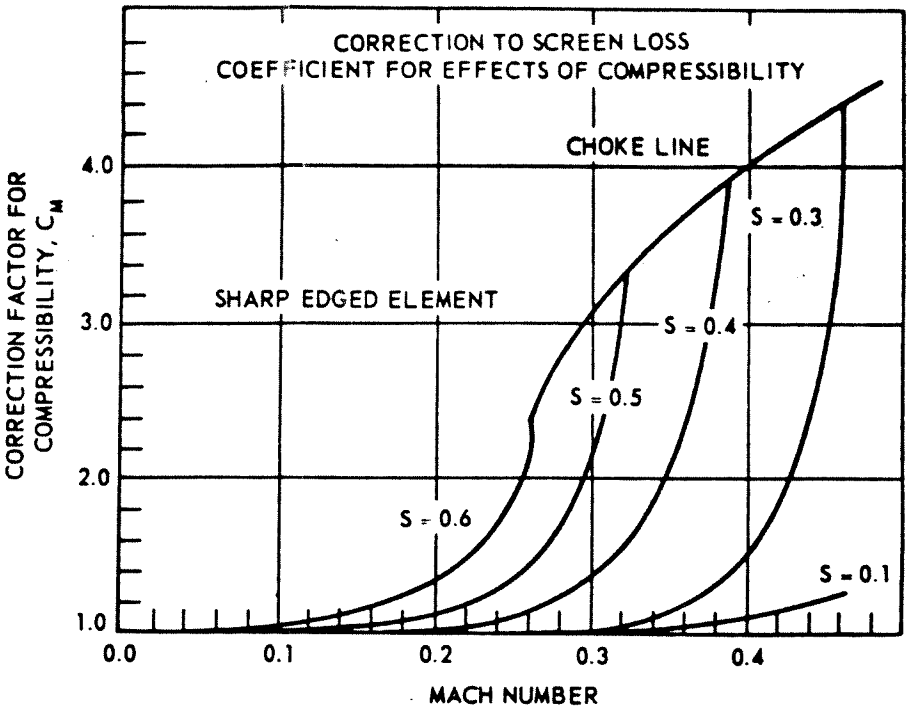


FIGURE 17b

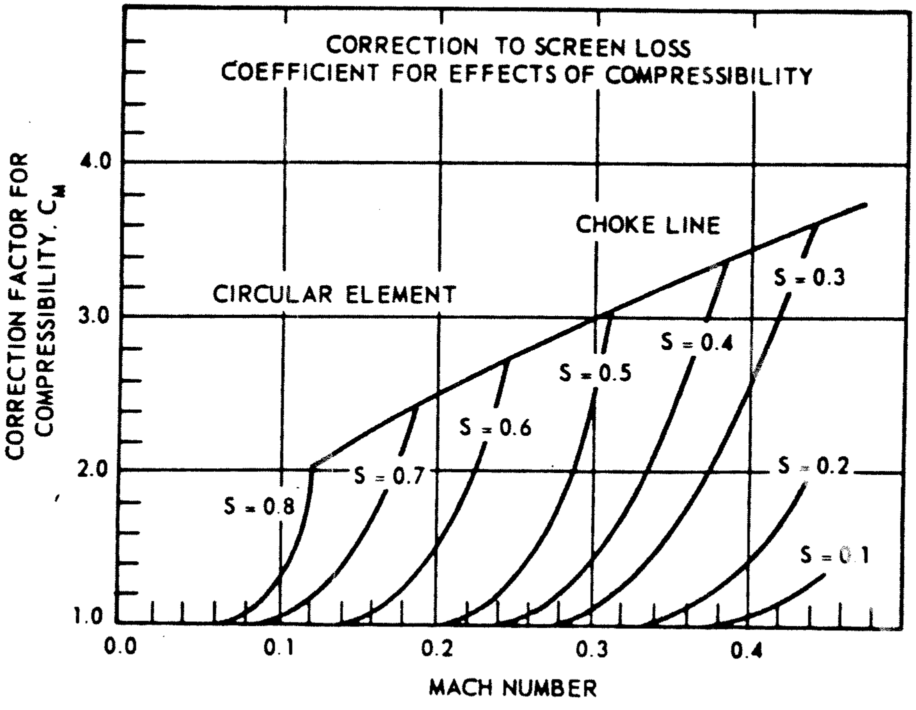


FIGURE 17a

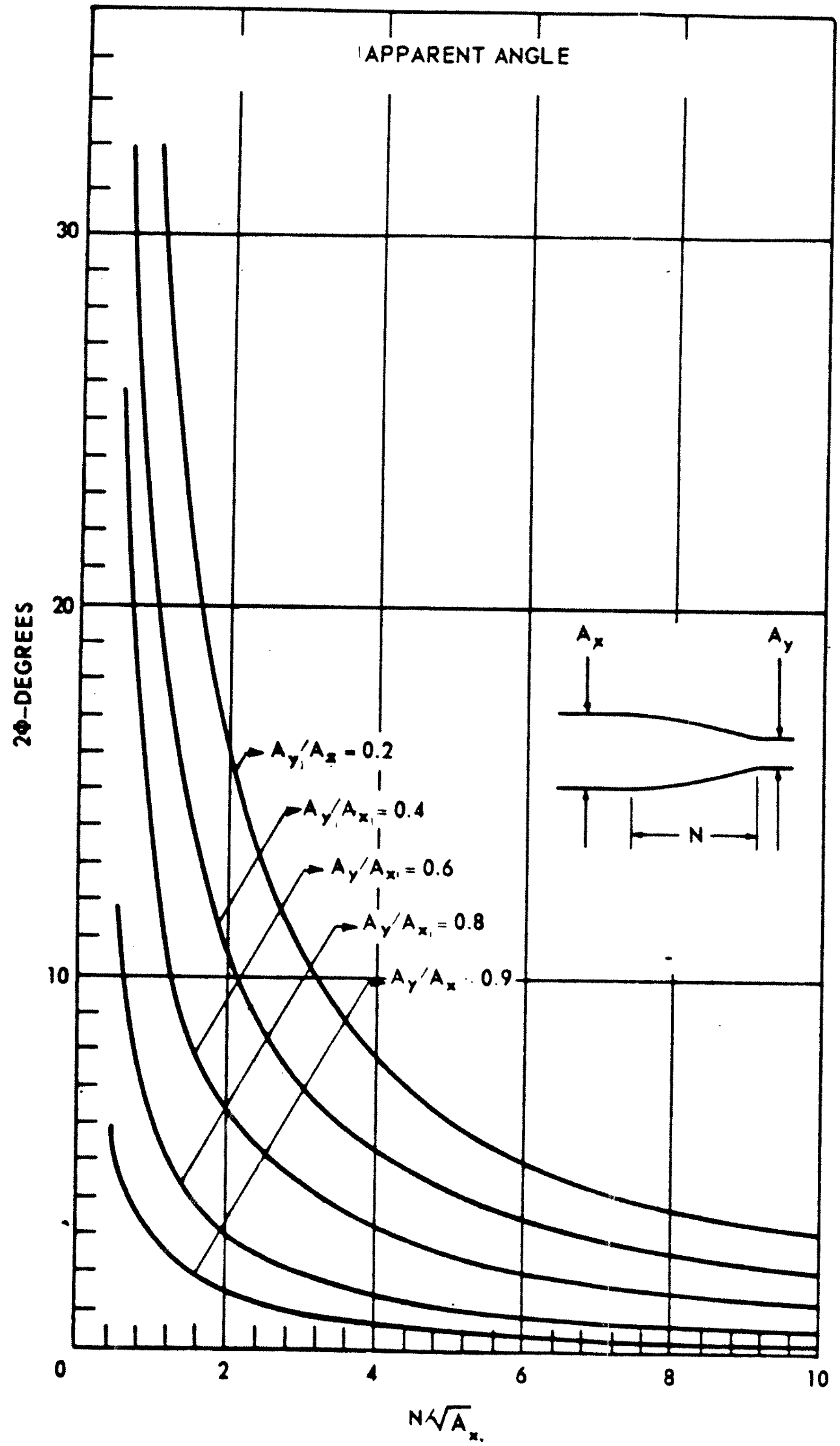

APPARENT ANGLE
2Φ–DEGREES
0
10
20
30
2
4
6
8
10
$N/\sqrt{A_x}$
A_x
A_y
N
$A_y/A_x = 0.2$
$A_y/A_x = 0.4$
$A_y/A_x = 0.6$
$A_y/A_x = 0.8$
$A_y/A_x = 0.9$

FIGURE 18

COMPRESSIBILITY CORRECTION
FOR SUDDEN EXPANSION, C_M

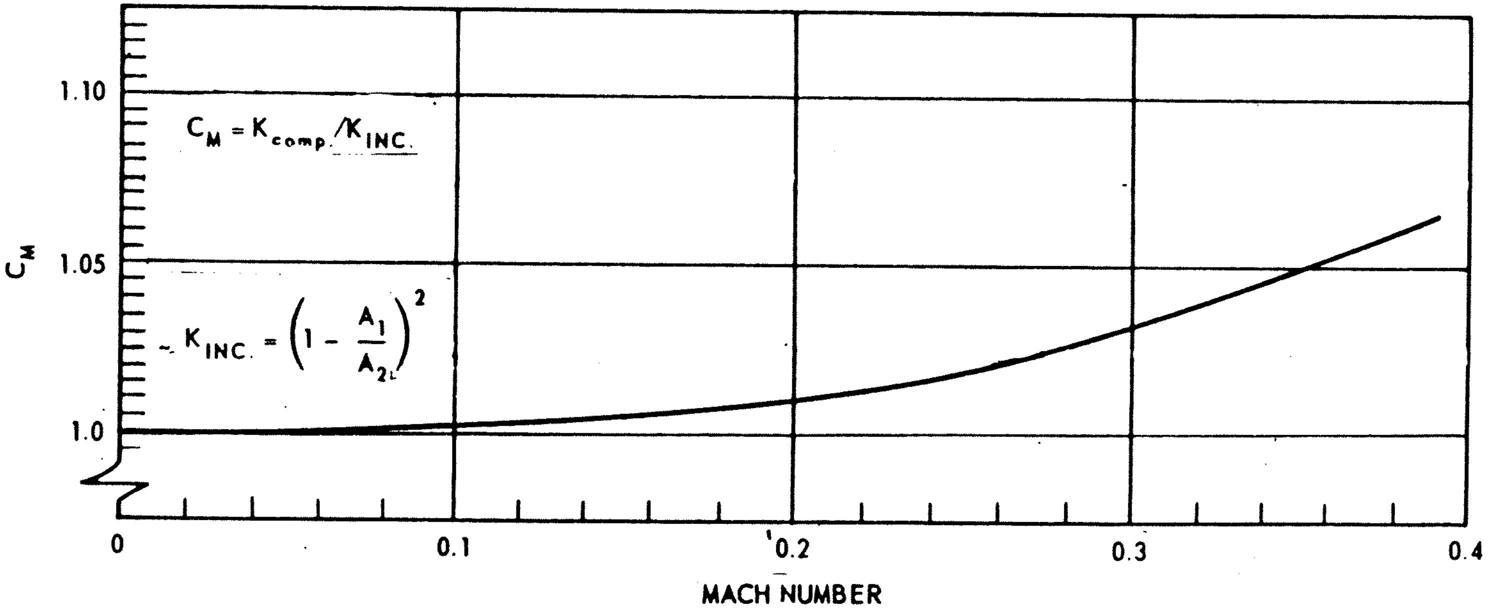


FIGURE 19

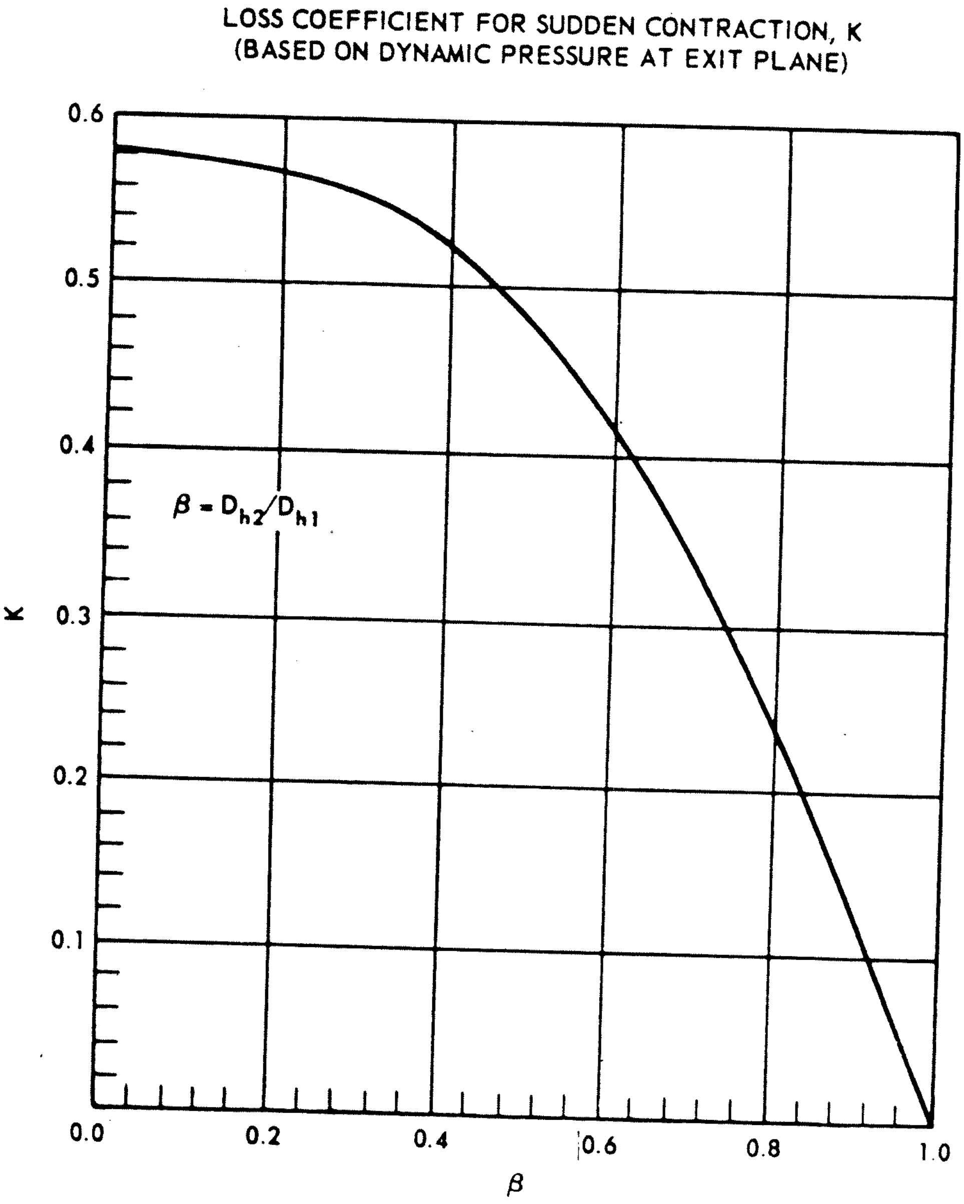

LOSS COEFFICIENT FOR SUDDEN CONTRACTION, K
(BASED ON DYNAMIC PRESSURE AT EXIT PLANE)
0.6
0.5
0.4
0.3
0.2
0.1
K
$\beta = D_{h2}/D_{h1}$
0.0
0.2
0.4
0.6
0.8
1.0
β

FIGURE 20

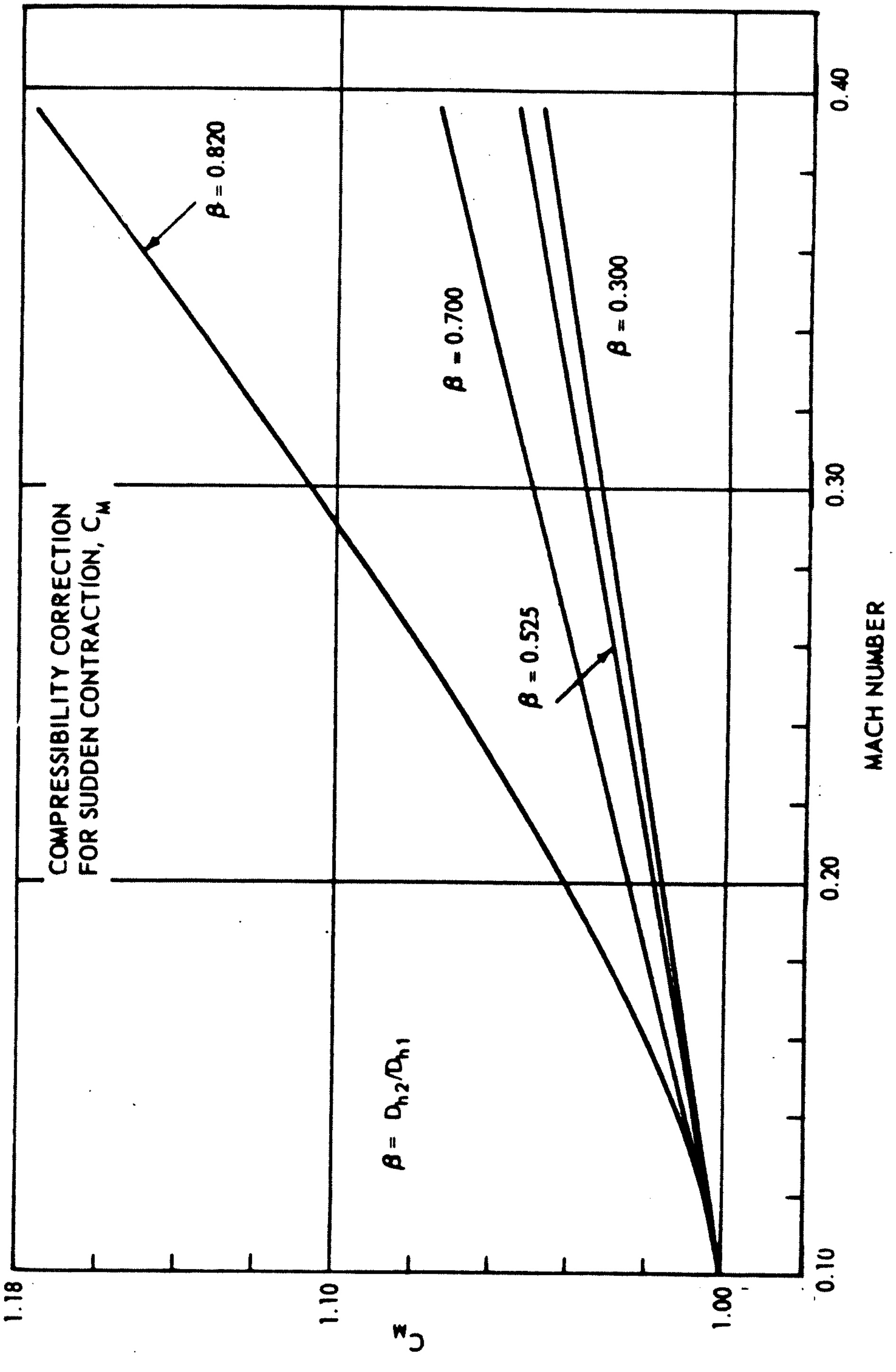

COMPRESSIBILITY CORRECTION
FOR SUDDEN CONTRACTION, C_M
$\beta = D_{h2}/D_{h1}$
$\beta = 0.820$
$\beta = 0.700$
$\beta = 0.525$
$\beta = 0.300$
C_M
1.18
1.10
1.00
0.10
0.20
0.30
0.40
MACH NUMBER

FIGURE 21

HEAD LOSS COEFFICIENTS FOR OBSTRUCTIONS IN DUCTS

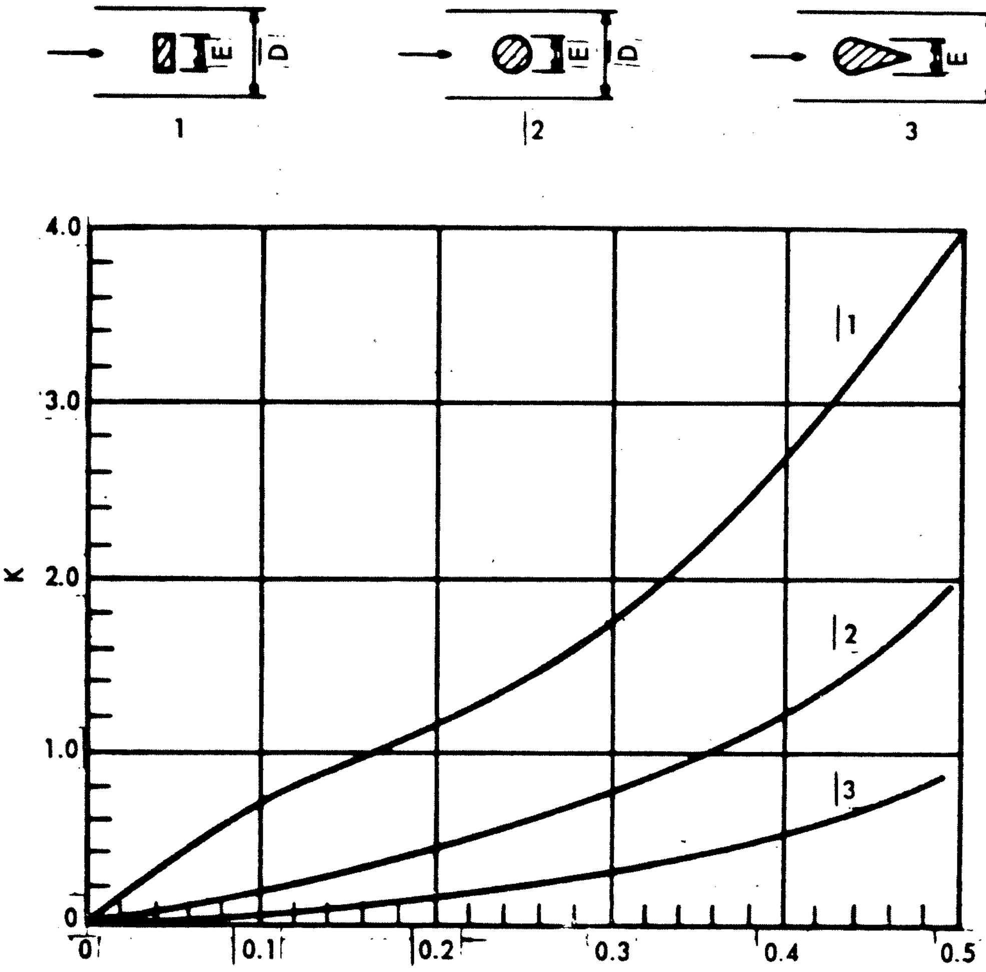


FIGURE 22

HEAD LOSS COEFFICIENTS FOR SQUARE EDGED ORIFICES IN A RUN OF DUCT

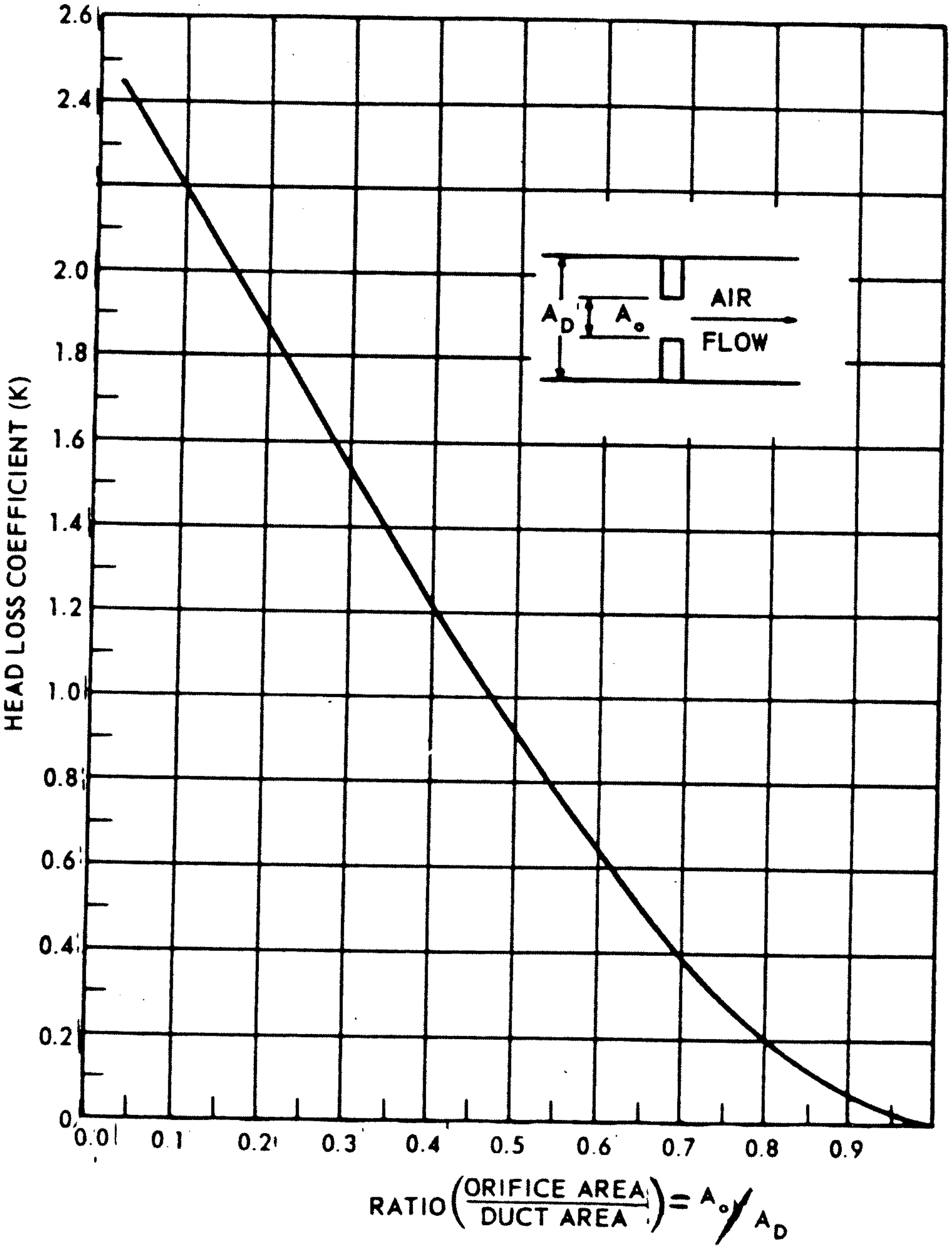


FIGURE 23

APPENDIX 1

Worksheets for Pressure Loss Calculations

The figures and paragraph numbers noted in the worksheets are those corresponding to the Design Data Sheet.

The worksheets are completed in three general steps:

1. Description of system and calculation of necessary flow parameters throughout the system (in the following worksheets).
2. Using the results of the above, the static pressure change through each component is determined on the appropriate worksheet. For unusual components, for which worksheets are not provided, a page should be inserted with the appropriate calculation thereon.
3. Using the results of steps (1) and (2), the duct system pressure loss is determined on the Summary Sheet.

Pressure Loss Worksheet

Definition of System

Project/Ship ________________________________ Date ____________

Flow Rate, m______#/sec T=________° F + 460 =______________________° R

Sketch: a. Indicate beginning and end of each component by a station number, n = 1, 2, 3 ....

b. Fully describe each component using length, relative radius, cross-sectional area, hydraulic diameter, etc.

System Total Pressure Loss (from Summary Sheet) inches H_2O ________________

System Static Pressure Loss (from Summary Sheet) inches H_2O ________________

Pressure Loss Worksheet

Flow Parameters

Acoustic Velocity, a = ______________________________ ft/sec (Table I)

Viscosity, μ = ______________________________ # /ft-sec (Table I)

Assuming p_{ave} = ______________ "H_2O x 5.19 = ________ # /ft², calculate density.

$$\rho = \frac{(\qquad)\ \#/\text{ft}^2}{53.3 \times (\qquad)^\circ\text{R}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\ \#/\text{ft}^3$$

Using ρ, μ, and a from above, calculate velocity, dynamic pressure, Reynolds number and Mach number at each station.

$$\text{Velocity, } V = \frac{m'}{\rho A} = \frac{(\qquad)\ \#/\text{sec}}{(\qquad)\ \#/\text{ft}^3 \times (A)\ \text{ft}^2} = \frac{(\qquad)}{(A)\ \text{ft}^2}$$

$$\text{Dynamic Pressure, } q = \frac{1}{2g}\rho V^2 = \frac{(\qquad)\ \#/\text{ft}^3 \times (V)^2\ \text{ft}^2/\text{sec}^2}{64.4}$$

$$= (\qquad) \times (V\ \text{ft/sec})^2$$

$$\text{Reynolds Number, } Re = \frac{m D_h}{\mu A} = \frac{(\qquad)\ \#/\text{sec} \times (D_h)\ \text{ft}}{(\qquad)\ \#/\text{ft-sec}\ (A)\ \text{ft}^2}$$

$$= (\qquad)\frac{(D_h)\ \text{ft}}{(A)\ \text{ft}^2}$$

$$\text{Mach Number, } M = \frac{V}{a} = \frac{(V)\ \text{ft/sec}}{(\qquad)\ \text{ft/sec}}$$

Pressure Loss Worksheet

Tabulation of Properties at Each Station

Station Number n	A ft^2	D_h ft	V ft/sec	q # /ft^2	Re x 10^{-5}	M

Pressure Loss Worksheet

Straight Duct

Entrance Station, n = ______________________

Length Parameter, $L/D_h = \frac{(\qquad)\ \text{ft}}{(\qquad)\ \text{ft}}$ = ______________________.

Reynolds Number, Re = ______________________

Relative Roughness, $\frac{\epsilon}{D_h}$ = ______________________

Mach Number, M = ______________________

Friction factor, f = ______________________ (Fig. 3)

Correction for compressibility, C_f = ______________________ (Fig. 4)

$$\Delta p\ (\text{loss}) = q_n \times \frac{L}{D_h} \times f \times C_f$$

$$= (\qquad) \times (\qquad) \times (\qquad) \times (\qquad)$$

$$= \underline{\hspace{6cm}}\ \#/\text{ft}^2$$

Pressure Change, $\Delta p\ (\#/\text{ft}^2)$ _

Pressure Loss Worksheet

Elbow

Entrance Station, n = ____________________

Bend Angle = ____________________ degrees

Aspect Ratio, b/w = ____

Relative Radius, R/D (or R/w) = ____________________

Splitters (No.) = ____________________

Hydraulic Diameter, D_h = ____________ ft

$$\frac{\text{Length Upstream to Elbow}}{\text{Hydraulic Diameter}} = L_m/D_h = \frac{(\qquad)\ \text{ft}}{(\qquad)\ \text{ft}} = \underline{\qquad\qquad}$$

$$\frac{\text{Length Downstream to Elbow}}{\text{Hydraulic Diameter}} = L_d/D_h = \frac{(\qquad)\ \text{ft}}{(\qquad)\ \text{ft}} = \underline{\qquad\qquad}$$

Reynolds Number, Re = ____________ x 10^5

Mach Number, M = ____________________

Area Ratio, A_1/A_2 = ____________________ $(A_1/A_2)^2$ = ____________

If $A_1/A_2 \neq 1$, determine inside relative radius, r_a/w_1 = ____________

$$K_{eff} = K \times C_{L_m} \times C_{L_d} \times C_{Re} \times C_{b/w} \times C_M \times C_s \times C_{\Delta A} \times C_l$$

(Fig. 5) (Fig. 6) (Fig. 7) (Fig. 8) (Fig. 9) (Fig. 10) (Fig. 11) (Fig. 12)
(2b of detail design)

= (   ) x (   ) x (   ) x (   ) x (   ) x (   ) x (   ) x (   ) x (   )

= ____________________

$$\Delta p = \left[K_{eff} + \left(\frac{A_1}{A_2}\right)^2 - 1\right] \times q_n = (\underline{\qquad} + \underline{\qquad} - 1) \times \underline{\qquad} = \underline{\qquad\qquad}$$

Pressure Change, Δp (#/ft^2) ____________

Pressure Loss Worksheet

Contraction (Gradual)

Entrance Station, n = ____________________

Reynolds Number, Re @ n = ____________________ ϵ/D_h = ______________

Friction Factor, f = __________________________________ (Fig. 3)

Average Dynamic Pressure, $q_{ave} = \frac{1}{2}(q_n + q_{n+1})$ = ____________ #/ft^2

Average Hydraulic Diameter, $D_{h_{(ave)}} = \frac{1}{2}\left(D_{h_{(1)}} + D_{h_{(2)}}\right)$ = ________ ft

Length Parameter, $N/D_{h_{(ave)}} = (\qquad)/(\qquad)$ = ____________________

Average Mach Number = $\frac{1}{2}(M_1 + M_2)$ = ________________________

Correction Factor, C_f = ______________________________ (Fig. 4)

Area (inlet) A_x = ________ ft^2; Area (exit) A_y = ________________ ft^2

Area Ratio = (A_y/A_x) = ____

Dimensionless Parameter, $N/\sqrt{A_x}$ = __________________________________

Apparent Contraction Angle, 2φ = __________________________ (Fig. 18)

Loss Coefficient, K = o (IF $2\varphi \leq 30°$)

___ (IF $2\varphi > 30°$ use fig. 20)

M = __________

C_M = ________________ (Fig. 21)

$$\Delta p = f \times \frac{N}{D_{h_{(ave)}}} \times q_{ave} \times C_f + \left\{ \left[(K \times C_M) + 1 - \left(\frac{A_{n+1}}{A_n}\right)^2 \right] \times q_{n+1} \right\}$$

$$= (\qquad) \times (\qquad) \times (\qquad) \times (\qquad) + \left\{ \left[(\qquad) + (\qquad) \right] \times (\qquad) \right\}$$

= ____________________ #/ft^2

Pressure Change, Δp (#/ft^2) __________

Pressure Loss Worksheet

Diffuser (Gradual enlargement)

Entrance Station, n = ____________________

Length, N = ______________ ft

Length Parameter, N/D, or N/w_1 = __________; $Ar = \frac{A_x}{A_y}$ = ______________

Expansion Angle, 2φ = ____________________

Downstream Duct Length = $L_d/w_2 = \frac{(\qquad)\ ft}{(\qquad)\ ft}$ = ____________________

Mach No. @n = ________________

C_p = ______________________ (Fig. 13)

C_{L_d} = ______________________ (Fig. 14)

C_M = ______________________ (Fig. 15)

$C_p\ (net) = C_p \times C_{L_d} \times C_M$

$= (\qquad) \times (\qquad) \times (\qquad)$

= ________________

$\Delta p = p_n - p_{n-1}$

$= -C_p\ (net) \times q_n$

$= -(\qquad) \times (\qquad)$

= - __________________ $\#/ft^2$

Pressure Change, $\Delta p\ (\#/ft^2)$ ____________

Pressure Loss Worksheet

Screens

Entrance Station, n = ______________________

Total Cross-sectional Area, A_n = ______________________ ft^2

Free Flow Area, A_f = ______________ ft^2

Blocked Area, $A_b = A_n - A_f$ = ______________ ft^2

Screen Solidity, $S = A_b/A_n$ = ______________________

$(1-S)^2$ = ______________

q_n = ______________ $\#/ft^2$

M_n = ______________

(a) Sharp Edged Screen Elements

K_s ______________ (Fig. 16b)

C_M ______________ (Fig. 17b)

$\Delta p = C_M \times K_s \times q_n$

= ______________________

(b) Circular Edged Screen Elements

$Re_d = \frac{\rho V d}{\mu}$ = ______________________

$Re_d/(1-S)$ = ______________________

$\frac{K_s(1-S)^2}{S}$ = __________ (Fig. 16a)

C_M = ______________ (Fig. 17)

$$\Delta p = C_M \times \frac{K_s(1-S)^2}{S} \times \frac{S}{(1-S)^2} \times q_n$$

= (   ) x (   ) x (   ) x (   )

= ______________ $\#/ft^2$

Pressure Change, Δp $(\#/ft^2)$ ______________

Pressure Loss Worksheet

Sudden Contraction

Entrance Station, n = ______________

Area, A_1 = ____________ ft^2

Area, A_2 = ____________ ft^2

Hydraulic Diameter, $D_{h_{(1)}}$ = _________ ft

Hydraulic Diameter, $D_{h_{(2)}}$ = _________ ft

$\beta = D_{h_{(2)}}/D_{h_{(1)}}$ = __________________

K = ____________________ (Fig. 20)

M = ________________________________

C_M = ____________________ (Fig. 21)

q_{n+1} = ____________________ $\#/ft^2$

$$\Delta p = \left\{(K \times C_M) + \left(1 - \left(\frac{A2}{A_1}\right)^2\right)\right\} \times q_n + 1$$

= ____________________ $\#/ft^2$

Pressure Change, Δp ($\#/ft^2$) ______________

Pressure Loss Worksheet

Sudden Enlargement

Entrance Station, n = ____________________

Area, A_1 = ____________________ ft^2

Area, A_2 = ____________________ Ft^2

$$K = \left(1 - \frac{A_1}{A_2}\right)^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

M = ________________________________

C_M = ____________________ (Fig. 19)

= ____________________ $\#/ft^2$

$$\Delta p = \left\{ (K \times C_M) - \left(1 - \left(\frac{A_1}{A_2}\right)^2\right) \right\} \times q_n$$

= ____________________ $\#/ft^2$

Pressure Change, Δp ($\#/ft^2$) ________________

Pressure Loss Worksheet

Inlet Louvers

Entrance Section, n = ____________

Determine Entrance Loss, K_1

K_1 = 0.5 (Table 3 and paragraph 9)

Determine Elbow Loss, K_2

Bend Angle __________
Aspect Ratio __________ (based on free flow area between a pair of vanes)
Radius Ratio 0.0
L_d/D_h 0.0

$K_2 = K \times C_{b/w} \times C_i \times C_{L_d}$

(Fig. 5) (Fig. 9)

$K_2 = (\quad) \times (\quad) \times (1.3) \times (2.8)$

K_2 = ____________________

$\Delta p = (K_1 + K_2) \times q_n$

Δp = (0.5 + ___) x (___) = _____

Pressure Change, Δp (#/ft^2) ____________

Pressure Loss Worksheet*

Entrance Section

Entrance Station, n = ____________

Loss Coefficient, K_i = ____________ (Table 3)

$\Delta p = K_i \times q_n = (\quad) \times (\quad)$

Δp = ____________

Pressure Change, Δp ($\#/ft^2$) ____________

*Worksheet applicable to obstructions, orifices & blockages.

Pressure Loss Worksheet
SUMMARY SHEET

Component Description	Page No.	Static Pressure Change, $p(\#/ft^2)$

Total Pressure Loss = Static Pressure Loss + $q_i - q_e$

= (   ) + (   ) - (   )

= ______________________________ $\#f/ft^2$

Total Pressure Loss/5.19 = Total Pressure Loss (inches H_2O) = ________ inches H_2O

Static Pressure Loss/5.19 = Static Pressure Loss (inches H_2O) = ________ inches H_2O

APPENDIX II

Sample Calculation—Pressure Loss Worksheet

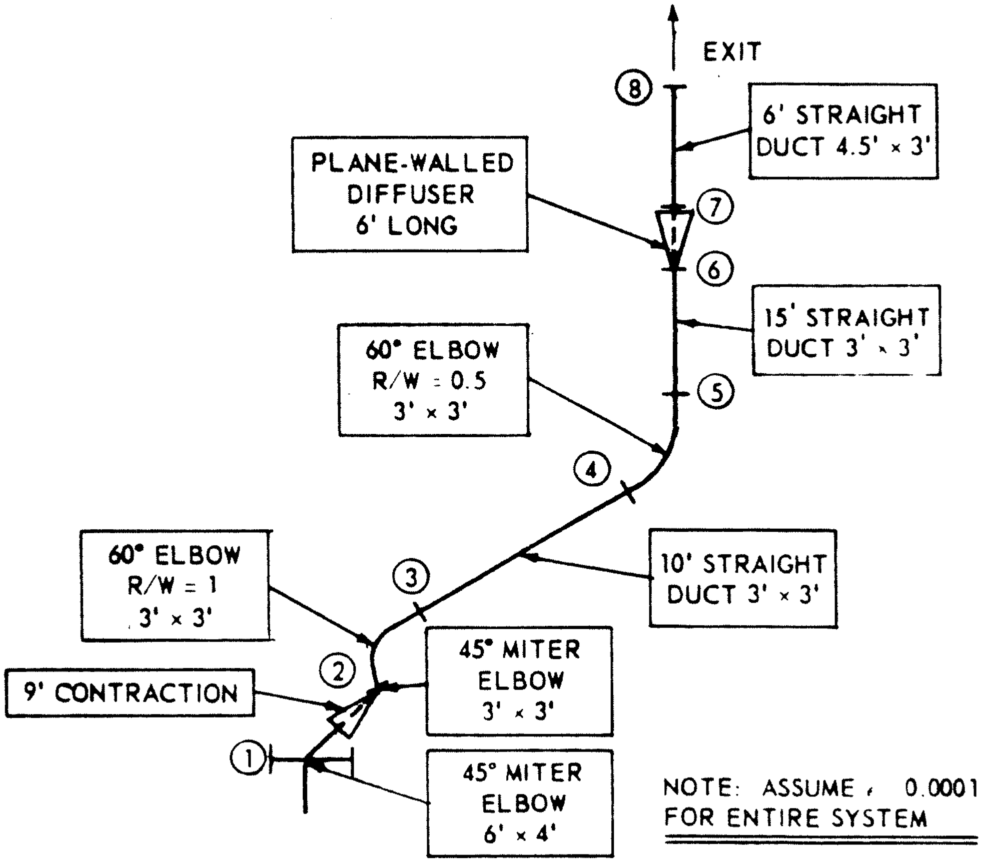
Definition of System

Title: BOILER UPTAKE SYSTEM

Flow Rate, m 70 # /sec T = 540 °F + 460 = 1000 °R

Sketch: a. Indicate beginning and end of each component by a station number, n = 1, 2, 3 ......

b. Fully describe each component using length, relative radius, cross-sectional area, hydraulic diameter, etc.



System Total Pressure Loss (from Summary Sheet) inches H_2O 3.75

System Static Pressure Loss (from Summary Sheet) inches H_2O 5.14

Sample Calculation—Pressure Loss Worksheet

Flow Parameters

Acoustic Velocity, $a = 1539$ ft/sec (Table I)

Viscosity, $\mu = \underline{192 \times 10^{-7}}$ #/ft-sec (Table I)

Assuming $p_{ave} = \underline{410 \text{ inches}}\ H_2O \times 5.19 = \underline{2128}$ #/ft^2, calculate average density

$$\rho = \frac{(2128)\ \#/\text{ft}^2}{53.3 \times (1000)\ ^\circ\text{R}} = \underline{3.99 \times 10^{-2}}\ \#/\text{ft}^3$$

Using ρ, μ, and from above, calculate velocity, dynamic pressure, Reynolds number and Mach number at each station.

$$\text{Velocity, } V = \frac{m}{\rho A} = \frac{(70)\ \#/\text{sec}}{(0.0399)\ \#/\text{ft}^3 \times (A)\ \text{ft}^2} = \frac{(1755)}{(A)\ \text{ft}^2}$$

$$\text{Dynamic Pressure, } q = \frac{1}{2g}\rho V^2 = \frac{(.0399)\ \#/\text{ft}^3 \times (V)^2\ \text{ft}^2/\text{sec}^2}{64.4}$$

$$= (6.20 \times 10^{-4}) \times (V\ \text{ft/sec})^2$$

$$\text{Reynolds Number, } Re = \frac{mD_h}{\mu A} = \frac{(70)\ \#/\text{sec} \times (D_h)\ \text{ft}}{(192 \times 10^{-7})\ \#/\text{ft-sec}\ (A)\text{ft}^2}$$

$$= (36.4 \times 10^5)\ \frac{(D_h)\ \text{ft}}{(A)\ \text{ft}^2}$$

$$\text{Mach Number, } M = \frac{V}{a} = \frac{(V)\ \text{ft/sec}}{(1539)\ \text{ft/sec}}$$

Sample Calculation—Pressure Loss Worksheet

Tabulation of Properties at Each Station

Station Number n	A ft^2	D_h ft	V ft/sec	q $\#/ft^2$	$Re \times 10^{-5}$	M
1	24	4.8	73.1	3.3	7.3	0.05
2	9	3.0	195.0	23.6	12.1	0.13
3	9	3.0	195.0	23.6	12.1	0.13
4	9	3.0	195.0	23.6	12.1	0.13
5	9	3.0	195.0	23.6	12.1	0.13
6	9	3.0	195.0	23.6	12.1	0.13
7	13.5	3.6	130.0	10.5	9.7	0.09
8	13.5	3.6	130.0	10.5	9.7	0.09

Sample Calculation—Pressure Loss Worksheet

Entrance Section

Entrance Station, n = ①

Loss Coefficient, K_i = .5 (Table 3)

$\Delta p = K_i \times q_n = (0.5) \times (3.3)$

$\Delta p = \underline{1.65}$

Pressure Change, Δp (#/ft^2) 1.65

Sample Calculation—Pressure Loss Worksheet

Elbow

Entrance Station, n = ①

Bend Angle = 45°

Aspect Ratio, b/w = 1.5

Relative Radius, R/D (or R/w) = 0

Splitters (No.) = 0

Hydraulic Diameter, D_h = 4.8 ft

$$\frac{\text{Length Upstream to Elbow}}{\text{Hydraulic Diameter}} = L_m/D_h = \frac{(0)\ \text{ft}}{(4.8)\ \text{ft}} = \underline{0}$$

$$\frac{\text{Length Downstream to Elbow}}{\text{Hydraulic Diameter}} = L_d/D_h = \frac{(9)\ \text{ft}}{(4.8)\ \text{ft}} = \underline{1.9}$$

Reynolds Number, Re = $\underline{7.3} \times 10^5$

Mach Number, M = 0.05

Area Ratio, $A_1/A_2 = \underline{1}$ $(A_1/A_2)^2 = \underline{1.0}$

If $A_1/A_2 \neq 1$, determine inside relative radius, r_a/w_1 = ________________

$$K_{eff} = K \times C_{L_m} \times C_{L_d} \times C_{Re} \times C_{b/w} \times C_M \times C_s \times C_{\Delta A} \times C_i$$

(Fig. 5) (Fig. 6) (Fig. 7) (Fig. 8) (Fig. 9) (Fig. 10) (Fig. 11) (Fig. 12)
(2b of detail design)

$$= (0.26) \times (1) \times (0.76) \times (1) \times (0.95) \times (1) \times (1) \times (1.3)$$

$$= \underline{0.247}$$

$$\Delta p = \left[K_{eff} + \left(\frac{A_1}{A_2}\right)^2 - 1\right] \times q_n = (\underline{0.247} + \underline{1.0} - 1) \times \underline{3.3} = \underline{0.82}$$

Pressure Change, $\Delta p(\#/\text{ft}^2)$ 0.82

Sample Calculation—Pressure Loss Worksheet

Contraction (Gradual)

Entrance Station, n = ①

Reynolds Numbers, Re @ n = 7.3×10^5 ϵ/D_h = 0.00002

Friction Factor, f = 0.0124 (Fig. 3)

Average Dynamic Pressure, $q_{ave} = \frac{1}{2}(q_n + q_{n+1}) =$ 13.6 #/ft^2

Average Hydraulic Diameter, $D_{h_{(ave)}} = \frac{1}{2}\left(D_{h_{(1)}} + D_{h_{(2)}}\right) =$ 3.9 ft

Length Parameter, $N/D_{h_{(ave)}} = (9)/(3.9) =$ 2.3

Average Mach Number = $\frac{1}{2}(M_1 + M_2) =$ 0.09

Correction Factor, C_f = 1.015 (Fig. 4)

Area (inlet) A_x = 24 ft^2; Area (exit) A_y = 9 ft^2

Area Ratio = (A_y/A_x) = 0.375

Dimensionless Parameter, $N/\sqrt{A_x}$ = 1.84

Apparent Contraction Angle, 2φ 13° (Fig. 18)

Loss Coefficient, K = 0 (IF $2\varphi \le 30°$)

_ (IF $2\varphi > 30°$, use fig. 20)

M = ______ C_M = ______ (Fig. 21)

$$\Delta p = f \times \frac{N}{D_{h_{(ave)}}} \times q_{ave} \times C_f + \left\{ \left[(K \times C_M) + 1 - \left(\frac{A_{n+1}}{A_n} \right)^2 \right] \times q_{n+1} \right\}$$

$$= (0.012) \times (2.300) \times (13.600) \times (1.015) + \{[(0) + (1-0.140)] \times (23.6)\}$$

$$= \underline{0.40 + 20.3} \ \#/\text{ft}^2$$

Pressure Change, Δp (#/ft^2) 20.7

Sample Calculation—Pressure Loss Worksheet

Elbow

Entrance Station, n = ②

Bend Angle = 45°

Asepot Ratio, b/w = 1

Relative Radius, R/D (or R/w) = 0

Splitters (No.) = 0

Hydraulic Diameter, D_h = 3 ft

$$\frac{\text{Length Upstream to Elbow}}{\text{Hydraulic Diameter}} = L_m/D_h = \frac{(9)\ \text{ft}}{(3)\ \text{ft}} = 3$$

$$\frac{\text{Length Downstream to Elbow}}{\text{Hydraulic Diameter}} = L_d/D_h = \frac{(0)\ \text{ft}}{(3)\ \text{ft}} = 0$$

Reynolds Number, Re = 12.1×10^5

Mach Number, M = 0.13

Area Ratio, $A_1/A_2 = 1$ $(A_1/A_2)^2 = 1.0$

If $A_1/A_2 \neq 1$, determine inside relative radius, r_a/w_i = ______

$$K_{eff} = K \times C_{L_m} \times C_{L_d} \times C_{Re} \times C_{b/w} \times C_M \times C_s \times C_{\Delta A} \times C_i$$

(Fig. 5) (Fig. 6) (Fig. 7) (Fig. 8) (Fig. 9) Fig. 10) (Fig. 11) (Fig. 12)
(2b of detail design)

$$= (0.26) \times (0.85) \times (0.73) \times (1) \times (1) \times (1.03) \times (1) \times (1) \times (1.0)$$

$$= 0.16$$

$$\Delta p = \left[K_{eff} + \left(\frac{A_1}{A_2}\right)^2 - 1\right] \times q_n = (0.16 + 1.0 - 1) \times 23.6 = 3.8$$

Pressure Change, Δp ($\#/ft^2$) 3.8

Sample Calculation—Pressure Loss Worksheet

Elbow

Entrance Station, n = ②

Bend Angle = 60°

Aspect Ratio, b/w = 1

Relative Radius, R/D (or R/w) = 1

Splitters (No.) = 0

Hydraulic Diameter, D_h = 3 ft

$$\frac{\text{Length Upstream to Elbow}}{\text{Hydraulic Diameter}} = L_m/D_h = \frac{(0)\ \text{ft}}{(3)\ \text{ft}} = \underline{0}$$

$$\frac{\text{Length Downstream to Elbow}}{\text{Hydraulic Diameter}} = L_d/D_h = \frac{(10)\ \text{ft}}{(3)\ \text{ft}} = \underline{3.33}$$

Reynolds Number, Re = $\underline{12.1} \times 10^5$

Mach Number, M = 0.13

Area Ratio, $A_1/A_2 = \underline{1}$ $(A_1/A_2)^2 = \underline{1.0}$

If $A_1/A_2 \neq 1$, determine inside relative radius, r_a/w_1 = ____________

$$K_{eff} = K \times C_{L_m} \times C_{L_d} \times C_{Re} \times C_{b/w} \times C_M \times C_s \times C_{\Delta A} \times C_i$$

(Fig. 5) (Fig. 6) (Fig. 7) (Fig. 8) (Fig. 9) (Fig. 10) (Fig. 11) (Fig. 12)
(2b of detail design)

$$= (0.23) \times (1) \times (0.72) \times (0.68) \times (1) \times (1) \times (1) \times (1.0)$$

$$= \underline{0.11}$$

$$\Delta p = \left[K_{eff} + \left(\frac{A_1}{A_2}\right)^2 - 1\right] \times q_n = (\underline{0.11} + \underline{1.0} - 1) \times \underline{23.6} = \underline{2.6}$$

Pressure Change, Δp (#/ft^2) $\underline{2.6}$

Sample Calculation—Pressure Loss Worksheet

Straight Duct

Entrance Station, n = ③

Length Parameter, $L/D_h = \frac{(10\ \text{ft})}{(3\ \text{ft})} = \underline{3.33}$

Reynolds Number, $Re = \underline{12.1 \times 10^5}$

Relative Roughness, $\frac{\epsilon}{D_h} = \underline{0.00003}$

Mach Number, $M = \underline{0.13}$

Friction factor, $f = \underline{0.0124}$ (Fig. 3)

Correction for compressibility, $C_f = \underline{1.015}$ (Fig. 4)

$$\Delta p\ (\text{loss}) = q_n \times \frac{L}{D_h} \times f \times C_f$$

$$= (23.6) \times (3.33) \times (0.0124) \times (1.015)$$

$$= \underline{1.0}\ \#/\text{ft}^2$$

Pressure Change, $\Delta p\ (\#/\text{ft}^2)$ $\underline{1.0}$

Sample Calculation—Pressure Loss Worksheet

Elbow

Entrance Station, n = ④

Bend Angle = 60°

Aspect Ratio, b/w = 1

Relative Radius, R/D (or R/w) = 0.5

Splitters (No.) = 0

Hydraulic Diameter, D_h = 3 ft

$$\frac{\text{Length Upstream to Elbow}}{\text{Hydraulic Diameter}} = L_m/D_h = \frac{(10)\text{ ft}}{(3)\text{ ft}} = \underline{3.33}$$

$$\frac{\text{Length Downstream to Elbow}}{\text{Hydraulic Diameter}} = L_d/D_h = \frac{(15)\text{ ft}}{(3)\text{ ft}} = \underline{5}$$

Reynolds Number, Re = $\underline{12.1} \times 10^5$

Mach Number, M = 0.13

Area Ratio, $A_1/A_2 = \underline{1}$ $(A_1/A_2)^2 = \underline{1.0}$

If $A_1/A_2 \neq 1$, determine inside relative radius, r_a/w_1 = ____________

$$K_{eff} = K \times C_{L_m} \times C_{L_d} \times C_{Re} \times C_{b/w} \times C_M \times C_s \times C_{\Delta A} \times C_i$$

(Fig. 5) (Fig. 6) (Fig. 7) (Fig. 8) (Fig. 9) (Fig. 10) (Fig. 11) (Fig. 12)
(2b of detail design)

$$= (0.52) \times (0.85) \times (0.82) \times (0.76) \times (1) \times (1) \times (1) \times (1) \times (1.0)$$

$$= \underline{0.27}$$

$$\Delta p = \left[K_{eff} + \left(\frac{A_1}{A_2}\right)^2 - 1\right] \times q_n = (\underline{0.27} + \underline{1.0} - \underline{1}) \times \underline{23.6} = \underline{6.4}$$

Pressure Change, Δp (#/ft^2) 6.4

Sample Calculation—Pressure Loss Worksheet

Straight Duct

Entrance Station, n = ⑤

Length Parameter, $L/D_h = \frac{(15)\ \text{ft}}{(3)\ \text{ft}} = \underline{5}$

Reynolds Number, $Re = \underline{12.1 \times 10^5}$

Relative Roughness, $\frac{\epsilon}{D_h} \equiv \underline{0.0003}$

Mach Number, $M = \underline{0.13}$

Friction factor, $f = \underline{0.0124}$ (Fig. 3)

Correction for Compressibility, $C_f = \underline{1.015}$ (Fig. 4)

$$\Delta p \text{ (loss)} = q_n \times \frac{L}{D_h} \times f \times C_f$$

$$= (23.6) \times (5) \times (0.0124) \times (1.015)$$

$$= \underline{1.5}\ \#/\text{ft}^2$$

Pressure Change, Δp ($\#/\text{ft}^2$) $\underline{1.5}$

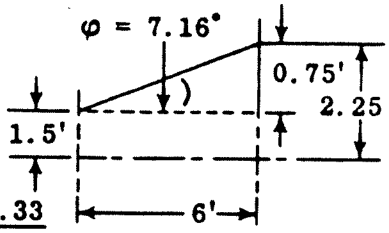
Sample Calculation—Pressure Loss Worksheet

Diffuser (Gradual enlargement)

Entrance Station, n = ⑥

Length, N = 6 ft

Length Parameter, N/D, or $N/w_1 = \underline{2}$; $Ar = \frac{A_x}{A_y} = \underline{1.5}$



Expansion Angle, $2\varphi = \underline{14.32°}$

Downstream Duct Length $= L_d/w_2 = \frac{(6)\text{ ft}}{(4.5)\text{ ft}} = \underline{1.33}$

Mach No. @n = $\underline{0.13}$

$C_p = \underline{0.50}$ (Fig. 13)

$C_{L_d} = \underline{1.01}$ (Fig. 14)

$C_M = \underline{1.00}$ (Fig. 15)

$$C_p\text{ (net)} = C_p \times C_{L_d} \times C_M$$

$$= (0.50) \times (1.01) \times (1.00)$$

$$= \underline{0.51}$$

$$\Delta p = p_n - p_{n-1}$$

$$= -C_p\text{ (net)} \times q_n$$

$$= -(0.51) \times (23.6)$$

$$= -\underline{12.0}\ \#/\text{ft}^2$$

Pressure Change, Δp ($\#/\text{ft}^2$) $\underline{12.0}$

Sample Calculation—Pressure Loss Worksheet

Straight Duct

Entrance Station, n = ⑦

Length Parameter, $L/D_h = \frac{(6)\text{ ft}}{(3.6)\text{ ft}} = \underline{1.67}$

Reynolds Number, $Re = \underline{9.7 \times 10^5}$

Relative Roughness, $\frac{\epsilon}{D_h} = \underline{0.00003}$

Mach Number, $M = \underline{0.09}$

Friction factor, $f = \underline{0.0124}$ (Fig. 3)

Correction for compressibility, $C_f = \underline{1.015}$ (Fig. 4)

$$\Delta p \text{ (loss)} = q_n \times \frac{L}{D_h} \times f \times C_f$$

$$= (10.5) \times (1.67) \times (0.0124) \times (1.015)$$

$$= \underline{0.2}\ \#/\text{ft}^2$$

Pressure Change, Δp (#/ft^2) $\underline{0.2}$

Sample Calculation—Pressure Loss Worksheet

SUMMARY SHEET

Component Description	Page No.	Pressure Loss, p(#/ft^2)
Entrance Loss		+ 1.65
Miter Elbow		+ 0.82
Contraction		+20.7
Miter Elbow		+ 3.8
Elbow		+ 2.6
Straight Duct		+ 1.0
Elbow		+ 6.4
Straight Duct		+ 1.5
Diffuser		-12.0
Straight Duct		+ 0.2
Static Pressure Loss		+26.67

Total Pressure Loss = Static Pressure Loss + $q_1 - q_e$

$= (26.67) + (3.3) - (10.5)$

$= \underline{19.47}$ #/ft^2

Total Pressure Loss/5.19 = Total Pressure Loss (inches H_2O) = $\underline{3.75}$ (inches H_2O)

Static Pressure Loss/5.19 = Static Pressure Loss (inches H_2O) = $\underline{5.14}$ (inches H_2O)