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ASME STS-1a–2003

ADDENDA

to

ASME STS-1–2000 EDITION
STEEL STACKS

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
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ASME STS-1a-2003

Following approval by the ASME STS Committee and ASME, and after public review, ASME STS-1a-2003 was approved by the American National Standards Institute on May 9, 2003.

Addenda to the 2000 edition of ASME STS-1 are issued in the form of replacement pages. Revisions, additions, and deletions are incorporated directly into the affected pages. It is advisable, however, that this page, the Addenda title and copyright pages, and all replaced pages be retained for reference.

SUMMARY OF CHANGES

This is the first Addenda to be published to ASME STS-1-2000.

Replace or insert the pages listed. Changes given below are identified on the pages by a margin note, **(a)**, placed next to the affected area. The pages not listed are the reverse sides of the listed pages and contain no changes.

Page	*Location*	*Change*
iv–vi	Roster	Updated to reflect Addenda
6	2.2.2	Subparagraph (c), second and last sentences revised
15–16	4.3.3.1	(1) Equations (4.1) through (4.3) revised (2) Second paragraph, second sentence revised
18–19	4.4.3	Equation (4.11) revised
	4.4.5	Subparagraphs (a) and (b) revised
21–22	4.10	Last nomenclature revised
	5.2.1	Equation (5.1) revised
25	5.5	I and ρ revised
37	Mandatory Appendix I	(1) Equation for G_f revised (2) Equation for N_1 revised
85	Nomandatory Appendix E	(1) g_c, $\phi(z)$, and $\phi(z_M)$ revised (2) Paragraph regarding tapered stacks deleted

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(a)

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Steel Stacks

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forms to service lights are recommended for corrosion resistant construction. See Sections 6 and 7.

(i) Rain caps are generally not required on full-time active stacks. When specified, a diameter of two times the stack diameter and a clear height of one stack diameter is recommended.

(j) Stack spark arresting screens of stainless steel material a minimum of two stack diameters high may be specified when needed.

(k) Metal stacks require no lightning protection other than proper grounding at the base per NFPA requirements. See Section 7.

(l) Stack internal shutoff dampers and stack cap dampers demand special consideration when specified.

(m) Straightening vanes to distribute flowing gas for effective testing should be specified as required.

(n) Splitter baffles are sometimes used when two stack inlets enter the stack opposite each other to reduce back pressure in the event that isolation dampers are not used.

(o) Gin pole or davit lifts are sometimes specified for hoisting instruments to the test platform.

(p) Top of stack roofs for multiple flue stacks and dual wall stacks should provide proper weather protection for the inside surfaces, while at the same time providing for expected differential expansion between flues and the stack outer shell. Consideration should be given to the effect of the buildup of ash on any flat surfaces.

(q) Noise pollution control may require acoustical suppressing sound attenuators within the stack.

1.8 Mechanical Section Symbols

DR_N = stack natural draft — water gage, in.
H_E = stack height above center line inlet, ft
T_A = absolute temperature of atmosphere, °Rankine
T_G = average absolute temperature of gas, °Rankine
B = barometric pressure — mercury absolute, in.
K = constant for breeching inlet angle
F = friction factor based on Reynolds number
d = density of gas, lb/ft^2
D_i = inside diameter(s) of stack sections, ft
D_t = inside diamter of stack at outlet, ft
W = mass flow rate of gas, lb/hr
FL_f = stack friction loss — water gage, in.
FL_{ex} = stack exit loss — water gage, in.
FL_{en} = stack entrance loss — water gage, in.
A = stack mean surface area, sq. in.
U = overall heat transfer coefficient
t_s = average gas temperature minus ambient temperature, °F
C_p = specific heat of gas Btu/lb, °F
t_g = gas temperature entering minus gas temperature leaving, °F
h_i = internal film coefficient Btu/hr-sq. ft, °F
h_a = airspace coefficient Btu/hr-sq. ft, °F
h_{ins} = insulation coefficient Btu/hr-sq. ft, °F
h_0 = external film coefficient Btu/hr-sq. ft, °F
t_h = temperature drop through the h component of the stack wall
h_l = lining coefficient Btu/hr-sq. ft, °F
V = gas velocity at stack inlet, ft/sec

1.9 Mechanical Section Definitions

appurtenances: stack specialty design items apart from shell and structural members.

cladding: thin metal overlaid over the base metal metallurgically and integrally bonded to the base metal.

EPRI: Electric Power Research Institute.

EPA: Environmental Protection Agency (may be Federal, State, or local) government regulatory authority.

false bottom: a cone or plate located just below the breeching opening to prevent gases from entering the lower section of stack.

NFPA: National Fire Protection Association.

test zone: section of stack designed for testing. The location of test ports in relationship to upstream and downstream flow pattern disturbances is well documented in Federal and State air quality rules and regulations.

truncated cone: a converging section reducing the exit diameter located at the top of the stack.

2 MATERIALS

2.1 Scope

Material specifications are intended to cover single or double wall stacks that are free-standing and self-supporting, guy or cable supported, or supported by structural steel braces or framework. Reference is made to the 1975 edition of Design and Construction of Steel Chimney Liners, published by the American Society of Civil Engineers.

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2.2 Materials

The Materials listed in the following sections are suggested for use based on their ability to meet the physical, mechanical, chemical, and environmental requirements of a given application. Acceptance of a material for a specific application must be based on service experience or independent verification of its suitability.

2.2.1 General Considerations

(a) Materials shall conform to the applicable requirements in the sections hereinafter detailed.

(b) The contractor shall submit one copy of the chemical-composition and mechanical-property mill test reports for all steels used to the owner for approval prior to construction unless otherwise indicated.

(c) When required for testing purposes, the contractor will furnish the owner with identified scrap samples of the shell plates.

(d) This section does not apply to linings and coatings of stacks. See Section 3.

(e) Corrosion allowances shall be considered (typically $\frac{1}{16}$ in. to $\frac{1}{8}$ in.) where carbon, high-strength, low alloy, and alloy steels are used. Experience or the results of tests should be used when selecting an allowance.

(a) **2.2.2 Shell and Base Plates.** For more information on this subject, see Tables B-1 through B-11 in Nonmandatory Appendix B.

(a) Shell and base plates typically may be of one or more of the following structural quality materials:

(1) Carbon steels conforming to the ASTM A 36, A 283, or A 529 Specifications;

(2) High-strength, low alloy steels conforming to the ASTM A 242, A 572, or A 588 Specifications;

(3) Stainless steels conforming to the ASTM A 666 Specification;

(4) Stainless chromium-nickel steel clad plate conforming to ASTM A 264 and nickel-base alloy clad steel conforming to ASTM A 265 may be considered for use as shell plate;

(5) Metals listed in Materials Appendix (i.e., Nonmandatory Appendix B), Table B-9 may be used not only as sheet linings and cladding but also as solid plate for shell plates.

(b) Pressure vessel quality carbon steels such as ASTM A 285, A 515, and A 516; alloy steels such as ASTM A 387; and stainless steels such as ASTM A 240 may be substituted for structural quality materials as appropriate.

(c) Carbon Steels such as ASTM A 516, Grades 55 through 70 and low alloy steels such as ASTM A 517, Grades A through T and ASTM A 537 are usually specified for service temperatures as low as −50°F (−46°C). Nickel-containing alloy steels such as ASTM A 203, Grades A and B are usually used for service temperatures as low as −75°F (−59°C); and ASTM Grades D, E, and F are often used for service temperatures of −150°F (−101°C). Nickel-containing alloy steels and nickel stainless steels are used for even lower temperatures. Suppliers of structural quality steels will provide data on notch toughness when specified.

(d) Protection against corrosion and/or oxidation may be required on interior and/or exterior surfaces depending on the materials utilized and the conditions encountered. Section 3 should be consulted and utilized as appropriate.

(e) Creep rupture tensile stresses for sustained loading and high-temperature service conditions must be considered as given in para. 4.4.8.

2.2.3 Stiffeners and Structural Braces and/or Framework

(a) Stiffeners and structural braces and/or framework typically may be of one or more of the following materials:

(1) Carbon steels conforming to the ASTM A 36, A 283, or A 529 Specifications;

(2) High-strength, low alloy steels conforming to the ASTM A 242, A 572, or A 588 Specifications;

(3) Stainless steels conforming to the ASTM A 240 or A 666 Specifications or nickel-containing alloys having compositions similar to those of the shell plate.

(b) Protection may be required against corrosion for components exterior to the shell and against corrosion and/or oxidation for components on the shell interior. Section 3 should be consulted and utilized as appropriate.

2.2.4 Guy Wires, Cables, or Fittings

(a) Guy wires and cables typically may be of one or more of the following materials, and consideration should be given to the initial stretch of the material:

(1) Aluminum-coated steel wire strand conforming to the ASTM A 474 Specification;

(2) Zinc-coated (galvanized) steel wire strand conforming to the ASTM A 475 and A 586 Specifications;

(3) Zinc-coated (galvanized) steel wire rope conforming to the ASTM A 603 Specification;

(4) Stainless steel wire strand conforming to the ASTM A 368 Specification.

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(b) Elementary chlorine: 0.1% by weight (1300 mg/m^3 at 20°C and 1 bar pressure)

(c) Hydrogen chloride: 0.1% by weight (1300 mg/m^3 at 20°C and 1 bar pressure)

3.5 Insulation, Jacketing, and Strapping

3.5.1 Insulation

(a) Insulation may be required on the stack exterior and/or interior, or between the walls of a dual wall stack.

(b) Insulating linings are covered in para. 3.2.4.2 on Inorganic Linings.

(c) There are numerous ASTM standards covering thermal insulating materials and their properties. These standards should be consulted and utilized in conjunction with the manufacturers' recommendations to meet the application requirements.

3.5.2 Jacketing and Strapping

(a) Jacketing may be of a material selected from one of the following ASTM Specifications:

(1) aluminum coated steel conforming to A 463;

(2) galvanized steel conforming to A 527;

(3) stainless steel conforming to A 666;

(4) aluminum conforming to B 209.

(b) Strapping may be of the same material as the jacketing, but stainless steel is usually preferred.

4 STRUCTURAL DESIGN

4.1 Scope

The structural design section includes currently acceptable methods for establishing structural configuration of steel stacks and stack elements to resist all external and internal loads imposed by the geography and topography of the site and by operating conditions.

4.2 General

4.2.1 Limitations. The design recommendations made in the Standard are applicable primarily to circular steel stacks.

4.2.2 Location. The stack design and construction shall be appropriate to the specific site, with particular consideration to local wind and seismic conditions, aircraft traffic, operating conditions, and local laws.

4.2.3 Drawings and Computations. Design drawings of the stack and all appurtenances shall be prepared showing all elements and details necessary for satisfactory fabrication and erection of the stack. Computations shall be prepared and submitted. All means of connection of material shall be specifically detailed with proper differentiation between shop and field connections.

4.3 Applied Loading

4.3.1 Dead Load. The dead load shall consist of the weight of steel stack, coatings, internal liner, insulation, and cladding, and all permanent accessories such as ladders, platforms, and gas sampling equipment. For dead load, the full plate thickness shall be used. The corroded plate area shall be used for stress calculations. For stacks possessing refractory lining, the applied weight of the refractory material shall be used to calculate dead load stresses.

4.3.2 Live Load. The minimum live load of 50 psf shall be included for platforms and walkways. This load need not be considered for wind or earthquake combinations. Consideration shall be given for accumulated ash loads, and moisture in the case of wet gases, on the stack walls and floors.

4.3.3 Wind Load. The wind load shall be calculated in accordance with procedures outlined in this section. The design shall also consider wind loads due to interference effects as stated in para. 4.3.3.7

4.3.3.1 Design Wind Force. The design load distribution is given by: **(a)**

$$w(z) = \overline{w}(z) + w_D(z) \tag{4.1}$$

where:

$$\overline{w}(z) = \frac{C_f\, q_z\, K_{zt}\, K_z\, D}{12(1 + 6.8I_{\bar{z}})} \tag{4.2}$$

and:

$$w_D(z) = \frac{3zM_0}{h^3}\left[G_f(1 + 6.8I_{\bar{z}}) - 1\right] \tag{4.3}$$

The velocity pressure, q_z, shall be calculated by:

$$q_z = 0.00256\, V^2 I \tag{4.4}$$

where the basic wind speed (V) is based on a three-second gust velocity and is selected in accordance with the provisions of paras. 4.3.3.2 through 4.3.3.4, the

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importance factor (I) is set forth in Tables I-2 and I-3 of Mandatory Appendix I, and the velocity pressure exposure coefficient (K_z) is given in Table I-4 of of Mandatory Appendix I in accordance with the provisions of paras. 4.3.3.5 and 4.3.3.7. Provisions of para. 4.3.3.5 shall be used to determine K_{zt} where applicable, but K_{zt} shall not be less than 1.0. The numerical coefficient 0.00256 shall be used, except where sufficient climatic data are available to justify the selection of a different value of this factor for a specific design application. Interference effects on the force coefficient (C_f) described in para. 4.3.3.7 shall be considered.

The basic wind speed V used in the determination of design wind loads is given in Fig. I-1 of Mandatory Appendix I, except as provided in paras. 4.3.3.2 through 4.3.3.4.

4.3.3.2 Special Wind Regions. The basic wind speed shall be increased where records or experience indicate that the wind speeds are higher than those reflected in Fig. I-1 of Mandatory Appendix I. Mountainous terrain, gorges and special regions shown in Fig. I-1 shall be examined for unusual wind conditions. The authority having jurisdiction shall, if necessary, adjust the values given in Fig. I-1 to account for higher local wind speeds. Such adjustment shall be based on meteorological information and an estimate of the basic wind speed obtained in accordance with the provisions of para. 4.3.3.3.

4.3.3.3 Estimation of Basic Wind Speeds From Regional Climatic Data. Regional climatic data shall only be used in lieu of the basic wind speeds given in Fig. I-1 when:

(a) approved extreme-value statistical-analysis procedures have been employed in reducing the data;

(b) the length of record, sampling error, averaging time, anemometer height, data quality, and terrain exposure have been taken into account.

4.3.3.4 Exposure Categories. An exposure category that adequately reflects the characteristics of ground surface irregularities shall be determined for the site at which the building or structure is to be constructed. Account shall be taken of variations in ground surface roughness that arises from natural topography and vegetation as well as from constructed features. The exposure in which a specific building or other structure is sited shall be assessed as being one of the following categories:

(a) Exposure A. Large city centers with at least 50% of the buildings having a height in excess of 70 ft. Use of this exposure category shall be limited to those areas for which terrain representative of Exposure A prevails in the upwind direction for a distance of at least 0.5 miles or 10 times the height of the steel stack, whichever is greater. Possible channeling effects or increased velocity pressures due to the steel stack being located in the wake of adjacent buildings shall be taken into account.

(b) Exposure B. Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced structures having the size of single-family dwellings or larger. Use of this exposure category shall be limited to those areas for which terrain representative of Exposure B prevails in the upwind direction for a distance of at least 1,500 ft or 10 times the height of the building or other structure, whichever is greater.

(c) Exposure C. Open terrain with scattered obstructions having heights generally less than 30 ft. This category includes flat, open country and grasslands.

(d) Exposure D. Flat, unobstructed areas exposed to wind flowing over open water for a distance of at least 1 mile. This exposure shall apply only to those steel stacks exposed to the wind coming from over the water. Exposure D extends inland from the shoreline a distance of 1,500 ft or 10 times the height of the stack, whichever is greater.

4.3.3.5 Wind Speed Over Hills and Escarpments. The provisions of this section shall apply to isolated hills or escarpments located in Exposures B, C, or D where the upwind terrain is free of such topographic features for a distance equal to $50H_H$ or 1 mile, whichever is smaller, as measured from the point at which H_H is determined. Wind speed-up over isolated hills and escarpments that constitute abrupt changes in the general topography shall be considered for steel stacks sited on the upper half of hills and ridges or near the edges of escarpments, illustrated in Fig. I-2 of Mandatory Appendix I, by using factor K_{zt}:

$$K_{zt} = (1 + K_1 K_2 K_3)^2 \qquad (4.5)$$

where K_1, K_2, and K_3 are given in Figure I-2 of Mandatory Appendix I. The effect of wind speed-up shall not be required to be considered when $H_H/L_h < 0.2$, or when $H_H < 15$ ft for Exposure D, or 30 ft for Exposure C, or < 60 ft for all other exposures.

4.3.3.6 Gust Effect Factor. The gust effect factor G_f for main wind-force resisting systems of steel stacks shall be calculated in accordance with the equations shown in Mandatory Appendix I.

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4.3.3.7 Force Coefficient Interference Effect. For grouped or clustered stacks having a center-to-center distance of 3.0 diameters or less, an increase in the force coefficient value of 20% is suggested in the absence of model wind tunnel testing or existing full scale data.

4.3.4 Seismic Load. Lateral seismic forces shall be considered in accordance with the guidelines described in this section. The procedure provided shall be followed in the U.S. as a minimum requirement. It has been found that, due to the low mass of steel stacks, those only in high seismic areas or those containing high mass distribution are governed by seismic loads.

4.3.4.1 Earthquake Response. The steel stack response to earthquake can be determined using the response spectrum method by using a horizontal response spectrum based upon a maximum ground acceleration of 1.0g with a damping value of 0.05, which is scaled to the specific site. The value of the acceleration, A_v, related to the effective peak velocity, shall be determined using Table D-2 in Nonmandatory Appendix D or the published value for the location. Using the value of A_v, the response spectrum scaling ratio is found in Table D-2 in Nonmandatory Appendix D. Linear interpolation may be used in between published values of A_v. The modal moment, shear and deflection response of each mode is scaled with the scaling ratio for the specific frequency of each mode. Modal responses for each mode are then added using the SRSS method (taking the square root of the sum of the squares of modal moment, shear deflection responses). In lieu of the response spectrum method, a static equivalent method may be used.

The mathematical model of the steel stack used in the analysis shall be sufficiently detailed to represent the steel stack, liner or coating, lateral support and foundation property and support conditions. A minimum of 10 elements and 5 modes of vibration should be used.

An example of the mathematical calculation of modal properties and response spectrum earthquake response is shown in Nonmandatory Appendix D.

4.3.5 Thermal Loads. Non-uniform distribution of flue gas across the steel stack or steel stack liner may cause differential temperatures. Unless the temperature distribution is uniform or linearly varying across the stack/liner diameter, thermal stresses will be induced in both longitudinal and circumferential directions. In addition, longitudinal bending stresses and shear stresses will be produced if the stack shell or liner that is subjected to non-uniform temperatures along its height is restrained from lateral movements. The thermal stresses should be considered in applicable stack and liner designs. Refer to 1975 ASCE Publication, Design and Construction of Steel Chimney Liners for more discussion of thermal effects.

For stacks to be subjected to high-temperature (>500°F) and/or fast plant startup or shutdown such as cyclic operation of combustion turbine, design consideration should be given to minimize the non-uniform thermal differentials that may exist between shell and stiffeners or other structural elements. Localized thermal stresses induced in the inner plates and stiffeners can be substantial and must be considered in the design.

4.3.6 Construction Loads. Consideration shall be given in the design for applied construction loads in combination with wind and seismic loads that may reasonably be expected to occur during construction.

4.3.7 Other Loads. Where applicable, additional loading such as expansion joint thrusts, pressure loads, or other loads unique to the specific case shall be considered in the design.

4.4 Allowable Stresses

The following formulas for determining allowable stresses are applicable for circular stacks and liners provided that Equation 4.6 is satisfied:

$$\frac{t}{D} \leq \frac{10F_y}{E} \tag{4.6}$$

An increase in allowable shell stresses due to wind or seismic loads shall not be allowed.

All other steel members shall comply with the requirements of the American Institute of Steel Construction (AISC) specification for the design, fabrication, and erection of structural steel for buildings, AISC Manual of Steel Construction, latest edition, with the exception that an increase in allowable shell stresses due to wind or seismic loads shall not be allowed. For stacks and liners meeting the requirements of Equation 4.6, the following four load cases must be satisfied.

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4.4.1 Case 1 Longitudinal Compression. The longitudinal compressive stress in cylindrical stacks and liners (P/A) shall not exceed the allowable limit, S_{cl}.

$$\frac{P}{A} \le S_{cl} \tag{4.7}$$

where:

$$S_{cl} = \frac{EtY}{4D\ (F.\ S.)}\ when\ \frac{t}{D} \le \frac{2.8\ F_y}{E} \tag{4.8}$$

or:

$$S_{cl} = \frac{F_y\ (1 - 0.3K_s)Y}{(F.S.)} \tag{4.9}$$

$$when\ \frac{2.8\ F_y}{E} < \frac{t}{D} \le \frac{10\ F_y}{E}$$

and:

$$Y = 1$$

$$when\ \frac{L_e}{r} \le 60\ and\ F_y \le 50\ ksi$$

$$and$$

$$Y = \frac{21{,}600}{18{,}000 + \left(\frac{L_e}{r}\right)^2}$$

$$when\ \frac{L_e}{r} > 60\ and\ F_y \le 50\ ksi$$

$$K_s = \left(\frac{\frac{10F_y}{E} - \frac{t}{D}}{\frac{7.2F_y}{E}} \right)^2$$

4.4.2 Case 2 Longitudinal Compression and Bending Combination. The combined longitudinal compressive and bending stress in cylindrical stacks and liners shall not exceed the allowable stress, S_{bl}.

$$\frac{P}{A} + \frac{MD}{2I_{section}} \le S_{bl} \tag{4.10}$$

where S_{bl} $(=S_{cl})$ is given in Equations (4.8) and (4.9) of para. 4.4.1.

NOTE: $Y=1$ for compression due to bending.

4.4.3 Case 3 Circumferential Stress. The circumferential stress f_c in the shell due to external wind pressure q_z between stiffeners spaced at distance, l_s, shall be determined using: (a)

$$f_c = \frac{q_z D}{288t} \tag{4.11}$$

The circumferential stress shall be less than the allowable stress, S_{cc}, calculated as:

$$S_{cc} = \frac{1.30EK\left(\frac{t}{D}\right)^{1.5}}{(F.S.)\left(\frac{l_s}{D}\right)}$$

$$when\ 0 \le \frac{t}{D} \le \frac{2.8\ F_y}{E},\ K = 1$$

$$when\ \frac{2.8\ F_y}{E} < \frac{t}{D} \le \frac{10F_y}{E},$$

$$K = 1.68\ \frac{F_y\ D}{Et} + 0.465 - \frac{0.0232\ Et}{F_y\ D}$$

where q_z = external wind pressure on stack shell at elevation under consideration, psf and C_f = 1.0

4.4.4 Case 4 Combined Longitudinal and Circumferential Compressive Stress. The combined longitudinal and circumferential compressive stress in cylindrical stacks and liners may be determined using the following formulae.

$$\frac{\left(\frac{P}{A}\right) + \frac{MD}{2I_{section}}}{S_{bl}} + \left(\frac{f_c}{S_{cc}}\right)^2 \le 1.0 \tag{4.13}$$

4.4.5 Circumferential Compression In Stiffeners. The size of stiffeners shall satisfy the following three requirements. (a)

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TABLE 4.1 FACTORS OF SAFETY

Load Combination	F.S.
Dead + Live + Other + Thermal + Along or Across Wind	1.50
Dead + Live + Other + Thermal + Seismic	1.50
Dead + Live + Other + Abnormal Thermal + Along Wind/4	1.33
Construction	1.33

(a) The stiffener and plate section shall have a moment of inertia equal to or greater than that determined by the following equation:

$$I_{s+p} \geq \frac{q l_s D^3 \, (F.S.)}{3456\, E} \qquad (4.14)$$

where q = external wind pressure, q_z or stack draft pressure, q_p.

(b) The stiffener and plate section shall have an area equal to or greater than that determined by the following equation:

$$A_{s+p} \geq \frac{q\, l_s D \, (\text{F.S.})}{288\, S_{ccs}} \qquad (4.15)$$

Circumferential compression in the stiffeners shall not exceed

$$S_{ccs} = \left[\frac{0.25EI}{R^2}\right]\frac{1}{F.S.}$$

in which I is the moment of inertia of the stiffener and a band of shell plate. The band of shell plate shall not exceed the $8 \times t$ projection beyond the stiffener.

(c) The stiffener and plate section shall have a section modulus equal to or greater than that determined by the following equation:

$$S_{s+p} \geq \frac{q_z D^2 l_s \, (F.S.)}{1830\, F_y} \qquad (4.16)$$

where q_z = *external wind pressure.*

4.4.6 Factors of Safety. The stack shall be designed for minimum factor of safety (F.S.) for the loading considerations given in Table 4.1

4.4.7 Minimum Structural Plate Thickness and Maximum Stiffener Spacing. Table 4.2 shows the minimum plate thickness to be used in the fabrication of steel stacks and steel liners and maximum stiffener spacing.

4.4.8 Creep Rupture Tensile Stress. For sustained loading and high-temperature service above 750°F, depending on the steel chemistry, the creep-rupture strength of the steel becomes a significant factor in determining the allowable design tension stress.

(a) Because of their nature, allowable creep stresses are only used to limit tension stresses or tensile bending stresses from loading combinations that will be sustained at elevated temperatures. Creep and creep-rupture are very dependent on the exact chemistry of the steel. Some carbon steels, such as ASTM A 36, are very susceptible to creep and creep rupture, while others are almost creep resistant. The exact chemical composition of the steel is necessary to quantify its creep and creep rupture properties.

(b) The design creep life should be selected based on the expected service life and service conditions. Design for creep is typically based on creep and rupture properties corresponding to a creep life of 100,000 hr. This creep design life is the duration presented in Section II of the ASME Boiler and Pressure Vessel Code. A shorter or longer creep design life may be appropriate depending on the expected service life of the stack.

(c) The maximum allowable creep tensile design stress, as taken from Section I of the ASME Boiler and Pressure Vessel Code, Rules for Construction of Power Boilers, should not exceed the lowest of the following two values:

(1) the average stress to produce a creep rate of 1% within 100,000 hr with a factor of safety of 1.0, and;

(2) the average stress to cause creep rupture after 100,000 hr with a factor of safety of 1.5.

(d) Selected allowable creep tensile design stresses for various steels used in ductwork and steel stacks are presented for reference (see Nonmandatory Appendix D) from the American Society of Civil Engineers (ASCE) 1995 publication, The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications, Section 3. The values presented in this book are intended to be used only as a reference. Creep rupture allowable tensile design stress used in stack design should be obtained from test data reflecting the

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TABLE 4.2 MINIMUM STRUCTURAL PLATE THICKNESS AND MAXIMUM STIFFENER SPACING

Inside Diameter, D ft	Minimum Structural Plate Thickness, in. [Note (1)]	Maximum Stiffener Spacing, ft
$D \le 3.5$	0.125	5 D
$3.5 < D \le 6.5$	0.1875	3 D
$6.5 < D \le 18.0$	0.1875	2 D
$D > 18.0$	0.25	$1\frac{1}{2}$ D

NOTE:
(1) Minimum plate thickness does not include corrosion allowance. If corrosion allowance is required, the minimum plate thickness shall be increased by the amount of the corrosion allowance.

precise chemical composition of the steel to be used in the stack fabrication.

4.5 Deflections

4.5.1 Lateral Deflection. The maximum deflection under the static design loading shall be calculated, and the foundation rotation or movement shall be considered in evaluating deflection. There is no practical limit placed on the maximum deflection a stack can experience; however, for large deflections, the resulting secondary stresses caused by P·Δ should be considered. The calculated maximum deflection shall also be considered in evaluating the suitability of equipment anchored to the stack.

4.5.2 Dual Wall or Multiflue Stacks. The forces due to contact between liners and the shell of dual wall or multiflue steel stacks due to any velocity wind up to the design velocity shall be considered at all elevations of the shell and liners.

4.6 Structural Shell Discontinuities

4.6.1 Discontinuities. Openings in the shell shall be designed to maintain the minimum factors of safety specified for the loading conditions.

(a) The top and bottom of the breeching opening shall be adequately reinforced to transfer the discontinuities of shell stress back to the full circumference of the shell.

(b) The sides of breeching openings shall act as columns or tension members to withstand the end reactions of the assumed horizontal girders above and below the opening. The strength of a plane cut through the opening at any elevation shall be adequate to withstand all applied loads on the section.

(c) The breeching opening reinforcement may serve as a means of connecting the breeching to the liner or shell. The applicable corrosion allowance shall be applied to the reinforcement if exposed to the flue gas.

4.6.2 Flanged Shell and/or Liner Connections. For information on flanged shell and/or liner connections, see CICIND or SMACNA publications in Nonmandatory Appendix F.

4.7 Base

The base ring and anchor bolts shall be designed to transfer the steel stack shear, compression, and tensile forces to the supporting structure or foundation in accordance with proven design methods. No strength increase will be permitted for wind or seismic loads.

4.8 Anchor Bolts

4.8.1 Anchor Bolt Tension. Anchor bolts shall be designed to transfer all tension and shear forces to the foundation unless other methods are incorporated to accomplish this purpose. The maximum anchor bolt tension, F_b, may be determined from the following relation for circular sections sufficiently away from discontinuities:

$$F_b = \frac{4\,M_b}{ND_{bc}} - \frac{P}{N} \qquad (4.17)$$

4.8.2 Anchor Bolt Material. All anchor bolt material shall conform to Section 2.

4.8.3 Anchor Bolt Loading. Anchor bolt capacities for tension and/or shear shall not exceed those given for size of bolt and material indicated in AISC, latest edition. No load increase in bolts will be permitted for wind or seismic loading.

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4.8.4 Load Transfers Between Anchor Bolts and Shell. Transfer of loads between anchor bolts and shell shall accommodate all loads and eccentricities. An increase in allowable shell stresses due to wind or seismic loads shall not be allowed.

4.9 Foundation

The foundation shall transfer all moment and shear loads (static and dynamic) to the supporting soil or piles. Concrete and steel reinforcement design shall comply with the latest edition of ACI 318 and ACI 301. A qualified geotechnical engineer shall review soil boring and pile capacity test results. The combined dead load of the stack plus the foundation weight, times the distance from the center of the weight to the toe shall be at least 1.5 times the design moment.

(a) 4.10 Section 4 Symbols and Definitions

A = cross-sectional area of stack plate, in.^{2}
A_{s+p} = area of stack stiffener and plate section, in.^{2}
A_v = effective peak velocity-related acceleration
b = stack diameter (used only in Mandatory Appendix I, Gust Factor Calculation), ft
$\bar{b}$ = coefficient given in Table I-1 of Mandatory Appendix I
C_f = force coefficient given in Table I-5 of Mandatory Appendix I
c = coefficient given in Table I-1 of Mandatory Appendix I
d = stack diameter (used in Mandatory Appendix I, Gust Factor Calculation), ft
D = diameter of stack at elevation under consideration, in.
D_{bc} = diameter of anchor bolt cirlce, in.
E = modulus of elasticity at mean shell temperature, psi
F_b = anchor bolt tension force, lbf
$F.S.$ = factor of safety
F_y = yield strength at mean shell temperature, psi
f_c = circumferential stress in the shell due to external wind pressure, psi
G_f = gust effect factor
H_H = height of hill or escarpment given in Figure I-2 of Mandatory Appendix I, ft
h = height of stack, ft
I = importance factor given in Table I-3 of Mandatory Appendix I
$I_{section}$ = moment of inertia of stack section, in.^{4}
I_{s+p} = moment of inertia of stack stiffener and plate section, in.^{4}
$I_{\bar{z}}$ = intensity of turbulence at height $\bar{z}$
K = circumfrential stress coeffecient
K_z = velocity pressure exposure coefficient evaluted at height z
K_{zt} = topographic factor for along wind pressure calculation
K_1, K_2 = topographic multipliers given in Figure I-2 of Mandatory Appendix I
K_3 = topographic multipliers given in Figure I-2 of Mandatory Appendix I
L_e = two times the overall stack height for cantilever stacks, or two times cantilever portion or height for guided stacks for stresses in that cantilevered section or the distance between lateral supports, for stresses in the section between lateral supports, in.
L_h = distance upwind of crest of hill or escarpment in Figure I-2 of Mandatory Appendix I to where the difference in ground elevation is half the height of hill or escarpment, ft
$L_{\bar{z}}$ = integral length scale of turbulence at the equivalent height, ft
l_s = spacing between circumferential stiffeners, determined as the sum of half of the distance to adjacent stiffeners on either side of the stiffener under consideration, in.
M = moment in stack at elevation under consideration due to wind or earthquake loads, lbf-in.
M_b = moment at the base of the stack due to wind or earthquake loads, lbf-in.
M_0 = moment at the base of the stack due to $\overline{w}$ (z) loading, lbf-ft
N = number of anchor bolts
N_1 = coefficient used to calculate the resonant response factor
n_1 = first natural frequency of the Stack, Hz
P = dead load of stack above elevation under consideration, lb
Q = background response factor
q_p = stack draft pressure, psf.
q_z = external wind pressure on stack shell at elevation under consideration, psf.
R = resonant response factor
R_b, R_d = coefficients used to calculate the resonant response factor
R_h, R_n = coefficients used to calculate the resonant response factor
r = weighted mean radius of gyration for elevation under consideration, in.
S_{bl} = allowable combined longitudinal compressive and bending stress, psi

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S_{cc} = allowable circumferential compressive stress in shell, psi
S_{ccs} = allowable circumferential compressive stress in stiffeners and band of shell plate, psi
S_{cl} = allowable longitudinal compressive stress in shell, psi
S_{s+p} = section modulus of stack stiffener and plate section, in.^{3}
t = stack shell or liner wall thickness, in.
V = basic wind speed corresponding to a 3-second gust speed at 33 ft above ground in exposure category C, and is associated with an annual probability of 0.02 of being equalled or exceeded (50-year mean recurrence interval), mph
$\bar{V}_{\bar{z}}$ = mean hourly wind speed, ft/sec
Y = coefficient used to calculate longitudinal compressive stress
z = elevation under consideration, ft
$\bar{z}$ = equivalent height of stack, ft
$\bar{\alpha}$ = coefficients given in Table I-1 of Mandatory Appendix I
β = total damping value
$\bar{\epsilon}$ = coefficients given in Table I-1 of Mandatory Appendix I
η = coefficient used to calculate the resonant response factor
$w(z)$ = total along-wind load on stack per unit height, lb-f/ft
$\overline{w}(z)$ = mean along-wind load on stack per unit length, lb-f/ft
$w_D(z)$ = fluctuating along-wind load on stack per unit height, lb-f/ft

5 DYNAMIC WIND LOADS

5.1 Scope

This section considers the dynamic wind load effects on steel stacks. Since steel stacks are flexible structures with low inherent structural damping and light in weight, the dynamic effects of wind shall be considered in the design.

5.2 Dynamic Responses

(a) **5.2.1 Dynamic Characteristics.** The dynamic characteristics of natural frequencies, corresponding mode shapes, and damping shall be considered in wind loading. All modes of vibration that could occur based upon the wind loads considered in the design shall be investigated.

Frequencies. Stack frequencies and corresponding mode shapes are a function of the stack configuration and the vertical and lateral support conditions. The frequencies and mode shapes shall be calculated using a suitable mathematical modeling method.

Mathematical Modeling. Appropriate detailed calculation methods shall be used for dynamic analysis of more complex configurations. These configurations include stacks with variable diameters and thickness, inner liners, stacks with internal coatings, guyed or laterally supported stacks, derrick supported stacks, or stacks with flexible foundations. The finite element analysis techniques shall be used in these cases. However, for simple stack configurations, simpler models can be used if justification can be provided.

(a) For steel stacks supported on rock or firm soil and/or supported on end bearing piles, a fixed base modeling approach is acceptable. For steel stacks supported on buildings, the interaction effects of the building shall be included. For steel stacks supported with shallow foundations on soil or on friction piles, appropriate methods of analysis shall be used to account for interaction effects. Parametric studies may be necessary to account for the uncertainty of soil properties.

Consideration should be given in the design to the corrosion or erosion of the stack or liner, which could affect the frequency.

(b) Damping. Steel stacks have relatively low inherent structural damping. Additional damping may be gained from the inclusion of a brick or refractory lining, foundation system, or aerodynamic methods which disrupt vortex formation, although the last may, in fact, reduce the damping.

For wind loads, the structural damping values (β_s) shown in Table 5.1 have been observed for steel stacks. Other damping values shown in Table 5.1 may be used for support conditions that have inherently large damping or utilize the damping methods of para. 5.3.2, when justified by results of testing or analysis. Consideration should be given to stacks supported on steel frames.

Aerodynamic damping shall also be considered. The aerodynamic damping value, β_a, is calculated as follows:

a) For along wind response:

$$\beta_a = \frac{C_f \rho \overline{D}\ \overline{V}_{\bar{z}}}{4\ \pi m_a n_1} \qquad (5.1)$$

Where m_a = mass per unit length of the top 1/3 of the stack

b) For vortex shedding when $\overline{V}_{\bar{z}}$ is in the vicinity (±30%) of $V_{z_{cr}}$, the aerodynamic damping is negative and shall be included. The procedures in Nonmandatory

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analyzed. One method of analyzing fatigue loads may be found in CICIND publication, Model Code for Steel Chimneys. (See Nonmandatory Appendix F.)

(a) **5.5 Section 5 Symbols and Definitions**

A = horizontal distance between stacks center lines, ft
$\bar{b}$ = coefficient given in Table I-1 of Mandatory Appendix I
C_f = force coefficient given in Table I-5 of Mandatory Appendix I
D = diameter of stack at elevation under consideration (ft)
$\bar{D}$ = mean diameter for the segment z_1 to z_2, or for stacks ±10% variation over the top $\frac{1}{3}$ the value of $\bar{D}$ is the average over the top $\frac{1}{3}$ (ft)
f_0 = ovalling natural frequency of the stack (Hz)
I = Importance Factor from Table I-3
l_s = spacing between circumferential stiffeners, determined as the sum of half the distance to adjacent stiffeners on either side of the stiffener under consideration (ft)
m_a = mass per unit length of upper $\frac{1}{3}$ of stack (lb/ft)
n_1 = natural frequency for mode being considered (Hz)
S = Strouhal number, usually used as 0.2 for single stacks and may vary due to Reynolds numbers and multiple stacks
S_s = minimum section modulus of stack stiffeners ($in.^3$)
t = stack shell or liner wall thickness (in.)
V = basic wind speed corresponding to a 3-second gust speed at 33 ft above ground in exposure category C, and is associated with an annual probability of 0.02 of being equalled or exceeded (50-year mean recurrence interval) (mph)
v_{co} = ovalling critical wind velocity (ft/sec)
V_c = critical wind speed for vortex shedding (ft/sec)
V_R = reference design speed, which is V factored by the importance factor $V\sqrt{I}$ (mph)
$\bar{V}_{\bar{z}}$ = mean hourly wind speed (ft/sec)
$V_{z_{cr}}$ = mean hourly wind speed at z_{cr} (ft/sec)
z_{cr} = elevation equal to $\frac{5}{6}$ stack height (ft)
$\bar{\alpha}$ = coefficients given in Table I-1 of Mandatory Appendix I
β = total damping value
β_a = aerodynamic damping value
β_s = structural damping value
ρ = density of air (lbm/ft^3)
σ_a = allowable tensile stress in stack stiffener (psi)
π = Pi (3.141593)

6 ACCESS AND SAFETY

6.1 Scope

This section applies to the design and construction of permanently installed equipment commonly used for accessing steel stacks. Equipment used in the construction, inspection, and demolition of steel stacks is not included.

6.2 General

6.2.1 Purpose. The access safety option of the Standard has the purpose of protecting persons by establishing minimum standards for the design, installation, and maintenance of equipment used to provide access to steel stacks.

6.2.2 Limitations. Access to a steel stack shall be provided and used only when required for inspection, testing, and maintenance. Access shall not be provided when prohibited by government regulations, local laws, or ordinances.

6.2.3 Maintenance of Equipment. All equipment used in providing access to steel stacks shall be maintained in a serviceable condition at all times. Inspection of ladders, platforms, and other equipment used to access steel stacks shall be made on a regular basis, preferably once each year.

6.2.4 Welding. All welding shall in accordance with the Structural Welding Code, Steel, AWS D1.1 latest edition) published by the American Welding Society, or Section IX of the ASME Boiler and Pressure Vessel Code, Welding and Brazing Qualifications.

6.2.5 OSHA. Ladders, platforms, and other equipment used to access steel stacks must conform to the OSHA Standard (29 CFR 1910).

6.2.6 Definitions

cage (also known as cage guard or basket guard): a barrier that is an enclosure mounted on the siderails of the fixed ladder or fastened to the structure to enclose the climbing space of the ladder (See Fig. 6-4.).

climbing protection device: a vertical support system other than a cage, used in conjunction with a ladder, which will limit a person's fall from a ladder without having to continuously manipulate the device.

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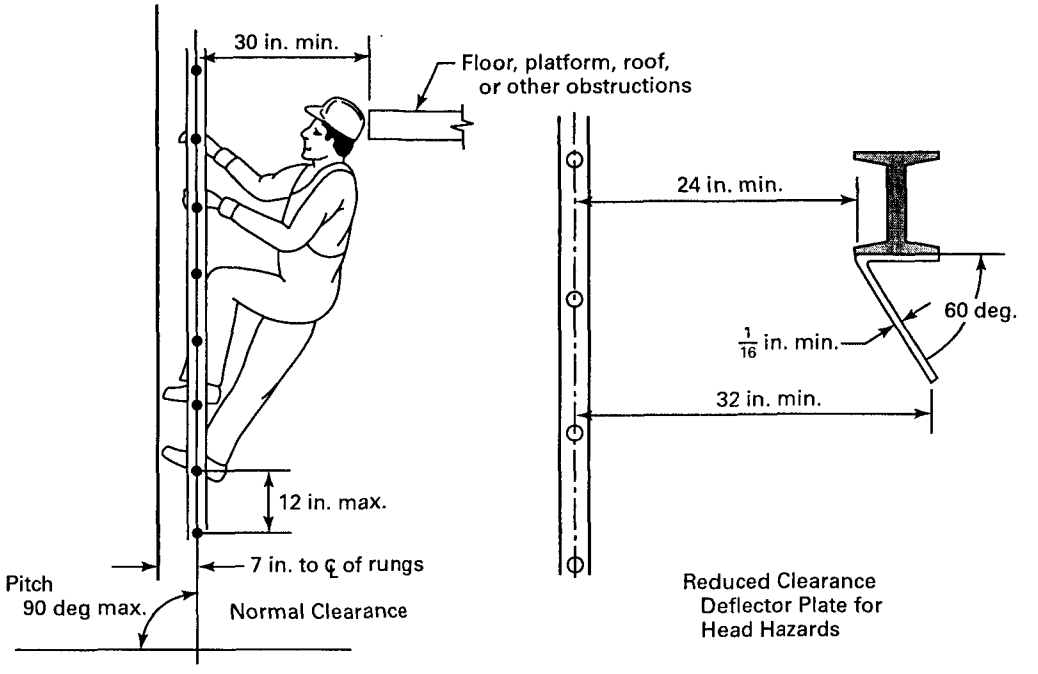

FIG. 6-1 MINIMUM LADDER CLEARANCES

grab bar: an individual handhold placed adjacent to, or as an extension above, a ladder for the purpose of providing safe access/egress for a user of the ladder.

ladder: a device incorporated or employing steps or rungs on which a person may step in ascending or descending, and siderails or grab bars for holding.

ladder, side step: a ladder that requires a person accessing or egressing to or from the ladder to step sideways.

ladder, step through: a ladder that requires a person accessing or egressing at the top to step between the siderails.

ladder support: a device for attaching a ladder to a structure, building, or equipment.

landing or rest platform: a surface that is used when transferring from one section of a ladder to another, or for resting.

length of climb: the total vertical distance a person could climb in traveling between the extreme points of access/egress for a fixed ladder, whether the ladder is of an unbroken length or consists of multiple sections. This total vertical distance is determined by including all spaces between all ladder steps or rungs, and all other vertical intervening spaces between the extreme points of access/egress.

pitch: the included angle between the horizontal and ladder, which is measured on the opposite (back) side of the ladder from the climbing side (See Fig. 6-1).

platform: a surface that is used for working, standing, or transferring from one ladder section to another.

serviceable: capable of performing its intended function within its design parameters.

siderail: the side members of fixed ladder joined at intervals by either rungs or steps.

toeboard: a barrier erected along the exposed edge of a platform to prevent objects from falling, which could create hazards to persons below.

well: a walled enclosure around a fixed ladder, which provides the person climbing the ladder with protection similar to a cage.

6.3 Fixed Ladders

6.3.1 Application. This section applies to new fixed ladders on new or existing steel stacks. Ladders used for steel stack access must conform to ANSI A14.3 (latest edition) Safety Code for Fixed Ladders.

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MANDATORY APPENDIX I
STRUCTURAL DESIGN
Gust Effect Factor Calculation

(a)

The gust effect factor is given by

$$G_f = 0.925\left(\frac{1 + 1.7\, I_{\bar{z}}\sqrt{g_Q^2\, Q^2 + g_R^2\, R^2}}{1 + 1.7\, I_{\bar{z}}\, g_v}\right)$$

where R, the resonant response factor, is given by

$$R = \sqrt{\frac{1}{\beta} R_n R_h R_B\,(0.53 + 0.47\, R_d)}$$

$$R_n = \frac{7.47\, N_1}{(1 + 10.3 N_1)^{5/3}}$$

$$N_1 = \frac{n_1 L_{\bar{z}}}{\overline{V}_{\bar{z}}}$$

$$R_l = \frac{1}{\eta} - \frac{1}{2\,\eta^2}(1 - e^{-2\eta}) \text{ for } \eta > 0$$

$$1 \text{ for } \eta = 0$$

$(l = h, B, d)$

$R_l = R_h$ setting $\eta = 4.6 n_1 h/\overline{V}_{\bar{z}}$
$R_l = R_B$ setting $\eta = 4.6 n_1 B/\overline{V}_{\bar{z}}$
$R_l = R_d$ setting $\eta = 15.4 n_1 d/\overline{V}_{\bar{z}}$
β = damping ratio

$$\overline{V}_{\bar{z}} = \overline{b}\left(\frac{\bar{z}}{33}\right)^{\bar{\alpha}} V$$

where $\overline{b}$ and $\overline{\alpha}$ are listed in Table I-1.

$$g_R = \sqrt{2\ 1n(3600 n_1)} + \frac{0.577}{\sqrt{2\ 1n(3600 n_1)}}$$

The factors g_Q and g_v may be taken equal to 3.4. V is the 3-sec gust speed in exposure C at the reference height (obtained from Fig. I-1.)

$$I_{\bar{z}} = c\left(\frac{33}{\bar{z}}\right)^{1/6}$$

where $I_{\bar{z}}$ = the intensity of turbulence at height $\bar{z}$, where $\bar{z}$ = the equivalent height of the structure (0.6 h but not less than z_{min} listed for each exposure in Table I-1, c is given in Table I-1 and Q represents the background response. Q is given by

$$Q = \sqrt{\frac{1}{1 + 0.63\left(\frac{B + h}{L_{\bar{z}}}\right)^{0.63}}}$$

where B = stack diameter, h = stack height; and $L_{\bar{z}}$ = the integral length scale of turbulence at the equivalent height

$$L_{\bar{z}} = l(\bar{z}/33)^{\bar{\epsilon}}$$

in which l and $\bar{\epsilon}$ are as listed in Table I-1.

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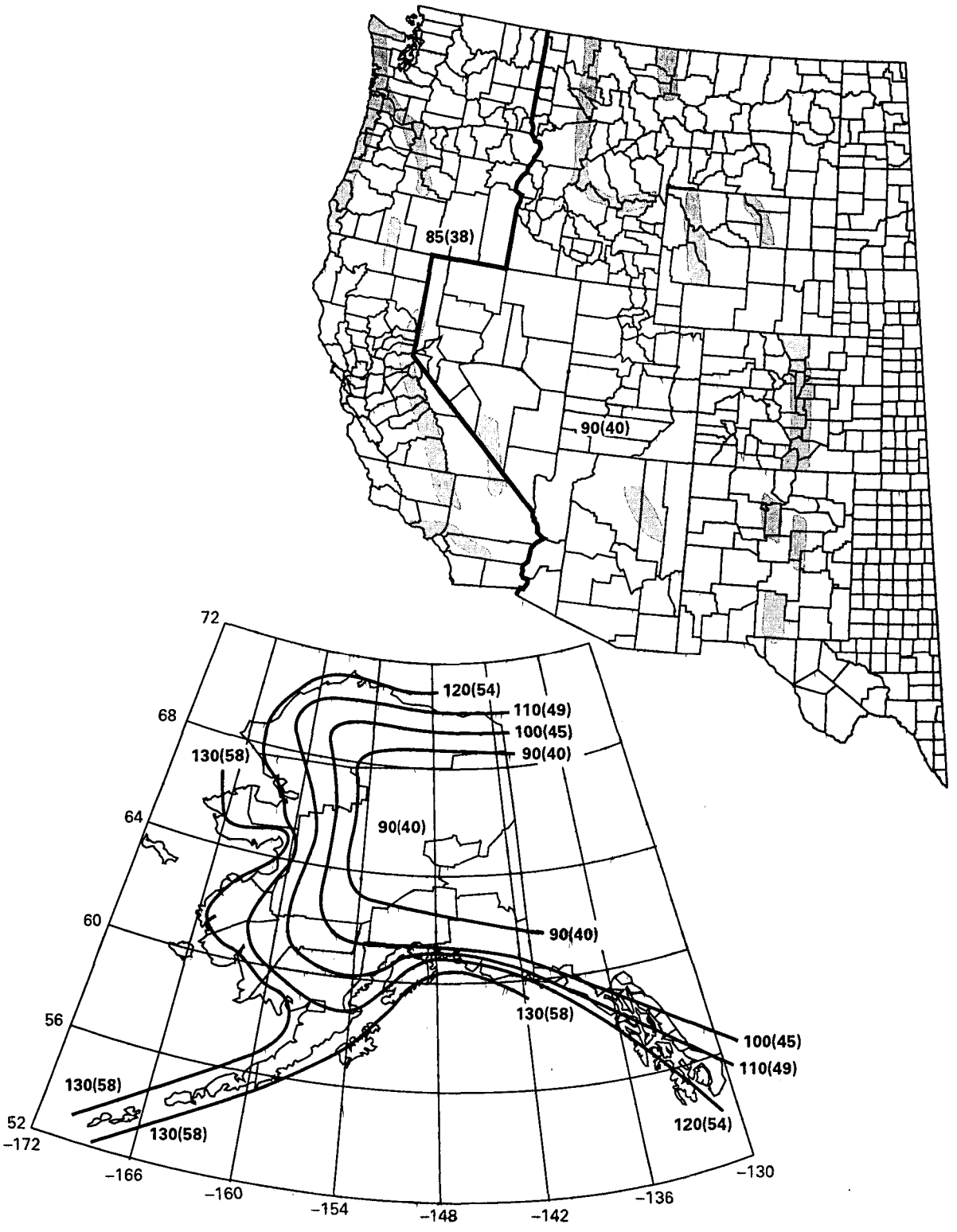

FIG. I-1 BASIC WIND SPEED

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A = center-to-center stack spacing for interference effects (ft)
A_1 = constant
A_2 = constant
$\hat{a}$ = maximum value amplitude for static equivalent design loads (ft)
a_s = maximum value amplitude for static equivalent fatigue loads (ft)
$\tilde{a}_M$ = r. m. s. dynamic displacement at $z = z_m$ (ft)
C_1 = constant for grouped/isolated stacks
C_2 = constant
C_M = mode shape constant
$\overline{D}$ = mean diameter for the segment z_1 to z_2, or for stacks with less than +/–10% variation over the top $\frac{1}{3}$ the value of $\overline{D}$ is the average over the top $\frac{1}{3}$ (ft)
H = height of steel stack (ft)
$\hat{g}$ = constant for maximum static equiv. loads
g = gravitational acceleration (32.2 ft/sec^2)
(a) g_c = gravitational constant (32.2 lbm-ft/lbf-sec^2)
g_s = constant for fatigue static equiv. loads
m_e = equivalent uniform mass per unit length (lbm/ft)
$m(z)$ = mass per unit length at height z (lbm/ft)
m_r = dimensionless mass
n_1 = natural frequency of mode (Hz)
R = constant for tapered stacks
S = strouhal number
V_c = critical speed for the segment z_1 to $z_2 = 5n_1\overline{D}$ (ft/sec)
$V_{z_{cr}}$ = mean hourly design speed (50-year return period) at the critical height z_{cr} used for evaluating the critical wind velocity (ft/sec)
z = height z under consideration (ft)
z_{cr} = $\frac{1}{2}(z_1 + z_2)$ or, for stacks with less than +/–10% variation over the top third, $z_{cr} = \frac{5}{6}H$ (ft)
z_M = height at maximum modal shape displacement (H for mode 1) (ft)
z_1, z_2 = upper and lower limits of a section of the stack over which the diameter changes by 30% (i.e., $\overline{D}$ ±15%) (ft)
a = amplification factor
β_a = aerodynamic damping
β_s = structural damping
λ = aspect ratio
ρ = air density (0.00238) (lbm-sec^2/ft^4)
$\phi(z)$ = normalized mode shape at height z (unitless) (a)
$\phi(z_M)$ = max normalized modal displacement $\phi(z)$ for mode at $z = z_M$, for the first mode $z = H$ (unitless) (a)
$\hat{\omega}(z)$ = equivalent static load (lbf/ft)
$\omega_s(z)$ = equivalent fatigue load (lbf/ft)

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ASME STS-1—2000
(Revision of ASME/ANSI STS-1-1992)

STEEL STACKS

AN AMERICAN NATIONAL STANDARD



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The American Society of Mechanical Engineers

AN AMERICAN NATIONAL STANDARD

STEEL STACKS

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FOREWORD

In early 1978, the American Society of Mechanical Engineers was approached by a group interested in formulating a standard for the design, fabrication, and erection of steel stacks and their appurtenances. They felt there was a need for such a code to establish a better level of standardization in the industry and for safeguarding the community. Because of the particular nature of stacks and their susceptibility to failures due to wind and seismic-induced vibrations, along with corrosion and erosion, the design process is a complex one. Additionally, recent regulations by the Environmental Protection Agency concerning emissions have placed a strong emphasis on on the mechanical design of stacks. In the last several decades, much research has been done and many papers written on the subject. While this investigation and research continue, it was the feeling of these persons that some formal guidelines be established at this time. Therefore, in April of 1979, a group comprised of stack users, researchers, designers, fabricators, and erectors convened at the United Engineering Center in New York City under the auspices of the American Society of Mechanical Engineers to formulate such a code.

With the above in mind, the group subdivided and began gathering information to formulate guidelines for mechanical design, material selection, the use of linings and coatings, structural design, vibration considerations, access and safety, electrical requirements, and fabrication and construction. When these were established, a section on maintenance and inspection was added. The following is a result of their work and investigation. The initial document was approved as an American National Standard in August 1986 and published as ASME/ANSI STS-1-1986 in May 1988.

During the next three years, the committee received comments from the public at large and from its own membership regarding the Standard's content. Several formulas needed correction and some of the symbols needed to be clarified. Section 6.3.3 regarding Earthquake Response was also reviewed and revised to allow for static rather than dynamic analysis in certain cases, and to correlate it with ASCE STD-7-88 (formerly ANSI A58-1). These changes were then submitted to the general membership and approved.

In 1994, the committee was reorganized to further review and update this steel stack Standard. Emphasis was given to the Structural Design and Vibrations chapters. Chapter 4, "Structural Design," was rewritten to be more compatible with the nomenclature, formulae, and symbols used in the Manual of Steel Construction - Allowable Stress Design (ASD), 9th Edition and Load and Resistance Factor Design (LRFD) 1st Edition. Chapter 5, "Vibrations," was revised to be more "user friendly". These and other chapters were updated to include the latest recognized applicable codes and standards. This revised standard was approved as an American National Standard on August 29, 2000 and reissued as STS-1-2000.

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Steel Stacks

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The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposals, including any pertinent documentation.

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Subject:	Cite the applicable paragraph number(s) and concise description.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
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CONTENTS

Foreword iii
Committee Roster v
Committee Correspondence ix

0 INTRODUCTION 1

1 MECHANICAL DESIGN 1

2 MATERIALS 5

3 LININGS AND COATINGS 8

4 STRUCTURAL DESIGN 15

5 DYNAMIC WIND LOADS 22

6 ACCESS AND SAFETY 25

7 ELECTRICAL 31

8 FABRICATION AND ERECTION 32

9 INSPECTION AND MAINTENANCE 34

Tables

4.1 Factors of Safety 19
4.2 Minimum Structural Plate Thickness and Maximum Stiffener Spacing 20
5.1 Representative Structural Damping Values (β_s) 23

Figures

6-1 Minimum Ladder Clearances 26
6-2 Ladder Dimensions, Support Spacing, and Side Clearances 28
6-3 Landing Platform Dimensions 29
6-4 Example of the General Construction of Cages 30

Mandatory Appendix

I Structural Design 37

Nonmandatory Appendices

A Mechanical Design 48
B Materials 57
C Linings and Coatings 66

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D Structural Design 70
E Example Calculations 77
F References 86

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STEEL STACKS

0 INTRODUCTION

The following Standard applies to steel stacks; that is, those stacks where the primary supporting shell is made of steel. It applies to both single- and multiple-walled steel stacks, either of which can be lined or unlined. It also applies to steel stacks that are guyed, or to certain aspects of tower stacks. The stack may be supported on a foundation or from another structure.

This Standard covers many facets of the design of steel stacks. It outlines the consideration which must be made for both the mechanical and structural design. It emphasizes what consideration must be taken for wind- and seismic-induced vibrations. It gives guidelines for the selection of material, linings, and coatings. It gives the requirements for lighting and lightning protection based upon existing building and federal codes. It gives the requirements for climbing and access based upon current Occupational Safety and Health Administration (OSHA) standards. It emphasizes the important areas regarding fabrication and construction. It outlines areas requiring maintenance and inspection following initial operation.

Although many of the topics within these guidelines may be used for all stacks, this Standard is intended to provide design guidelines for stacks containing non-flammable gases such as combustion exhaust gases at low internal pressures. For stacks containing combustible gases under pressure such as flare stacks and flammable vents, additional design considerations must be addressed, including design for internal pressure, design for internal deflagration pressure, and compatibility with adjoining piping design that is in accordance with piping and/or vessel design codes such as ASME B31.3 and Section VIII of the ASME Boiler and Pressure Vessel Code. In addition, the materials of construction referenced in this Standard may not be allowed for use with flammable gases under pressure per ASME B31.3 and Section VIII of the ASME BPVC; materials suitable for pressure containment of flammable gases are listed in these codes. No attempt is made within this Standard to define the need or the methods to be used to consider these additional design considerations.

The information presented has been prepared in accordance with established engineering principles utilizing state-of-the-art information. It is intended for general information. While every effort has been made to ensure its accuracy, the information should not be relied upon for any specific application without the consultation of a competent, licensed professional engineer to determine its suitability. It is therefore recommended that Engineering/Design drawings of the stack bear the Professional Engineer Seal, signature, and date.

Nothing in the Standard shall be construed to alter or subvert the requirements of any existing code or authority having jurisdiction over the facility. Furthermore, alternate methods and materials to those herein indicated may be used, provided that the engineer can demonstrate their suitability to all affected agencies and authorities.

1 MECHANICAL DESIGN

1.1 Scope

Mechanical design includes sizing of the gas passage, both in diameter and height; and the drop in gas temperature as heat is transferred through the stack wall. Methods for calculating draft, draft losses, and heat losses are given. Differential expansion of stack components is discussed. Design considerations for stack appurtenances are established.

1.2 General

The purpose of a stack is to vent process exhaust gases to the atmosphere. The mechanical design of stacks is now controlled in part by air pollution rules and regulations. Heights and diameters are set by a balance between structural stability and function, while at the same time meeting the requirements for air pollution control dispersion of the gases to the atmosphere. The heights of steel stacks have increased to satisfy ambient air quality, and stack inlet gas temperatures have decreased as more heat energy is recovered. The importance of attention to stack heat losses has therefore increased. Stack minimum metal temperature should be held above the acid dew point of the vented gases, if possible. Stacks are being designed with many

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appurtenances to monitor the gases and make stack inspections.

1.3 Size Selection (Height, Diameter, and Shape)

1.3.1 Height. Stack height may be set by one or more factors.

(a) Environmental Protection Agency (EPA) regulations may set the required stack height for downwash due to local terrain or adjacent structures, or to disperse pollutants at a minimum height above the site. Refer proposed stack location and purposes to the proper EPA authorities for the minimum height requirement under controlling air pollution control regulations. See Federal register part II EPA 40CFR, part 51, Stack Height Regulation (July 8, 1985).

(b) The National Fire Protection Association (NFPA) sets minimum height of high-temperature stacks above building roofs and structures for fire protection and human safety. Local codes are often more stringent and must be followed. A minimum of 8 ft of height above a roof surface or roof mounted structure within 25 ft of a stack emitting gases above 200°F (93°C) should be maintained.

(c) The draft requirement of the process to be vented may establish stack height. Formulas to calculate available draft are presented in subsequent paragraphs.

(d) The effective height of a stack considering plume rise may be increased by installing a nozzle or truncated cone at the top to increase the exit velocity of the gases. Several plume rise formulas are available but in actual practice, plume rise can be essentially negated by high wind velocities, low temperatures, and site conditions.

1.3.2 Diameters. The stack diameter may be set by one or more factors.

(a) Gas passage diameter is usually established by the volume of process gas flowing and available draft (natural draft minus draft losses). Velocities in a round stack between 2400 and 3600 ft/min are most common. Stacks venting saturated gases sometimes limit maximum stack velocities between 1800 and 2400 ft/min to reduce entrained or condensed moisture from leaving the stack exit. Tests by EPRI give different ranges for each type inner surface (see EPRI Wet Stack Design Guide TR-107099-1996).

(b) Stack shell diameters may be controlled by transportation shipping limitations. Caution should be taken to ensure that mechanical performance and structural stability are maintained.

(c) Structural stability may control a stack shell diameter selection and therefore, any size selection based on mechanical criteria must be maintained as tentative until a structural analysis can confirm its acceptability.

(d) Future increases in stack gas volume should be considered as well as future changes in process gas temperatures and gas quality in the diameter selection.

(e) EPA regulations may set stack exit diameter because of plume rise considerations. EPA requirements have sometimes set stack diameters in the test zone to provide optimum velocities for testing.

1.3.3 Shape. The shape of the stack varies with designers' preferences.

(a) Stacks generally are cylindrical in shape for efficiency in structural stability and economy in fabrication. Cylindrical shapes may vary in diameter throughout the height of the stack; however, diameter changes shall occur at an angle not exceeding 30 deg from the vertical.

(b) Other geometrical shapes such as octagonal, triangular, etc. must be considered special and particular attention given to dynamic stability as well as mechanical design. Unusual shapes for aesthetic appearance should be treated both structurally and mechanically as unusual and basic engineering design standards should be followed.

1.4 Available Draft

The available draft without fan assistance equals the natural draft minus draft losses.

1.4.1 Natural Draft. The approximate natural draft of a stack is calculated from the following equation:

$$DR_N = 7.57\, H_E \left(\frac{1}{T_A} - \frac{1}{T_G}\right) \frac{B}{30} \qquad (1.1)$$

where,

DR_N = stack natural draft—water gage, in.
H_E = stack height above center line inlet, ft
T_A = absolute temperature of atmosphere, °R
T_G = average absolute temperature of gas, °R
B = barometric pressure—mercury absolute, in.

Differences in gas absolute density due to composition and moisture have been neglected.

1.4.2 Draft Losses. Stack draft losses are entrance losses, friction losses, and exit losses. Draft losses are calculated from the following formula:

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(a) Entrance loss

$$FL_{en} = 0.003\ KdV^2 \tag{1.2}$$

(b) Friction Loss

$$FL_f = \frac{2.76}{B}(F)(T_g)\left(\frac{HE}{D_i^5}\right)\left(\frac{W}{10^5}\right)^2 \tag{1.3}$$

(c) Exit Loss

$$FL_{ex} = \left(\frac{2.76}{B}\right)\left(\frac{T_g}{D_t^4}\right)\left(\frac{W}{10^5}\right)^2 \tag{1.4}$$

where,

K = breeching inlet angle factor (see Nonmandatory Appendix A, Table A-1)
d = gas density, lb/cu. ft
V = gas velocity at inlet, ft/sec
B = barometric pressure—mercury absolute, in.
F = friction factor based on Reynolds number (see Fig. A-1 in Nonmandatory Appendix A)
T_g = average absolute temperature of gas, °R
H_E = stack height above center line of inlet, ft
D_i = inside diameter(s) of stack section, ft
D_t = inside diameter of stack at outlet, ft
W = mass flow rate of gas, lb/hr
FL_f = stack friction loss—water gage, in.
FL_{ex} = stack exit loss—water gage, in.
FL_{en} = stack entrance loss—water gage, in.

The total of the calculated losses comprises the total stack draft loss.

(d) Total Loss

$$FL_{\text{total}} = FL_{en} + FL_f + FL_{ex} \text{ water gage, in.} \tag{1.5}$$

Consideration should be given to the possible gas expansion or compression draft loss in large or unusually shaped entrances. Consideration should also be given to stack draft losses caused by stack mounted sound attenuators, stack dampers, or stack caps.

1.5 Heat Loss (See Nonmandatory Appendix A, Figures A-2 to A-9)

1.5.1 Ambient Conditions. Since the heat loss through the walls of a stack varies with ambient conditions, it is necessary to establish the desired design criteria. The low ambient temperature expected should be specified, as well as an average normal wind speed.

1.5.2 Insulation and Linings. Insulation and linings affect total heat loss.

(a) Insulation is applied to outer surface of the stack or between the shells of a dual wall stack. A thickness is selected to reduce the stack heat loss to the desired level or to provide a maximum stack exterior surface temperature. Insulation should be selected for the maximum temperature to which it will be exposed. Insulation should be held to the stack shell as recommended by the insulation manufacturer for the job conditions. When thicknesses over 1½ in. are used, two layers should be specified so that joints can be staggered. An appropriate outer surface weather protection should be specified for external applied insulation. Metal lagging should be secured with metal bands on maximum 24 in. centers.

(b) Stack linings are used for either heat loss reduction, as a protective coating, or both. A thickness is selected for the job conditions. Specify a service temperature range. Lining reinforcing and attachments to stack shell should be per manufacturer's recommendation.

(c) Stack surface cladding, either internal or external, will affect heat loss and should be considered in heat loss calculations.

1.5.3 Film Coefficients. Internal and external film coefficients affect heat loss.

(a) The internal stack surface film coefficient varies with gas velocity, gas temperature, stack diameter, and surface roughness. The effect of both maximum and minimum gas flow velocity on film coefficients should be studied in heat loss calculations. Therefore, the range of expected gas flow should be specified.

(b) The external stack surface film coefficient varies with ambient wind speed and stack diameter. A wind speed of 15 mph is suggested for establishing a maximum heat loss unless field data can prove higher or lower average velocities.

1.5.4 Heat Loss Calculations. Heat loss through the wall(s) of a stack can be calculated with the following formula:

Heat Transferred Through the Stack Wall

$$Q = U \times A \times t_s \tag{1.6}$$

Heat Loss in Flowing Gas Entering Versus Leaving

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$$Q = W \times C_p \times t_g \quad (1.7)$$

Combining Eqs. (1) and (2)

$$U \times A \times t_s = W \times C_p \times t_g \quad (1.8)$$

$$t_s = \left(\frac{t_{in} + t_{out}}{2}\right) - t_{amb} \quad (1.9)$$

$$t_g = t_{in} - t_{out} \quad (1.10)$$

$$U \times A \times \left(\frac{t_{in} + t_{out}}{2}\right) - t_{amb} = W \times C_p \times (t_{in} - t_{out}) \quad (1.11)$$

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_a} + \frac{1}{h_{ins}} + \frac{1}{h_l} + \frac{1}{h_o} \quad (1.12)$$

Heat Loss Through the Stack Wall Section

$$Q/A = U \times t_s \quad (1.13)$$

Heat Loss Through Each Component of the Stack Wall Section

$$Q/A = h \times t_h \quad (1.14)$$

Heat Loss Formula

A = stack mean surface area, sq. ft
U = overall heat transfer coefficient
t_s = average gas temperature minus ambient temperature, °F
W = gas flow, lb/hr
C_p = specific heat of gas, Btu/lb, °F
t_g = gas temperature entering minus gas temperature leaving, °F
h_i = internal film coefficient Btu/hr-sq. ft, °F
h_a = airspace coefficient Btu/hr-sq. ft, °F
h_{ins} = insulation coefficient Btu/hr-sq. ft, °F
h_l = lining coefficient Btu/hr-sq. ft, °F
h_o = external film coefficient Btu/hr-sq. ft, °F
t_h = temperature drop through the h component of the stack wall, °F

1.5.5 Other Heat Loss Considerations That Affect Minimum Metal Temperatures

(a) When gases enter a stack above the base, consideration should be given to the use of a false bottom to prevent gas temperatures below the dew point in the nonactive lower part of the stack. This false bottom should be well drained and of a shape to prevent solids buildup.

(b) Since ambient air winds will enter the top of the stack, especially at low stack flow velocities, and hence cause low exit metal temperatures, some provision should be made to reduce the resulting top-of-stack corrosion problems. The top of the stack may be fabricated of corrosion-resisting alloys or a truncated discharge cone utilized to increase stack exit velocities.

1.6 Thermal Expansion

Differential expansion between components of a stack should be carefully studied in areas to include:

(a) between external and internal shells of a dual wall or multi-flue stack;
(b) at breeching openings;
(c) at test and instrument ports;
(d) at test platform, catwalk, and ladder attachment brackets;
(e) at building braces and guide lugs;
(f) at roof flashing and counterflashing;
(g) at stack tops and truncated cone;
(h) between stack shells and external insulation;
(i) at weld joints between dissimilar metals.

1.7 Appurtenances

Attachments to a stack may include the following:

(a) Access doors of an appropriate size should be located for access to inspect the inside bottom base of the stack and at other selected locations for inspection and maintenance.

(b) False bottoms located just below the lower stack inlet are recommended.

(c) Drains in false bottoms and/or foundations should be installed to direct water away from the stack base and anchor bolts.

(d) Test and instrument ports should be located and sized for each specific application.

(e) Consideration should be given to providing inspection ports spaced appropriately over the height of the stack.

(f) An access ladder and test platforms should be selected for job conditions with the required size of the test platforms in the width specified.

(g) A painter's track and trolley may be specified on painted stacks. If test platforms and lighting access platforms are specified, consideration should be given to the use and location of multiple painter's trolleys and tracks. See Section 6.

(h) Lighting requirements are established by Federal Aviation Administration (FAA) directives. Access plat-

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forms to service lights are recommended for corrosion resistant construction. See Sections 6 and 7.

(i) Rain caps are generally not required on full-time active stacks. When specified, a diameter of two times the stack diameter and a clear height of one stack diameter is recommended.

(j) Stack spark arresting screens of stainless steel material a minimum of two stack diameters high may be specified when needed.

(k) Metal stacks require no lightning protection other than proper grounding at the base per NFPA requirements. See Section 7.

(l) Stack internal shutoff dampers and stack cap dampers demand special consideration when specified.

(m) Straightening vanes to distribute flowing gas for effective testing should be specified as required.

(n) Splitter baffles are sometimes used when two stack inlets enter the stack opposite each other to reduce back pressure in the event that isolation dampers are not used.

(o) Gin pole or davit lifts are sometimes specified for hoisting instruments to the test platform.

(p) Top of stack roofs for multiple flue stacks and dual wall stacks should provide proper weather protection for the inside surfaces, while at the same time providing for expected differential expansion between flues and the stack outer shell. Consideration should be given to the effect of the buildup of ash on any flat surfaces.

(q) Noise pollution control may require acoustical suppressing sound attenuators within the stack.

1.8 Mechanical Section Symbols

DR_N = stack natural draft — water gage, in.
H_E = stack height above center line inlet, ft
T_A = absolute temperature of atmosphere, °Rankine
T_G = average absolute temperature of gas, °Rankine
B = barometric pressure — mercury absolute, in.
K = constant for breeching inlet angle
F = friction factor based on Reynolds number
d = density of gas, lb/ft^2
D_i = inside diameter(s) of stack sections, ft
D_t = inside diamter of stack at outlet, ft
W = mass flow rate of gas, lb/hr
FL_f = stack friction loss — water gage, in.
FL_{ex} = stack exit loss — water gage, in.
FL_{en} = stack entrance loss — water gage, in.
A = stack mean surface area, sq. in.
U = overall heat transfer coefficient
t_s = average gas temperature minus ambient temperature, °F
C_p = specific heat of gas Btu/lb, °F
t_g = gas temperature entering minus gas temperature leaving, °F
h_i = internal film coefficient Btu/hr-sq. ft, °F
h_a = airspace coefficient Btu/hr-sq. ft, °F
h_{ins} = insulation coefficient Btu/hr-sq. ft, °F
h_0 = external film coefficient Btu/hr-sq. ft, °F
t_h = temperature drop through the h component of the stack wall
h_l = lining coefficient Btu/hr-sq. ft, °F
V = gas velocity at stack inlet, ft/sec

1.9 Mechanical Section Definitions

appurtenances: stack specialty design items apart from shell and structural members.

cladding: thin metal overlaid over the base metal metallurgically and integrally bonded to the base metal.

EPRI: Electric Power Research Institute.

EPA: Environmental Protection Agency (may be Federal, State, or local) government regulatory authority.

false bottom: a cone or plate located just below the breeching opening to prevent gases from entering the lower section of stack.

NFPA: National Fire Protection Association.

test zone: section of stack designed for testing. The location of test ports in relationship to upstream and downstream flow pattern disturbances is well documented in Federal and State air quality rules and regulations.

truncated cone: a converging section reducing the exit diameter located at the top of the stack.

2 MATERIALS

2.1 Scope

Material specifications are intended to cover single or double wall stacks that are free-standing and self-supporting, guy or cable supported, or supported by structural steel braces or framework. Reference is made to the 1975 edition of Design and Construction of Steel Chimney Liners, published by the American Society of Civil Engineers.

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2.2 Materials

The Materials listed in the following sections are suggested for use based on their ability to meet the physical, mechanical, chemical, and environmental requirements of a given application. Acceptance of a material for a specific application must be based on service experience or independent verification of its suitability.

2.2.1 General Considerations

(a) Materials shall conform to the applicable requirements in the sections hereinafter detailed.

(b) The contractor shall submit one copy of the chemical-composition and mechanical-property mill test reports for all steels used to the owner for approval prior to construction unless otherwise indicated.

(c) When required for testing purposes, the contractor will furnish the owner with identified scrap samples of the shell plates.

(d) This section does not apply to linings and coatings of stacks. See Section 3.

(e) Corrosion allowances shall be considered (typically $\frac{1}{16}$ in. to $\frac{1}{8}$ in.) where carbon, high-strength, low alloy, and alloy steels are used. Experience or the results of tests should be used when selecting an allowance.

2.2.2 Shell and Base Plates. For more information on this subject, see Tables B-1 through B-11 in Nonmandatory Appendix B.

(a) Shell and base plates typically may be of one or more of the following structural quality materials:

(1) Carbon steels conforming to the ASTM A 36, A 283, or A 529 Specifications;

(2) High-strength, low alloy steels conforming to the ASTM A 242, A 572, or A 588 Specifications;

(3) Stainless steels conforming to the ASTM A 666 Specification;

(4) Stainless chromium-nickel steel clad plate conforming to ASTM A 264 and nickel-base alloy clad steel conforming to ASTM A 265 may be considered for use as shell plate;

(5) Metals listed in Materials Appendix (i.e., Nonmandatory Appendix B), Table B-9 may be used not only as sheet linings and cladding but also as solid plate for shell plates.

(b) Pressure vessel quality carbon steels such as ASTM A 285, A 515, and A 516; alloy steels such as ASTM A 387; and stainless steels such as ASTM A 240 may be substituted for structural quality materials as appropriate.

(c) Carbon Steels such as ASTM A 516, Grades 55 through 70 and low alloy steels such as ASTM A 517, Grades A through T and ASTM A 537 are usually specified for service temperatures as low as -50°F (-46°C). Nickel-containing alloy steels such as ASTM A 503, Grades A and B are usually used for service temperatures as low as -75°F (-59°C); and ASTM Grades D, E, and F are often used for service temperatures of −150°F (−101°C). Nickel-containing alloy steels and nickel stainless steels are used for lower temperatures. Suppliers of structural quality steels will provide data on notch toughness when specified.

(d) Protection against corrosion and/or oxidation may be required on interior and/or exterior surfaces depending on the materials utilized and the conditions encountered. Section 3 should be consulted and utilized as appropriate.

(e) Creep rupture tensile stresses for sustained loading and high-temperature service conditions must be considered as given in para. 4.4.8.

2.2.3 Stiffeners and Structural Braces and/or Framework

(a) Stiffeners and structural braces and/or framework typically may be of one or more of the following materials:

(1) Carbon steels conforming to the ASTM A 36, A 283, or A 529 Specifications;

(2) High-strength, low alloy steels conforming to the ASTM A 242, A 572, or A 588 Specifications;

(3) Stainless steels conforming to the ASTM A 240 or A 666 Specifications or nickel-containing alloys having compositions similar to those of the shell plate.

(b) Protection may be required against corrosion for components exterior to the shell and against corrosion and/or oxidation for components on the shell interior. Section 3 should be consulted and utilized as appropriate.

2.2.4 Guy Wires, Cables, or Fittings

(a) Guy wires and cables typically may be of one or more of the following materials, and consideration should be given to the initial stretch of the material:

(1) Aluminum-coated steel wire strand conforming to the ASTM A 474 Specification;

(2) Zinc-coated (galvanized) steel wire strand conforming to the ASTM A 475 and A 586 Specifications;

(3) Zinc-coated (galvanized) steel wire rope conforming to the ASTM A 603 Specification;

(4) Stainless steel wire strand conforming to the ASTM A 368 Specification.

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(b) Fittings for guys and cables should comply with manufacturers' standards and be of aluminum-coated, zinc-coated (galvanized), or stainless steel as appropriate. Aluminum and zinc coating weights and stainless steel grade should match those of the guys or cables on which they are used.

2.2.5 Anchor Bolts, Washers, and Nuts

(a) Anchor bolts may be of threaded bolt and stud stock normally used as connectors, or of round stock of structural material that may be threaded. They are typically one of the following specifications:

(1) Carbon steel threaded fasteners conforming to the ASTM A 307 Specification;

(2) Carbon steel bolts for general applications conforming to the ASTM A 449 Specification;

(3) Alloy steel bolts, studs, and threaded fasteners conforming to the ASTM A 354 Specification;

(4) Alloy steel bolts and studs with enhanced impact properties conforming to the ASTM A 687 Specification;

(5) Carbon steel conforming to the ASTM A 36 Specification;

(6) High-strength, low alloy steels conforming to the ASTM A 572 or A 588 Specification.

(b) Material for washers shall conform to the ASTM F 436 Specification and correspond to the anchor bolt material.

(c) Material for nuts shall conform to the ASTM A 563 Specification and correspond to the anchor bolt material.

(d) Protection against corrosion may be required. Section 3 should be consulted and utilized as appropriate.

(e) Double nutting or an appropriate locking device is recommended.

2.2.6 Bolts, Washers, and Nuts

(a) Unless otherwise specified, carbon and high-strength steel bolts conforming to the ASTM A 307, A 325, or A 449 Specifications will be utilized.

(b) High-strength alloy steel bolts may be required and these should conform to the ASTM A 354 or A 490 Specifications.

(c) For high-temperature applications, bolt material should conform to the ASTM A 193 B7 Specification covering alloy and stainless steels. Stainless steel bolts are also covered under the ASTM F 593 Specification.

(d) Unless otherwise specified, nuts should conform to the ASTM A 563 Specification. Stainless/heat resisting nuts shall be of a material corresponding to that of the bolt unless galling/seizing considerations dictate otherwise.

(e) Washers shall conform to the ASTM F 436 Specification. Stainless/heat resisting washers shall be of a material corresponding to that of the bolt.

(f) Protection from corrosion may be required. Section 3 should be consulted and utilized as appropriate.

2.2.7 Appurtenances

(a) Ladders, cages, and stairs may be constructed of one or more of the following materials:

(1) structural steels and stainless steels conforming to the standards under para. 2.2.2(a);

(2) carbon steel sheet and strip conforming to the ASTM A 569 and A 570 Specification;

(3) high-strength, low alloy sheet and strip conforming to the ASTM A 606 and A 607 Specification.

(b) Platforms and grating may be constructed of one or more of the materials listed below:

(1) materials under 2.2.7(a);

(2) stainless steels conforming to the ASTM A 666 Specification;

(3) aluminum conforming to the ASTM B 221 Specification. Reference is made to the National Association of Architectural Metal Manufacturers (NAAMM) Manual for metal bar grating and stair treads.

(c) Handrails, toe plates, etc., typically are made of one of the following materials:

(1) carbon structural steel conforming to the ASTM A 36 or A 20 Specifications;

(2) high-strength, low alloy steel conforming to the ASTM A 242, A 588, or A 618 Specifications;

(3) aluminum conforming to the ASTM B 221 Specification;

(4) stainless steels conforming to the ASTM A 666 and A 554 Specifications.

(d) Access doors, instrument and sampling ports

(1) Access doors shall be of a material matching the shell plates or cast iron.

(2) Instrument and sampling ports shall be of a material of matching or higher alloy content than the shell plates.

(e) Painter's trolley and ring

(1) A painter's trolley and ring may be of carbon steel or high-strength, low-alloy steels as specified under para. 2.2.3 provided suitable corrosion protection is applied.

(2) Ring also may be of a material such as Type 304 or Type 316 stainless steel conforming to the ASTM A 240 or A 666 Specifications. Adequate structural supports are to be provided.

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(f) Stack Rain Caps

(1) Unless otherwise specified, stack rain caps shall be of the same composition as the stack shell.

(2) Because of potential corrosion problems, stainless steel conforming to the ASTM A 240 Specification or higher alloyed corrosion resistant materials should be considered.

(g) *Drain Systems.* A system should be provided for collecting and routing rain and condensate from the interior of the stack to a single collection point at grade level 2. Drain pipe shall be of corrosion resistant material such as Type 304 or Type 316 stainless steel conforming to the ASTM A 240 or A 666 Specifications, nickel alloy or plastic.

2.2.8 Welding Electrodes

(a) AWS D1.1 - Structural Welding Code Steel is usually specified for structural welding of steel stacks. As an alternative, ASME BPVC, Section IX, Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operations may be specified.

(b) Welding electrodes with a minimum tensile strength of 70 ksi are to be used for carbon steel applications in steel stack construction . The type of electrode specified is a function of the welding process to be used.

(c) For high-temperature applications, above 750°F (400°C), using high-strength low alloy steels, welding electrodes with a minimum tensile strength of 80 ksi are to be used.

(d) For steel stack construction using alloy steels, such as ASTM A 335 and A 387, E8018-B2L electrode with welding procedures conforming to AWS D10.8 - Recommended Practice for Welding of Chromium-Molybdenum Steel Piping and Tubing should be used.

(e) When stainless steels and nickel alloys are used as plate, sheet, or as clad plate, the following specifications apply:

(1) ANSI/AWS A5.4 Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding

(2) ANSI/AWS A5.9 Specification for Bare Stainless Steel Welding Electrodes and Rods

(3) ANSI/AWS A5.11 Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding

(4) ANSI/AWS A5.14 Specification of Nickel and Nickel Alloy Bare Welding Electrodes and Rods

(5) ANSI/AWS A5.1 Specification for Covered Carbon Steel Arc Welding Electrodes

(6) ANSI/AWS A5.18 Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding

(7) ANSI/AWS A5.20 Specification for Carbon Steel Electrodes for Flux Cored Arc Welding

(f) When welds are made between dissimilar metals, the type of electrode to be used should be based on the higher grade material being welded.

(g) As with the design of the stack metal, proper consideration must be given to the reduction in weld metal strength when exposed to high temperatures. The temperature-based strength reductions for the weld metal should be assumed to be the same as that for the base metal.

3 LININGS AND COATINGS

3.1 Scope

This section will provide the designer with information that will help him to determine whether or not an interior lining and/or an exterior coating should be used on the stack, the types of linings and coatings that may be considered, and the general chemical and thermal limitations associated with each type. Considerations with respect to the use of insulating linings and exterior insulation also are presented.

3.2 Linings

(a) Linings for the interior of steel stacks may be required to provide resistance to corrosive gases, vapors, or condensates; to provide resistance to heat; and to maintain stack surface temperatures for the prevention of condensate corrosion.

(b) To determine if a lining should be used, a complete thermal analysis of the entire system from heat source to stack outlet should be performed giving primary consideration to the stack surface temperature. A complete chemical and physical analysis of the flue gas should also be performed to determine the presence of chemically corrosive constituents and the characteristics of particulate loading.

3.2.1 Temperature/Corrosion. The metal surface temperatures of uninsulated, unlined steel stacks may fall below flue gas dew points within the stack or at the stack outlet.

The most commonly quoted stack temperature is the flue temperature at the stack inlet. It is also the most misleading because it is the metal surface temperature that is of importance. Uninsulated unlined steel stacks can have metal surface temperatures 60% or more below the flue temperatures at the stack inlet, whereas

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stacks with external insulation often will have metal surface temperatures that are only slightly lower than the inlet flue gas temperature.

Critical corrosion temperatures are not absolute values covering all situations, but present focal points for more detailed study, i.e., if stack surface temperatures fall below acid condensation dew points, external insulation and/or higher flue gas velocities could correct the situation. External insulation can be used to maintain stack surface temperature at least 50°F (10°C) above the flue gas dew point. If metal temperatures are exceeded, internal linings may be used to provide a solution.

(a) 120°F (49°C). This is the water dew point, the condensation point of nitric acid, hydrofluoric acid, and sulfurous acid.

(b) 145°F (63°C). This is the temperature at which hydrochloric acid condenses. Chlorides are found in most coals.

(c) 275°F (135°C). This is the sulfuric acid dew point of No. 2 fuel oil having a 0.6% sulfur content.

(d) 320°F (160°C). The sulfuric acid dew point of No. 6 fuel oil having a 2% to 8% sulfur content.

(e) 400°F (204°C). The maximum theoretical acid dew point, assuming all sulfur present was converted into sulfur trioxide.

(f) 800°F (427°C). Temperatures above this point induce structural changes that render non-stabilized grades of stainless steel susceptible to intergranular corrosion. The temperature range for this effect is 800°F (427°C) to 1650°F (899°C).

3.2.2 Other Critical Temperatures

(a) 160°F (71°C). It has been found that irreversible damage takes place when skin is in contact with material at 160°F (71°C) for one second. Reversible injury occurs at 154°F (68°C) for one second, and the threshold of pain is about 140°F (60°C) for one second contact.

(b) 400°F (204°C). Average coefficients of linear thermal expansion for carbon, alloy, stainless steels, and nickel alloys are shown in Appendix B, Table B-1. These coefficients are of interest when welding carbon and alloy steels to stainless steels for service at temperatures of 400°F (204°C) and above.

(c) 750°F (400°C). For carbon steel such as ASTM A 36, creep becomes a design consideration at temperatures above 750°F (400°C). Creep is defined as the time-dependent permanent deformation which occurs after the application of a load to a metal in or above the creep temperature range. ASTM A 242 and ASTM A 588 high-strength low alloy steels may be used where steels with oxidation resistance and creep rupture properties superior to that of carbon steel are required. ASTM A 242 is the more resistant of the two and may be used at a temperature about 100°F higher than that of carbon steel (850°F or 455°C). Care should be exercised if using A 588 at 800°F (427°C) and above because of relatively low ductility.

(d) 850°F (455°C). The temperature at which creep becomes important for alloy steels.

(e) 1050°F (565°C). The temperature at which creep becomes important for chromium-nickel austenitic stainless steels.

(f) 1150°F (620°C) to 2000°F (1093°C). The temperature range over which the stainless steels depending on their alloy content, provide useful resistance to scaling. Refer to Nonmandatory Appendix B, Table B-2 for information on maximum temperatures for alloy and stainless steels to avoid excessive scaling.

3.2.3 Environmental Severity Levels. (See Nonmandatory Appendix C, Table C-1)

(a) Chemical Environment. Constituents within the flue gas that will affect the corrosivity of the environment and thereby the suitability of linings include oxides of sulfur (So_x), oxides of nitrogen (NO_x), chlorides (Cl), and fluorides (F).

(1) Mild. Flue surface temperatures above acid dew points (pH = 4 to 8)

(2) Moderate. Flue surface temperatures below acid dew points on an intermittent basis, but normally above the acid dew points (pH = 2 to 4).

(3) Severe. Flue surface temperatures below the acid dew points for all operating cycles (pH = less than 2).

(b) Temperature Environments. Temperature levels also contribute to the severity of the environment particularly as they relate to the suitability of organic linings. Temperatures that remain constant or steady may be less of a problem than those that are cyclic.

(1) Mild. Temperatures up to, but not exceeding, 200°F (93°C).

(2) Moderate. Temperatures from 200°F (93°C) to 350°F (177°C).

(3) Severe. Temperatures greater than 350°F (177°C).

3.2.4 Classifications of Linings (See Nonmandatory Appendix C, Table C-1 and Table C-2)

3.2.4.1 Organic Linings. Most acid-resistant organic linings fail or lose their flexibility and ability to resist liquid or vapor penetration at temperatures over 300°F (149°C). Some manufacturers claim that their products can perform up to 500°F (260°C). Often-

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times, the combination of the chemical environment, together with the temperature environment, will be synergistic in nature, and require more careful selection of a lining. Before choosing a particular lining, the designer should contact the manufacturer to ensure the suitability of the product for the requirements at hand.

(a) Organic resin. Polyester, novolac phenolic epoxy, novolac epoxy, epoxy, vinyl ester, etc. Linings comprised of chemical resinous compounds based on carbon chains or rings, and also containing hydrogen with or without oxygen, nitrogen, and other elements. The formulations incorporate hardening agents to cure the resins, and usually fillers or reinforcement to provide desirable physical properties. Application is in liquid form (solution, dispersion, etc.) using spray, roller, or trowel.

(b) Organic elastomers. Fluoropolymers, natural rubber, butyl rubber, and urethane asphalts, etc. Linings based on natural or synthetic polymers which, at room temperature, return rapidly to their approximate initial dimension and shape after substantial deformation by a weak stress and subsequent release of that stress. Application is in sheet or liquid form.

Due to the great number of variations of formulations by manufacturers of organic linings, this document will not be more specific in this regard. There are ASTM standards that can be used to evaluate certain properties of organic linings, and where standards do not exist or when further information is needed regarding specific products, their performance, and recommended usages are required, the linings manufacturers should be contacted.

3.2.4.2 Inorganic Linings

(a) Inorganic cementitious concrete monolithics. Linings comprised of materials other than hydrocarbons and their derivatives. These protective barriers are comprised of inert mixtures of chemically inert, solid aggregate filers and a cementing agent. The cementing agent may be an acid setting agent contained in the powder and a silicate binder, which subsequently hardens by the chemical reaction between the setting agent and the silicate binder, or a high alumina cement binder that hardens by hydration. Application is by troweling, casting, or guniting. Refractory installation quality control guidelines, monolithic refractory linings inspection and testing, and materials used shall be in accordance with API – RP936. Included are the following:

(1) Acid-resistant concrete. These linings are based on silicate chemical setting cements and utilize chemically inert fillers. Particularly suited for severe chemical environments and mild/moderate temperature environments.

(2) Acid-alkali-resistant concrete. These linings are generally based on a combined silicate chemically-resistant cement, with inert aggregate fillers. Particularly suited under moderate chemical environments and mild/moderate temperature environments.

(3) Refractory concrete. These linings are typically based on high alumina, hydraulically setting cement binders, utilizing inert refractory-type aggregate fillers. Suitable for mild chemical environments and severe temperature environments.

(4) Insulating concrete for temperatures to 650°F (899°C). Typical formulations include: expanded clay, slag, or fuel ash, combined with a high alumina hydraulic cement binder; a calcined diatomite aggregate filler and high alumina cement; a perlite or vermiculite aggregate filler combined with a high alumina cement binder. Suited for application where temperature is the main environmental condition to be addressed.

(5) Insulating concrete for temperatures up to 2200°F (1204°C). Linings are based on high-temperature insulating aggregate fillers utilizing a high alumina hydraulic setting cement binder. Particularly suited where the temperature environment and insulation characteristics of the lining are important.

(b) Inorganic masonry. Linings comprised of nonmetallic chemically inert masonry units, such as brick or foamed closed cellular glass block, bonded together with a mortar having adequate adhesion to the units, and possessing suitable chemical and thermal resistance for the anticipated exposure. Included are the following:

(1) Foamed closed cellular glass block. Linings constructed of this unit are highly insulative. Borosilicate-type glass compositions are most suited for withstanding severe chemical environments and severe temperature environments as defined by this Standard.

(2) Firebrick. Linings of brick having appropriate alumina content to be chemically and physically stable at high temperatures, and installed with a suitable refractory mortar, may be used to temperatures of 2200°F (1204°C).

(3) Acid-resistant brick. These linings are constructed of chemically-resistant bricks, which are normally laid in chemical-resistant mortar for use where there are severe chemical and thermal environments. The acid-resisting brick should be specified in accordance with either ASTM C 279 or ASTM C 980.

(4) Insulating firebrick linings. These linings are comprised of lightweight, porous refractory brick having much lower thermal conductivity and heat storage capacity than firebrick and installed with high-temperature refractory mortars and used in very high-temperature environments where insulation quality is desirable.

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3.2.4.3 Metallic Linings and Cladding. See Nonmandatory Appendix C, Table C-1.

Metallic linings and cladding should be considered for use whenever resistance to corrosion and/or elevated temperature is a concern. High performance metals and alloys including stainless steels, nickel-based alloys and titanium are available for use as linings or as cladding on carbon-steel plate. Usually, the metallic linings are $^1/_{16}$ in. (1.6 mm) thick although thickness of $^1/_8$ in. (3.2 mm) also are used. Cladding thickness can range from 5% to 50% of the total plate thickness, but for light gauge, $^1/_4$-in. (6.4 mm) carbon steel, the preferred thickness is $^1/_{16}$ in. (1.6 mm) or 25% of the total plate thickness. Metallic linings are applied to the substrate and welded together by the overlap joint method as described in NACE Standard Recommended Practice RP0292-98. Metal cladding is applied to carbon steel plate by either the hot, sandwich-rolling process or the explosive bonding process. The roll bonded clad-plate product with the cladding metallurgically bonded to the carbon steel is available from the mill. Clad plate may be installed as described in NACE Standard Recommended Practice RP0199-99.

When selecting stainless steels and nickel alloys for corrosive applications, a brief description of the effects of some of the alloying elements may be helpful. Chromium (Cr) is most important from the stand point of developing the passive or protective film which forms on the surface of the alloy in air or oxidizing environments. Nickel (Ni) is important in that it helps to expand the passivity limits of the alloy thereby contributing to improved corrosion resistance. It also is responsible for the maintenance of the desirable austenitic microstructure, which provides good ductility, fabricability, and weldability. Molybdenum (Mo) is the most important element for providing pitting and crevice corrosion resistance, and Nitrogen (N) and Tungsten (W) are helpful in this regard. Nitrogen also increases the strength of the alloy and helps to maintain the austenitic microstructure. ASTM G-48 offers standard test methods for evaluating pitting and crevice corrosion resistance in chloride environments.

The most important element for increasing oxidation (corrosion) resistance of steels at temperatures of 1,000°F (538°C) and above is chromium. Other elements such as silicon (Si), aluminum (Al) and the rare earth elements such as cerium (Ce) also increase oxidation resistance, particularly when added to alloys containing chromium.

To avoid intergranular corrosion in certain acidic environments, intergranular carbide precipitation (ICP) resulting from welding must be prevented. ICP can be prevented by the use of low-carbon (L) grades (less than 0.03 C) or the addition of stabilizing elements such as titanium (Ti) and columbium (Cb).

3.3 Coatings

(a) The terms *paint* and *coating* are sometimes difficult to differentiate. The term *coating* is a more generic classification that includes paint. While the primary function of a coating is to provide protection, a paint may have the additional function of color along with protection. The color properties of a paint may be more important than the protective properties. In this document, the word *coating* will also mean paint.
Stacks that are constructed of carbon steel may require coatings to protect the steel from corrosion by the atmospheres to which it is exposed; to provide an aesthetically pleasing structure; and to be in accordance with underwriter codes and government regulations pertaining to aviation safety. Some low alloy steels, such as ASTM A 242 and A 588 exhibit superior atmospheric corrosion resistance to carbon steels and may not require an exterior coating depending on the corrosivity of the atmosphere. Stacks that are constructed of stainless steel or higher alloys should be resistant to atmospheric corrosion.

(b) Since a stack is subjected to outdoor exposure, careful consideration for sunlight and weathering must be given, together with an awareness of discoloration, fading, brittleness, etc.

(c) In assessing the corrosive effects of the environment, careful consideration should be given to the top portion of the stack where washdown may create a more severe condition.

(d) The type of coating required will depend upon the color, pigmentation, maximum temperature reached by the steel skin, and the duration of the higher temperatures.

(e) The majority of heat-resistant coatings use heat-resistant pigments, either inorganic or metallic.

(f) In coating steel stacks, water-based paints or emulsions have not shown good performance, and tend to exhibit bleeding.

3.3.1 Classification of Coatings. See Nonmandatory Appendix C, Table C-2.

(a) Oil Based Coating System. Such a coating system is suitable for providing excellent protection when subjected to outside rural weather conditions, but only protects against very mild industrial fumes and mild marine environments. This coating system is not recommended for corrosive environments, tends to exhibit

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very slow drying characteristics in curing, and embrittles and yellows with aging.

(b) Alkyd Coating System. This type of coating shows excellent resistance to weathering in rural environments. It shows poor acid chemical resistance, and shows only fair performance in marine salt environments. This system is easy to apply, exhibits good color retention and gloss, is economical, and is easy to recoat. However, it is very limited in its usage.

(c) Phenolic Coating System. This system is excellent in moderate/severe chemical corrosive atmospheres, and exhibits good weathering resistance. It shows excellent resistance in very humid environments.

(d) Vinyl Coatings. These coatings are normally used in severe chemical environments, and not usually used as stack coatings because they are expensive. However, these coatings do exhibit excellent resistance to weathering, and provide a good degree of flexibility.

(e) One-Coat Shop Painting for Structural Steel. This type of coating is not for protecting steel exposed to weathering for greater than a six-month period even in normal rural or mild industrial environments, or marine exposures.

(f) Coal-Tar Epoxy Coating. Used extensively in marine and chemical environments. These coatings have a tendency to embrittle during early years of exposure and, hence, require relatively rigid substrate to show good performance. They are less expensive than the two-component epoxies, normally black in color, and require an SSPC-PC#5 surface preparation.

(g) Zinc-Rich Painting Systems (Inorganic). This coating provides excellent protection to the steel from weathering and is suited for high humidity and marine atmospheres. It is not particularly suited for acid resistance. However, when it is top-coated, it provides good resistance to exposure to chemical fumes. It requires an SSPC-SP#10 minimum surface preparation with a surface profile of 1 to 2 mils in order to obtain total adhesion.

(h) Epoxy Coating System. This coating provides good resistance to industrial fumes and marine atmosphere exposures. These coatings exhibit good flexibility, hardness, toughness, and are of a high solids content. Although they tend to chalk quickly under weathering, they retain excellent chemical resistance.

(i) Novolac Epoxy System. This coating provides excellent resistance to industrial fumes and marine atmosphere exposures. These coatings exhibit good flexibility, hardness, toughness, and are of 100% solids content. They have a higher temperature resistance than an epoxy system and better chemical resistance.

(j) Novolac Phenolic Epoxy System. This coating provides excellent resistance to industrial fumes and marine atmosphere exposures. These coatings exhibit flexibility, hardness, excellent toughness, and are of 100% solids content. They have a higher temperature resistance than novolac epoxy systems and better chemical resistance.

(k) Chlorinated Rubber. This coating is similar to a vinyl and provides a good tough film, which has good abrasion resistance and possesses excellent weathering characteristics. It also shows excellent resistance to mineral acids and to marine environments in salt water. Normally limited to 160°F (71°C) performance temperature.

(l) Silicones. Silicones provide excellent heat resistance and may be used up to 1,200°F (649°C). They have superior exterior weathering, minimum film erosion, as shown by chalking resistance, gloss retention, and color retention. They show good resistance to mild chemical exposure. The properties depend upon the amount of silicone resin present and the type of modified agent used. Pure silicone, together with aluminum pigment, provides an excellent durable coating resistant to high temperature, and is also expensive.

(m) Two-Component Urethane System. A two-component catalyzed cured aliphatic urethane provides a hard, tough, and abrasion-resistant coating, which shows excellent weathering characteristics and gloss retention. It also possesses good chemical resistance to mild acids and alkalis, and shows excellent adhesion to steel. However, during application, it tends to be moisture-sensitive; yet, upon curing, it exhibits excellent resistance to humidity, marine environments, and mild corrosive environments.

(n) Acrylics. These coatings show excellent color and gloss retention for outdoor application. However, they are very limited in their chemical resistance. They are economical, and provide satisfactory performance in rural environments, where there is nothing more than very mild fume conditions. They do not exhibit as good properties as vinyl or chlorinated rubbers with respect to chemical resistance.

3.3.2 Important Coating Considerations

(a) environment (rural, industrial, and marine);
(b) exposure to temperature;
(c) weathering;
(d) aesthetic color retention;
(e) durability;
(f) surface preparation;
(h) cost;

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(i) coating manufacturer's recommendation.

3.3.3 Curing Methods

(a) Air oxidation (alkyds, epoxy);

(b) Solvent evaporation (vinyls, chlorinated rubber, coal-tar, and acrylics);

(c) Chemical reaction (epoxies, polyurethanes, vinyl esters, and inorganic zincs);

(d) Heat cure (silicones and high-bake phenolics).

3.3.4 Primer

(a) The primer is the most critical element in most coating systems because it is responsible for preserving the metallic state of the substrate, and it must anchor the total coating system to the steel. Surface preparation is very important.

(b) In general, the more severe the environment, or the longer the requirement for protection, the greater will be the coating dry film thickness required. Care should be taken, however, in the application of high build systems to thin walled structures and other dimensionally unstable substrates. Thick films, particularly those of rigid thermal sets, are less able to provide the necessary flexibility to substrate movements (expansion and contraction) than are thin films, and can easily undergo adhesive and cohesive failure leading to subsequent disbondment.

(c) It is to be noted that temperatures are to refer to the exterior steel surfaces, and not to the flue gas temperatures within the stacks.

(d) For external steel surface temperatures between 450°F (232°C) and 900°F (482°C), two coats of aluminum pigmented silicone resin-based coatings have been shown to provide excellent performance.

(e) For external steel surface temperatures between 450°F (232°C) and 900°F (482°C), a zinc primer, followed by a top-finished coat of a modified silicone, has shown excellent performance.

(f) All coatings should be applied in strict accordance with the manufacturer's instructions, observing minimum application temperatures, catalyst, type, addition rates and thinners, and the amounts allowed.

3.3.5 Reference Documents

(a) Good Painting Practice, Steel Structures Painting Manual, Vol. 1, published by the Steel Structures Painting Council, Pittsburgh, Pennsylvania.

(b) Systems and Specifications, Steel Structures Painting Manual, Vol. 2, published by the Steel Structures Painting Council, Pittsburgh, Pennsylvania.

(c) Coatings and Linings Handbook, published by NACE International, Houston, Texas.

(d) Permanence of Organic Coatings (STP-1), published by the American Society for Testing and Materials, West Conshohocken, Pennsylvania.

3.3.6 Design Considerations

(a) Edges;

(b) Deep, square corners;

(c) Discontinuous areas (bolt heads, corners, etc.);

(d) Weld and weld spatter;

(e) Skip welds;

(f) Back-to-back angles;

(g) Effective separation of faces of dissimilar metals;

(h) Separation materials of suitable shape and thickness (gaskets, butyl tape, etc.);

(i) Structural materials, guy wires, cables, fittings, bolts, nuts, washers, ladders, cages, grating, and other accessories may be protected from atmospheric corrosion by the use of hot-dip galvanized coatings. These should be applied in accordance with the ASTM A 153 Specification, and should involve the appropriate coating weight, Classes A, B, and C, which are in order of increasing zinc coating weight;

(j) Hot-dip galvanized coatings should not be used on material in contact with unpainted A 242 or A 588 steels;

(k) Because of potential corrosion problems with stack rain-caps, stainless steels conforming to the ASTM A 240 Specification or higher alloy, corrosion-resistant materials should be considered in their construction;

(l) Galvanizing of such items as hand rails, ladders, and other items of suitable size and shape affords long-term protection in nonaggressive atmospheric environments;

(m) Silicone coatings have been well-known for some time for their good color and gloss retention when exposed to exterior weathering. Unmodified silicones are expensive, and must cure at 400°F to 500°F (204°C to 260°C). Air drying properties, lower cost, and hardness in adhesion are obtained by copolymerizing silicones with organic polymers. The copolymers show practically no film erosion and, therefore, are very slow to chalk;

(n) Inorganic zinc pigmented coatings, when properly applied to blast-cleaned surfaces, show good resistance to atmospheric exposure.

3.3.7 Due to the great number of variations of formulations by coating manufacturers, this document will not be more specific in this regard. When standards do not exist, or when further information is needed regarding specific products, their performance, and rec-

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ommended usages, the coating manufacturers should be contacted.

3.4 Corrosion

3.4.1 Attack Due to Sulfur Oxides [From the Model Code on Steel Chimneys (CICIND)]

(a) The most common form of internal chemical attack is due to acids formed by the condensation of sulfur oxides in the flue gas. Sulfur is found in all solid and liquid fuels to varying degrees and can also be found in gaseous fuels. During the combustion process, nearly all sulfur in the fuel is oxidized to sulfur dioxide (SO_2), which is absorbed by condensing water vapor to form sulfurous acid.

(b) A small quantity of sulfur dioxide (SO_2) is oxidized to sulfur trioxide (SO_3). The quantity depends in a complex manner upon the sulfur content of the fuel, the amount of excess air available during combustion, temperature in the combustion chamber, and the presence of catalysts such as iron oxides. This small concentration of SO_3 (usually measured in ppm) gives rise to most of the acid corrosion problems encountered in chimneys. This is because on condensation, the SO_3 ions combine with water vapor to form sulfuric acid, whose concentration can be as high as 85%.

(c) Condensation of these acids takes place when the temperature of the flue gas falls below their acid dew point, or when the flue gas comes into contact with a surface at or below the relevant acid dew point temperature.

(d) The acid dew point temperature of sulfuric acid depends upon the concentration of SO_3 in the flue gas. Provided the temperature of the surfaces with which the flue gas can come into contact is maintained at least 50°F (10°C) above the acid dew point estimated in Fig. C-1 in Nonmandatory Appendix C, there is no danger of acid corrosion due to this cause. An adiabatic saturation curve showing sulfuric acid concentrations for various temperatures and operating conditions together with suggested material is shown in Fig. C-2 in Nonmandatory Appendix C.

(e) The acid dew point of sulfurous acid is about 120°F (49°C), a little above the water dew point. If the fuel is contaminated, other acids, such as hydrochloric and nitric acid can be expected to condense in the same temperature range. Thus, even if fuel and combustion processes are chosen to minimize production of SO_3, or if flue gases are scrubbed to remove most of the SO_3 and SO_2, severe corrosion can be expected if the temperatures of the flue gas, or the surfaces with which it can come into contact, fall below 149°F (65°C), or the acid dew point temperature relevant to the reduced SO_3 concentration, if this is higher. Again, a safety margin of 50°F (10°C) above the acid dew point determined from charts Tables C-1 and C-2 in Nonmandatory Appendix C.

3.4.2 Attack Due to Chlorine, Chlorides, and Fluorides

(a) Chlorides and fluorides may be found in all solid fuels, including refuse, and in many liquid fuels. Upon combustion, chlorides and fluorides are transformed into free chloride and fluoride ions, respectively, which, on contact with water vapor, are transformed into hydrochloric acid and hydrofluoric acid. The highest condensation temperature at which hydrochloric acid has been found is 140°F (60°C). The condensation temperature for hydrofluoric acid can be even lower. Thus, when any flue surface falls below this acid dew point, very serious corrosion will occur. This dew point is close to that of the water dew point and the sulfurous acid dew point. Therefore, even very small amounts of chlorides and fluorides, if allowed to concentrate such as under deposits, can cause serious corrosion problems. For example, chloride levels under deposits have been found to be as high as 100,000 ppm necessitating the use of the most corrosion-resistant materials.

(b) Hydrogen chloride, hydrogen fluoride, and free chlorine in flue gases also become corrosive in their vapor stage. Stainless steels are attacked at temperatures above 600°F (316°C). Fluoride vapors are corrosive to stainless steels at temperatures above 480°F (249°C).

3.4.3 Limited Acid Corrosion Exposure. Limited exposure to acid corrosion conditions can be permitted in stacks, which, for most of the time, are safe from chemical attack, provided the flue gas does not contain halogens (chlorine, chlorides, fluorides, etc.).

3.4.4 Critical Corrosion Factors

(a) Air leaks

(b) Fin cooling of flanges, spoilers, or other attachments

(c) Cooling through support points

(d) Downdraft effects at top of the chimney:

(1) Presence of chlorides or fluorides in the flue gas condensate can radically increase corrosion rates.

(2) Regardless of temperatures, corrosion can occur if halogen concentrations exceed the following limits:

(a) Hydrogen fluoride: 0.025% by weight (300 mg/m^3 at 20°C and 1 bar pressure)

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(b) Elementary chlorine: 0.1% by weight (1300 mg/m^3 at 20°C and 1 bar pressure)

(c) Hydrogen chloride: 0.1% by weight (1300 mg/m^3 at 20°C and 1 bar pressure)

3.5 Insulation, Jacketing, and Strapping

3.5.1 Insulation

(a) Insulation may be required on the stack exterior and/or interior, or between the walls of a dual wall stack.

(b) Insulating linings are covered in para. 3.2.4.2 on Inorganic Linings.

(c) There are numerous ASTM standards covering thermal insulating materials and their properties. These standards should be consulted and utilized in conjunction with the manufacturers' recommendations to meet the application requirements.

3.5.2 Jacketing and Strapping

(a) Jacketing may be of a material selected from one of the following ASTM Specifications:

(1) aluminum coated steel conforming to A 463;

(2) galvanized steel conforming to A 527;

(3) stainless steel conforming to A 666;

(4) aluminum conforming to B 209.

(b) Strapping may be of the same material as the jacketing, but stainless steel is usually preferred.

4 STRUCTURAL DESIGN

4.1 Scope

The structural design section includes currently acceptable methods for establishing structural configuration of steel stacks and stack elements to resist all external and internal loads imposed by the geography and topography of the site and by operating conditions.

4.2 General

4.2.1 Limitations. The design recommendations made in the Standard are applicable primarily to circular steel stacks.

4.2.2 Location. The stack design and construction shall be appropriate to the specific site, with particular consideration to local wind and seismic conditions, aircraft traffic, operating conditions, and local laws.

4.2.3 Drawings and Computations. Design drawings of the stack and all appurtenances shall be prepared showing all elements and details necessary for satisfactory fabrication and erection of the stack. Computations shall be prepared and submitted. All means of connection of material shall be specifically detailed with proper differentiation between shop and field connections.

4.3 Applied Loading

4.3.1 Dead Load. The dead load shall consist of the weight of steel stack, coatings, internal liner, insulation, and cladding, and all permanent accessories such as ladders, platforms, and gas sampling equipment. For dead load, the full plate thickness shall be used. The corroded plate area shall be used for stress calculations. For stacks possessing refractory lining, the applied weight of the refractory material shall be used to calculate dead load stresses.

4.3.2 Live Load. The minimum live load of 50 psf shall be included for platforms and walkways. This load need not be considered for wind or earthquake combinations. Consideration shall be given for accumulated ash loads, and moisture in the case of wet gases, on the stack walls and floors.

4.3.3 Wind Load. The wind load shall be calculated in accordance with procedures outlined in this section. The design shall also consider wind loads due to interference effects as stated in para. 4.3.3.7

4.3.3.1 Design Wind Force. The design load distribution is given by:

$$w(Z) = \overline{w}(Z) + w_D(z) \tag{4.1}$$

where:

$$\overline{w}(Z) = \frac{C_f q_z K_{Zt} K_Z D}{12(1 + 6.8\bar{I}_{\bar{z}})} \tag{4.2}$$

and:

$$w_D(Z) = \frac{3ZM_0}{h^3}\left[G_f(1 + 6.8\bar{I}_{\bar{z}}) - 1\right] \tag{4.3}$$

The velocity pressure, q_z, shall be calculated by:

$$q_z = 0.00256\, V^2 I \tag{4.4}$$

where the basic wind speed (V) is based on a three-second gust velocity and is selected in accordance with the provisions of paras. 4.3.3.2 through 4.3.3.4, the

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importance factor (I) is set forth in Tables I-2 and I-3 of Mandatory Appendix I, and the velocity pressure exposure coefficient (K_z) is given in Table I-4 of of Mandatory Appendix I in accordance with the provisions of paras. 4.3.3.5 and 4.3.3.7. Provisions of para. 4.3.3.6 shall be used to determine K_{zt} where applicable, but K_{zt} shall not be less than 1.0. The numerical coefficient 0.00256 shall be used, except where sufficient climatic data are available to justify the selection of a different value of this factor for a specific design application. Interference effects on the force coefficient (C_f) described in para. 4.3.3.7 shall be considered.

The basic wind speed V used in the determination of design wind loads is given in Fig. I-1 of Mandatory Appendix I, except as provided in paras. 4.3.3.2 through 4.3.3.4.

4.3.3.2 Special Wind Regions. The basic wind speed shall be increased where records or experience indicate that the wind speeds are higher than those reflected in Fig. I-1 of Mandatory Appendix I. Mountainous terrain, gorges and special regions shown in Fig. I-1 shall be examined for unusual wind conditions. The authority having jurisdiction shall, if necessary, adjust the values given in Fig. I-1 to account for higher local wind speeds. Such adjustment shall be based on meteorological information and an estimate of the basic wind speed obtained in accordance with the provisions of para. 4.3.3.3.

4.3.3.3 Estimation of Basic Wind Speeds From Regional Climatic Data. Regional climatic data shall only be used in lieu of the basic wind speeds given in Fig. I-1 when:

(a) approved extreme-value statistical-analysis procedures have been employed in reducing the data;

(b) the length of record, sampling error, averaging time, anemometer height, data quality, and terrain exposure have been taken into account.

4.3.3.4 Exposure Categories. An exposure category that adequately reflects the characteristics of ground surface irregularities shall be determined for the site at which the building or structure is to be constructed. Account shall be taken of variations in ground surface roughness that arises from natural topography and vegetation as well as from constructed features. The exposure in which a specific building or other structure is sited shall be assessed as being one of the following categories:

(a) Exposure A. Large city centers with at least 50% of the buildings having a height in excess of 70 ft. Use of this exposure category shall be limited to those areas for which terrain representative of Exposure A prevails in the upwind direction for a distance of at least 0.5 miles or 10 times the height of the steel stack, whichever is greater. Possible channeling effects or increased velocity pressures due to the steel stack being located in the wake of adjacent buildings shall be taken into account.

(b) Exposure B. Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced structures having the size of single-family dwellings or larger. Use of this exposure category shall be limited to those areas for which terrain representative of Exposure B prevails in the upwind direction for a distance of at least 1,500 ft or 10 times the height of the building or other structure, whichever is greater.

(c) Exposure C. Open terrain with scattered obstructions having heights generally less than 30 ft. This category includes flat, open country and grasslands.

(d) Exposure D. Flat, unobstructed areas exposed to wind flowing over open water for a distance of at least 1 mile. This exposure shall apply only to those steel stacks exposed to the wind coming from over the water. Exposure D extends inland from the shoreline a distance of 1,500 ft or 10 times the height of the stack, whichever is greater.

4.3.3.5 Wind Speed Over Hills and Escarpments. The provisions of this section shall apply to isolated hills or escarpments located in Exposures B, C, or D where the upwind terrain is free of such topographic features for a distance equal to $50H_H$ or 1 mile, whichever is smaller, as measured from the point at which H_H is determined. Wind speed-up over isolated hills and escarpments that constitute abrupt changes in the general topography shall be considered for steel stacks sited on the upper half of hills and ridges or near the edges of escarpments, illustrated in Fig. I-2 of Mandatory Appendix I, by using factor K_{zt}:

$$K_{zt} = (1 + K_1 K_2 K_3)^2 \qquad (4.5)$$

where K_1, K_2, and K_3 are given in Figure I-2 of Mandatory Appendix I. The effect of wind speed-up shall not be required to be considered when $H_H/L_h < 0.2$, or when $H_H < 15$ ft for Exposure D, or 30 ft for Exposure C, or < 60 ft for all other exposures.

4.3.3.6 Gust Effect Factor. The gust effect factor G_f for main wind-force resisting systems of steel stacks shall be calculated in accordance with the equations shown in Mandatory Appendix I.

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4.3.3.7 Force Coefficient Interference Effect. For grouped or clustered stacks having a center-to-center distance of 3.0 diameters or less, an increase in the force coefficient value of 20% is suggested in the absence of model wind tunnel testing or existing full scale data.

4.3.4 Seismic Load. Lateral seismic forces shall be considered in accordance with the guidelines described in this section. The procedure provided shall be followed in the U.S. as a minimum requirement. It has been found that, due to the low mass of steel stacks, those only in high seismic areas or those containing high mass distribution are governed by seismic loads.

4.3.4.1 Earthquake Response. The steel stack response to earthquake can be determined using the response spectrum method by using a horizontal response spectrum based upon a maximum ground acceleration of 1.0g with a damping value of 0.05, which is scaled to the specific site. The value of the acceleration, A_v, related to the effective peak velocity, shall be determined using Table D-2 in Nonmandatory Appendix D or the published value for the location. Using the value of A_v, the response spectrum scaling ratio is found in Table D-2 in Nonmandatory Appendix D. Linear interpolation may be used in between published values of A_v. The modal moment, shear and deflection response of each mode is scaled with the scaling ratio for the specific frequency of each mode. Modal responses for each mode are then added using the SRSS method (taking the square root of the sum of the squares of modal moment, shear deflection responses). In lieu of the response spectrum method, a static equivalent method may be used.

The mathematical model of the steel stack used in the analysis shall be sufficiently detailed to represent the steel stack, liner or coating, lateral support and foundation property and support conditions. A minimum of 10 elements and 5 modes of vibration should be used.

An example of the mathematical calculation of modal properties and response spectrum earthquake response is shown in Nonmandatory Appendix D.

4.3.5 Thermal Loads. Non-uniform distribution of flue gas across the steel stack or steel stack liner may cause differential temperatures. Unless the temperature distribution is uniform or linearly varying across the stack/liner diameter, thermal stresses will be induced in both longitudinal and circumferential directions. In addition, longitudinal bending stresses and shear stresses will be produced if the stack shell or liner that is subjected to non-uniform temperatures along its height is restrained from lateral movements. The thermal stresses should be considered in applicable stack and liner designs. Refer to 1975 ASCE Publication, Design and Construction of Steel Chimney Liners for more discussion of thermal effects.

For stacks to be subjected to high-temperature (> 500°F) and/or fast plant startup or shutdown such as cyclic operation of combustion turbine, design consideration should be given to minimize the non-uniform thermal differentials that may exist between shell and stiffeners or other structural elements. Localized thermal stresses induced in the inner plates and stiffeners can be substantial and must be considered in the design.

4.3.6 Construction Loads. Consideration shall be given in the design for applied construction loads in combination with wind and seismic loads that may reasonably be expected to occur during construction.

4.3.7 Other Loads. Where applicable, additional loading such as expansion joint thrusts, pressure loads, or other loads unique to the specific case shall be considered in the design.

4.4 Allowable Stresses

The following formulas for determining allowable stresses are applicable for circular stacks and liners provided that Equation 4.6 is satisfied:

$$\frac{t}{D} \leq \frac{10F_y}{E} \tag{4.6}$$

An increase in allowable shell stresses due to wind or seismic loads shall not be allowed.

All other steel members shall comply with the requirements of the American Institute of Steel Construction (AISC) specification for the design, fabrication, and erection of structural steel for buildings, AISC Manual of Steel Construction, latest edition, with the exception that an increase in allowable shell stresses due to wind or seismic loads shall not be allowed. For stacks and liners meeting the requirements of Equation 4.6, the following four load cases must be satisfied.

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4.4.1 Case 1 Longitudinal Compression. The longitudinal compressive stress in cylindrical stacks and liners (P/A) shall not exceed the allowable limit, S_{cl}.

$$\frac{P}{A} \le S_{cl} \tag{4.7}$$

where:

$$S_{cl} = \frac{EtY}{4D\ (F.\ S.)}\ when\ \frac{t}{D} \le \frac{2.8\ F_y}{E} \tag{4.8}$$

or:

$$S_{cl} = \frac{F_y\ (1 - 0.3K_s)Y}{(F.S.)} \tag{4.9}$$

$$when\ \frac{2.8\ F_y}{E} < \frac{t}{D} \le \frac{10\ F_y}{E}$$

and:

$$Y = 1$$

$$when\ \frac{L_e}{r} \le 60\ and\ F_y \le 50\ ksi$$

and

$$Y = \frac{21{,}600}{18{,}000 + \left(\frac{L_e}{r}\right)^2}$$

$$when\ \frac{L_e}{r} > 60\ and\ F_y \le 50\ ksi$$

$$K_s = \left(\frac{\frac{10F_y}{E} - \frac{t}{D}}{\frac{7.2F_y}{E}} \right)^2$$

4.4.2 Case 2 Longitudinal Compression and Bending Combination. The combined longitudinal compressive and bending stress in cylindrical stacks and liners shall not exceed the allowable stress, S_{bl}.

$$\frac{P}{A} + \frac{MD}{2I_{section}} \le S_{bl} \tag{4.10}$$

where S_{bl} $(=S_{cl})$ is given in Equations (4.8) and (4.9) of para. 4.4.1.

NOTE: $Y=1$ for compression due to bending.

4.4.3 Case 3 Circumferential Stress. The circumferential stress f_c in the shell due to external wind pressure q_z between stiffeners spaced at distance, l_s, shall be determined using:

$$f_c = \frac{q_z^2}{288t} \tag{4.11}$$

The circumferential stress shall be less than the allowable stress, S_{cc}, calculated as:

$$S_{cc} = \frac{1.30EK\left(\frac{t}{D}\right)^{1.5}}{(F.S.)\left(\frac{l_s}{D}\right)}$$

$$when\ 0 \le \frac{t}{D} \le \frac{2.8\ F_y}{E},\ K = 1$$

$$when\ \frac{2.8\ F_y}{E} < \frac{t}{D} \le \frac{10F_y}{E},$$

$$K = 1.68\frac{F_y\ D}{Et} + 0.465 - \frac{0.0232\ Et}{F_y\ D}$$

where q_z = external wind pressure on stack shell at elevation under consideration, psf and C_f = 1.0

4.4.4 Case 4 Combined Longitudinal and Circumferential Compressive Stress. The combined longitudinal and circumferential compressive stress in cylindrical stacks and liners may be determined using the following formulae.

$$\frac{\left(\frac{P}{A}\right) + \frac{MD}{2I_{section}}}{S_{bl}} + \left(\frac{f_c}{S_{cc}}\right)^2 \le 1.0 \tag{4.13}$$

4.4.5 Circumferential Compression In Stiffeners. The size of stiffeners shall satisfy the following three requirements.

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TABLE 4.1 FACTORS OF SAFETY

Load Combination	F.S.
Dead + Live + Other + Thermal + Along or Across Wind	1.50
Dead + Live + Other + Thermal + Seismic	1.50
Dead + Live + Other + Abnormal Thermal + Along Wind/4	1.33
Construction	1.33

(a) The stiffener and plate section shall have a moment of inertia equal to or greater than that determined by the following equation:

$$I_{s+p} \geq \frac{q l_s D^3 (F.S.)}{3456\ E} \qquad (4.14)$$

where q = external wind pressure or stack draft pressure.

(b) The stiffener and plate section shall have an area equal to or greater than that determined by the following equation:

$$A_{s+p} \geq \frac{q\ l_s D\ (\text{F.S.})}{288\ S_{ccs}} \qquad (4.15)$$

Circumferential compression stiffeners shall not exceed

$$S_{ccs} = \left[\frac{0.25EI}{R^2}\right]\frac{1}{F.S.}$$

in which I is the moment of inertia of the stiffener and a band of shell plate. The band of shell plate shall not exceed the $8 \times t$ projection beyond the stiffener.

(c) The stiffener and plate section shall have a section modulus equal to or greater than that determined by the following equation:

$$S_{s+p} \geq \frac{q_z D^2 l_s\ (F.S.)}{1830\ F_y} \qquad (4.16)$$

where q_z = *external wind pressure.*

4.4.6 Factors of Safety. The stack shall be designed for minimum factor of safety (F.S.) for the loading considerations given in Table 4.1

4.4.7 Minimum Structural Plate Thickness and Maximum Stiffener Spacing. Table 4.2 shows the minimum plate thickness to be used in the fabrication of steel stacks and steel liners and maximum stiffener spacing.

4.4.8 Creep Rupture Tensile Stress. For sustained loading and high-temperature service above 750°F, depending on the steel chemistry, the creep-rupture strength of the steel becomes a significant factor in determining the allowable design tension stress.

(a) Because of their nature, allowable creep stresses are only used to limit tension stresses or tensile bending stresses from loading combinations that will be sustained at elevated temperatures. Creep and creep-rupture are very dependent on the exact chemistry of the steel. Some carbon steels, such as ASTM A 36, are very susceptible to creep and creep rupture, while others are almost creep resistant. The exact chemical composition of the steel is necessary to quantify its creep and creep rupture properties.

(b) The design creep life should be selected based on the expected service life and service conditions. Design for creep is typically based on creep and rupture properties corresponding to a creep life of 100,000 hr. This creep design life is the duration presented in Section II of the ASME Boiler and Pressure Vessel Code. A shorter or longer creep design life may be appropriate depending on the expected service life of the stack.

(c) The maximum allowable creep tensile design stress, as taken from Section I of the ASME Boiler and Pressure Vessel Code, Rules for Construction of Power Boilers, should not exceed the lowest of the following two values:

(1) the average stress to produce a creep rate of 1% within 100,000 hr with a factor of safety of 1.0, and;

(2) the average stress to cause creep rupture after 100,000 hr with a factor of safety of 1.5.

(d) Selected allowable creep tensile design stresses for various steels used in ductwork and steel stacks are presented for reference (see Nonmandatory Appendix D) from the American Society of Civil Engineers (ASCE) 1995 publication, The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications, Section 3. The values presented in this book are intended to be used only as a reference. Creep rupture allowable tensile design stress used in stack design should be obtained from test data reflecting the

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TABLE 4.2 MINIMUM STRUCTURAL PLATE THICKNESS AND MAXIMUM STIFFENER SPACING

Inside Diameter, D ft	Minimum Structural Plate Thickness, in. [Note (1)]	Maximum Stiffener Spacing, ft
$D \le 3.5$	0.125	5 D
$3.5 < D \le 6.5$	0.1875	3 D
$6.5 < D \le 18.0$	0.1875	2 D
$D > 18.0$	0.25	$1\frac{1}{2}$ D

NOTE:
(1) Minimum plate thickness does not include corrosion allowance. If corrosion allowance is required, the minimum plate thickness shall be increased by the amount of the corrosion allowance.

precise chemical composition of the steel to be used in the stack fabrication.

4.5 Deflections

4.5.1 Lateral Deflection. The maximum deflection under the static design loading shall be calculated, and the foundation rotation or movement shall be considered in evaluating deflection. There is no practical limit placed on the maximum deflection a stack can experience; however, for large deflections, the resulting secondary stresses caused by $P{\cdot}\Delta$ should be considered. The calculated maximum deflection shall also be considered in evaluating the suitability of equipment anchored to the stack.

4.5.2 Dual Wall or Multiflue Stacks. The forces due to contact between liners and the shell of dual wall or multiflue steel stacks due to any velocity wind up to the design velocity shall be considered at all elevations of the shell and liners.

4.6 Structural Shell Discontinuities

4.6.1 Discontinuities. Openings in the shell shall be designed to maintain the minimum factors of safety specified for the loading conditions.

(a) The top and bottom of the breeching opening shall be adequately reinforced to transfer the discontinuities of shell stress back to the full circumference of the shell.

(b) The sides of breeching openings shall act as columns or tension members to withstand the end reactions of the assumed horizontal girders above and below the opening. The strength of a plane cut through the opening at any elevation shall be adequate to withstand all applied loads on the section.

(c) The breeching opening reinforcement may serve as a means of connecting the breeching to the liner or shell. The applicable corrosion allowance shall be applied to the reinforcement if exposed to the flue gas.

4.6.2 Flanged Shell and/or Liner Connections. For information on flanged shell and/or liner connections, see CICIND or SMACNA publications in Nonmandatory Appendix F.

4.7 Base

The base ring and anchor bolts shall be designed to transfer the steel stack shear, compression, and tensile forces to the supporting structure or foundation in accordance with proven design methods. No strength increase will be permitted for wind or seismic loads.

4.8 Anchor Bolts

4.8.1 Anchor Bolt Tension. Anchor bolts shall be designed to transfer all tension and shear forces to the foundation unless other methods are incorporated to accomplish this purpose. The maximum anchor bolt tension, F_b, may be determined from the following relation for circular sections sufficiently away from discontinuities:

$$F_b = \frac{4\,M_b}{ND_{bc}} - \frac{P}{N} \qquad (4.17)$$

4.8.2 Anchor Bolt Material. All anchor bolt material shall conform to Section 2.

4.8.3 Anchor Bolt Loading. Anchor bolt capacities for tension and/or shear shall not exceed those given for size of bolt and material indicated in AISC, latest edition. No load increase in bolts will be permitted for wind or seismic loading.

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4.8.4 Load Transfers Between Anchor Bolts and Shell. Transfer of loads between anchor bolts and shell shall accommodate all loads and eccentricities. An increase in allowable shell stresses due to wind or seismic loads shall not be allowed.

4.9 Foundation

The foundation shall transfer all moment and shear loads (static and dynamic) to the supporting soil or piles. Concrete and steel reinforcement design shall comply with the latest edition of ACI 318 and ACI 301. A qualified geotechnical engineer shall review soil boring and pile capacity test results. The combined dead load of the stack plus the foundation weight, times the distance from the center of the weight to the toe shall be at least 1.5 times the design moment.

4.10 Section 4 Symbols and Definitions

A = cross-sectional area of stack plate, in.^{2}
A_{s+p} = area of stack stiffener and plate section, in.^{2}
A_v = effective peak velocity-related acceleration
b = stack diameter (used only in Mandatory Appendix I, Gust Factor Calculation), ft
$\bar{b}$ = coefficient given in Table I-1 of Mandatory Appendix I
C_f = force coefficient given in Table I-5 of Mandatory Appendix I
c = coefficient given in Table I-1 of Mandatory Appendix I
d = stack diameter (used in Mandatory Appendix I, Gust Factor Calculation), ft
D = diameter of stack at elevation under consideration, in.
D_{bc} = diameter of anchor bolt cirlce, in.
E = modulus of elasticity at mean shell temperature, psi
F_b = anchor bolt tension force, lbf
$F.S.$ = factor of safety
F_y = yield strength at mean shell temperature, psi
f_c = circumferential stress in the shell due to external wind pressure, psi
G_f = gust effect factor
H_H = height of hill or escarpment given in Figure I-2 of Mandatory Appendix I, ft
h = height of stack, ft
I = importance factor given in Table I-3 of Mandatory Appendix I
$I_{section}$ = moment of inertia of stack section, in.^{4}
I_{s+p} = moment of inertia of stack stiffener and plate section, in.^{4}
$I_{\bar{z}}$ = intensity of turbulence at height $\bar{z}$
K = circumfrential stress coeffecient
K_z = velocity pressure exposure coefficient evaluted at height z
K_{zt} = topographic factor for along wind pressure calculation
K_1, K_2 = topographic multipliers given in Figure I-2 of Mandatory Appendix I
K_3 = topographic multipliers given in Figure I-2 of Mandatory Appendix I
L_e = two times the overall stack height for cantilever stacks, or two times cantilever portion or height for guided stacks for stresses in that cantilevered section or the distance between lateral supports, for stresses in the section between lateral supports, in.
L_h = distance upwind of crest of hill or escarpment in Figure I-2 of Mandatory Appendix I to where the difference in ground elevation is half the height of hill or escarpment, ft
$L_{\bar{z}}$ = integral length scale of turbulence at the equivalent height, ft
l_s = spacing between circumferential stiffeners, determined as the sum of half of the distance to adjacent stiffeners on either side of the stiffener under consideration, in.
M = moment in stack at elevation under consideration due to wind or earthquake loads, lbf-in.
M_b = moment at the base of the stack due to wind or earthquake loads, lbf-in.
M_0 = moment at the base of the stack due to $\overline{w}$ (z) loading, lbf-ft
N = number of anchor bolts
N_1 = coefficient used to calculate the resonant response factor
n_1 = first natural frequency of the Stack, Hz
P = dead load of stack above elevation under consideration, lb
Q = background response factor
q_p = stack draft pressure, psf.
q_z = external wind pressure on stack shell at elevation under consideration, psf.
R = resonant response factor
R_b, R_d = coefficients used to calculate the resonant response factor
R_h, R_n = coefficients used to calculate the resonant response factor
r = weighted mean radius of gyration for elevation under consideration, in.
S_{bl} = allowable combined longitudinal compressive and bending stress, psi
S_{cc} = allowable circumferential compressive stress in shell, psi
S_{ccs} = allowable circumferential compressive stress in stiffeners and band of shell plate, psi

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S_{cl} = allowable longitudinal compressive stress in shell, psi
S_{s+p} = section modulus of stack stiffener and plate section, in.^{3}
t = stack shell or liner wall thickness, in.
V = basic wind speed corresponding to a 3-second gust speed at 33 ft above ground in exposure category C, and is associated with an annual probability of 0.02 of being equalled or exceeded (50-year mean recurrence interval), mph
$\overline{V}_{\bar{z}}$ = mean hourly wind speed, ft/sec
Y = coefficient used to calculate longitudinal compressive stress
z = elevation under consideration, ft
$\bar{z}$ = equivalent height of stack, ft
$\bar{\alpha}$ = coefficients given in Table I-1 of Mandatory Appendix I
β = total damping value
$\bar{\epsilon}$ = coefficients given in Table I-1 of Mandatory Appendix I
η = coefficient used to calculate the resonant response factor
$w(z)$ = total along-wind load on stack per unit height, lb-f/ft
$\overline{w}(z)$ = mean along-wind load on stack per unit length, lb-f/ft
$\overline{w}_D(z)$ = fluctuating along-wind load on stack per unit height, lb-f/ft

5 DYNAMIC WIND LOADS

5.1 Scope

This section considers the dynamic wind load effects on steel stacks. Since steel stacks are flexible structures with low inherent structural damping and light in weight, the dynamic effects of wind shall be considered in the design.

5.2 Dynamic Responses

5.2.1 Dynamic Characteristics. The dynamic characteristics of natural frequencies, corresponding mode shapes, and damping shall be considered in wind loading. All modes of vibration that could occur based upon the wind loads considered in the design shall be investigated.

Frequencies. Stack frequencies and corresponding mode shapes are a function of the stack configuration and the vertical and lateral support conditions. The frequencies and mode shapes shall be calculated using a suitable mathematical modeling method.

Mathematical Modeling. Appropriate detailed calculation methods shall be used for dynamic analysis of more complex configurations. These configurations include stacks with variable diameters and thickness, inner liners, stacks with internal coatings, guyed or laterally supported stacks, derrick supported stacks, or stacks with flexible foundations. The finite element analysis techniques shall be used in these cases. However, for simple stack configurations, simpler models can be used if justification can be provided.

(a) For steel stacks supported on rock or firm soil and/or supported on end bearing piles, a fixed base modeling approach is acceptable. For steel stacks supported on buildings, the interaction effects of the building shall be included. For steel stacks supported with shallow foundations on soil or on friction piles, appropriate methods of analysis shall be used to account for interaction effects. Parametric studies may be necessary to account for the uncertainty of soil properties.

Consideration should be given in the design to the corrosion or erosion of the stack or liner, which could affect the frequency.

(b) Damping. Steel stacks have relatively low inherent structural damping. Additional damping may be gained from the inclusion of a brick or refractory lining, foundation system, or aerodynamic methods which disrupt vortex formation, although the last may, in fact, reduce the damping.

For wind loads, the structural damping values (β_s) shown in Table 5.1 have been observed for steel stacks. Other damping values shown in Table 5.1 may be used for support conditions that have inherently large damping or utilize the damping methods of para. 5.3.2, when justified by results of testing or analysis. Consideration should be given to stacks supported on steel frames.

Aerodynamic damping shall also be considered. The aerodynamic damping value, β_a, is calculated as follows:

a) For along wind response:

$$\beta_a = \frac{C_f \rho \overline{D}\, \overline{V}_{\bar{z}}}{4 \pi m_a n_1} \tag{5.1}$$

Where m_a = mass per unit length of the top $1/3$ of the stack

b) For vortex shedding when $\overline{V}_{\bar{z}}$ is in the vicinity (±30%) of $V_{z_{cr}}$, the aerodynamic damping is negative and shall be included. The procedures in Nonmandatory Appendix E may be used to calculate the negative aerodynamic damping.

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TABLE 5.1 REPRESENTATIVE STRUCTURAL DAMPING VALUES (β_s)

Support	Damping Value	
Type Welded Stack	Rigid Support (1)	Elastic Support (2)
Unlined	0.002	0.004
Lined (3)	0.003	0.006

NOTES:
(1) Foundations on bedrock, end-bearing piles or other rigid base support conditions.
(2) For foundations with friction piles or mat foundations on soil or other elastic base support conditions.
(3) Lining must consist of a minimum 2 in. thick, nominally 100pcf density liner material for stack to be considered lined for the use of this table.

The total damping shall be as follows:

$$\beta = \beta_s + \beta_a \tag{5.2}$$

5.2.2 Wind Responses

(a) Vortex Shedding. Across Wind Loads for plumb or nearly plumb (less than ±10% diameter variation over the top 1/3) stacks, the mean hourly speed at 5/6 height above ground, $V_{z_{cr}}$ (ft/sec), shall be used for evaluating the critical vortex shedding velocity. The value of $V_{z_{cr}}$ shall be calculated as follows:

$$V_{z_{cr}} = \bar{b}\left(\frac{Z_{cr}}{33}\right)^{\bar{\alpha}} \frac{22}{15} V_R \tag{5.3}$$

The critical wind speed for vortex shedding (ft/sec) for any mode of vibration is given by:

$$V_c = n_1 \overline{D}/S \tag{5.4}$$

(1) Vortex shedding loads shall be calculated for all modes of vibration where $V_c < V_{z_{cr}}$. The procedure in Nonmandatory Appendix E may be used. Fatigue analysis must be considered. The vortex shedding loads need not be combined with along wind loads.

(2) Vortex shedding loads shall be calculated for all modes of vibration where $V_{z_{cr}} < V_c < 1.2\ V_{z_{cr}}$. The procedure in Nonmandatory Appendix E may be used. The resulting loads may be reduced by the factor $\left(\frac{V_{z_{cr}}}{V_c}\right)^2$. Fatigue analysis need not be considered.

(3) If $V_c > 1.2\ V_{z_{cr}}$, then response vortex shedding can be ignored.

For variable diameter stacks, a range of critical speeds must be considered. The procedure in Nonmandatory Appendix E may be used for variable diameter stacks.

(b) Ovalling. The intermediate application of vortex forces on the stack could cause ovalling resonance. The lined stack is more resistant to ovalling because the lining contributes to a high natural frequency and increased damping for the elastic ring; therefore, ovalling need not be considered for lined stacks. The unlined stack possesses very little damping to restrict ovalling, and may experience excessive stresses and deflections at the critical ovalling wind velocity. For unlined steel stacks, the ovalling natural frequency is calculated as follows:

$$f_o = \frac{680t}{D^2} \tag{5.5}$$

and the critical wind velocity for ovalling is

$$v_{co} = \frac{f_o D}{2S} \tag{5.6}$$

If the v_{co} is less than $\overline{V}_{\bar{z}}$, the unlined stack should be reinforced with ring stiffeners meeting the requirements of Table 4.2. The required minimum section modulus of stiffener, S_s (in.^{3}), with respect to the neutral axis of its cross section parallel to the longitudinal axis of the stack is:

$$S_s = (2.52 \times 10^{-3})\,(v_{co})^2\, D^2\, l_s/\sigma_a \tag{5.7}$$

where σ_a shall be 0.6 F_y

In the area where helical strakes are attached to the stack, ring stiffeners may be omitted if it can be proven that the helical strakes provide adequate stiffness.

(c) Interference Effects. A stack downwind of another stack may experience larger vortex shedding loads than an unobstructed stack. When the distance between stacks A divided by the diameter $\overline{D}$ of the obstructed stack is less than 15, the Strouhal number S shall be deter-

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mined from equation 5.8. The resulting increase in vortex shedding velocity and resulting loads shall be considered. This increase may result in increasing the critical velocity beyond the design consideration value of 1.2 $V_{z_{cr}}$ for wind directions near the line of the stacks.

$$S = 0.16 + \frac{1}{300}\left(\frac{A}{\overline{D}} - 3\right) \text{ for } A/\overline{D} \le 15 \quad (5.8)$$

$$S = 0.20 \text{ for } A/\overline{D} > 15$$

For all stacks that are identical and have center-to-center distances of less than three mean diameters, or for stacks that are not identical, interference effects shall be established by reference to model test, or other studies of similar arrangements.

5.3 Prevention of Excessive Vibrations

Many methods have been used to prevent excessive vibrations in stack designs. It is not the purpose of this Standard to determine the exact method to be used in the design of stacks, but rather to indicate some methods that have been successfully used. One or more of the following methods have been shown to prevent or diminish resonant vibrations: aerodynamic methods, damping methods, and stiffening methods.

5.3.1 Aerodynamic Methods. Aerodynamic methods disrupt the formation of vortices on the sides of the stack and limit the source of vibration.

Helical Strakes. A three-start set of curved plate helical strakes 120 deg apart on the stack circumference may be attached to the outer surface of the stack with the strake plate approximately perpendicular to the stack surface at all points. The pitch of the helix should be five times the aerodynamic diameter and the strake should project $^1/_{10}$ diameter from the aerodynamic diameter. Strakes of adequate structural thickness should be provided on the top $^1/_3$ of the stack height. Each strake is to be aerodynamically continuous except at specific locations where cuts may be necessary to clear ring stiffeners or other attachments. The maximum gap allowed between the stack shell and helical strake shall be equal to 0.1 x strake width. The presence of strakes significantly increases the drag forces and a drag force coefficient of 1.4 used in conjunction with the outside diameter (including insulation and lagging) of the stack is recommended. Segments of flat vertical strakes at helical locations are not acceptable methods for disrupting vortices.

Shrouds. Stability against lateral vibration can also be achieved by mounting a perforated cylindrical shroud that covers the upper 30% of the stack length. The gap between shroud and stack should be 6% to 12% of the stack diameter and the perforations should be circular holes measuring 5% to 7% of the stack diameter on the side, and should comprise a minimum of 30% of the shroud surface area. Values stated are minimums and may be modified if proven by testing.

5.3.2 Damping Methods. The second category consists of attachments and auxiliary structures that absorb dynamic energy from the moving stack.

Mass Damper. The mass damper represents a secondary mass-spring system attached to the top of the stack. The mass ratio of the secondary system to the equivalent mass of a stack at the attachment location is normally not more than 5%. This method has demonstrated the capability to provide a damping value of up to approximately 0.05.

Preformed Fabric Pads. The control of damping in a stack is obtained by installing a preformed fabric pad at the base of the stack. The placement of the fabric pads shall be such as to ensure that all stress paths between the stack and its support are through segments of the fabric pads. This will require the addition of a preformed fabric pad (washer) and steel backing plate beneath each anchor bolt nut. This method has been demonstrated to provide a damping value up to approximately 0.03.

Other Devices. Other devices such as hanging chains or impact damping between the lining and the shell (of dual wall or multiflue stacks) have been proven to increase damping in a stack system during vibration. The damping values provided shall be documented by design or testing.

5.3.3 Stiffness Methods. The response to vortex shedding can be significantly affected by changing the critical diameter, stack height, mass distribution, or adding lateral supports or guy wires to the stack system. Changes to these factors can be used to increase the critical velocity beyond 1.2 $V_{z_{cr}}$ or lower the critical velocity to an acceptable level.

5.4 Fatigue

For normally proportioned steel stacks over the height range considered in this Standard that will not experience large tip amplitude motion due to vortex shedding, fatigue loads need not be considered. For stacks which experience large tip motion, fatigue loads shall be

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analyzed. One method of analyzing fatigue loads may be found in CICIND publication, Model Code for Steel Chimneys. (See Nonmandatory Appendix F.)

5.5 Section 5 Symbols and Definitions

A = horizontal distance between stacks center lines, ft
$\bar{b}$ = coefficient given in Table I-1 of Mandatory Appendix I
C_f = force coefficient given in Table I-5 of Mandatory Appendix I
D = diameter of stack at elevation under consideration (ft)
$\bar{D}$ = mean diameter for the segment z_1 to z_2, or for stacks ±10% variation over the top $\frac{1}{3}$ the value of $\bar{D}$ is the average over the top $\frac{1}{3}$ (ft)
f_0 = ovalling natural frequency of the stack (Hz)
I = Importance Factor from Table I-2
l_s = spacing between circumferential stiffeners, determined as the sum of half the distance to adjacent stiffeners on either side of the stiffener under consideration (ft)
m_a = mass per unit length of upper $\frac{1}{3}$ of stack (lb/ft)
n_1 = natural frequency for mode being considered (Hz)
S = Strouhal number, usually used as 0.2 for single stacks and may vary due to Reynolds numbers and multiple stacks
S_s = minimum section modulus of stack stiffeners ($in.^3$)
t = stack shell or liner wall thickness (in.)
V = basic wind speed corresponding to a 3-second gust speed at 33 ft above ground in exposure category C, and is associated with an annual probability of 0.02 of being equalled or exceeded (50-year mean recurrence interval) (mph)
v_{co} = ovalling critical wind velocity (ft/sec)
V_c = critical wind speed for vortex shedding (ft/sec)
V_R = reference design speed, which is V factored by the importance factor $V\sqrt{I}$ (mph)
$\bar{V}_{\bar{z}}$ = mean hourly wind speed (ft/sec)
$V_{z_{cr}}$ = mean hourly wind speed at z_{cr} (ft/sec)
z_{cr} = elevation equal to $\frac{5}{6}$ stack height (ft)
$\bar{\alpha}$ = coefficients given in Table I-1 of Mandatory Appendix I
β = total damping value
β_a = aerodynamic damping value
β_s = structural damping value
ρ = density of air (lb/ft^3)
σ_a = allowable tensile stress in stack stiffener (psi)
π = Pi (3.141593)

6 ACCESS AND SAFETY

6.1 Scope

This section applies to the design and construction of permanently installed equipment commonly used for accessing steel stacks. Equipment used in the construction, inspection, and demolition of steel stacks is not included.

6.2 General

6.2.1 Purpose. The access safety option of the Standard has the purpose of protecting persons by establishing minimum standards for the design, installation, and maintenance of equipment used to provide access to steel stacks.

6.2.2 Limitations. Access to a steel stack shall be provided and used only when required for inspection, testing, and maintenance. Access shall not be provided when prohibited by government regulations, local laws, or ordinances.

6.2.3 Maintenance of Equipment. All equipment used in providing access to steel stacks shall be maintained in a serviceable condition at all times. Inspection of ladders, platforms, and other equipment used to access steel stacks shall be made on a regular basis, preferably once each year.

6.2.4 Welding. All welding shall in accordance with the Structural Welding Code, Steel, AWS D1.1 latest edition) published by the American Welding Society, or Section IX of the ASME Boiler and Pressure Vessel Code, Welding and Brazing Qualifications.

6.2.5 OSHA. Ladders, platforms, and other equipment used to access steel stacks must conform to the OSHA Standard (29 CFR 1910).

6.2.6 Definitions

cage (also known as cage guard or basket guard): a barrier that is an enclosure mounted on the siderails of the fixed ladder or fastened to the structure to enclose the climbing space of the ladder (See Fig. 6-4.).

climbing protection device: a vertical support system other than a cage, used in conjunction with a ladder, which will limit a person's fall from a ladder without having to continuously manipulate the device.

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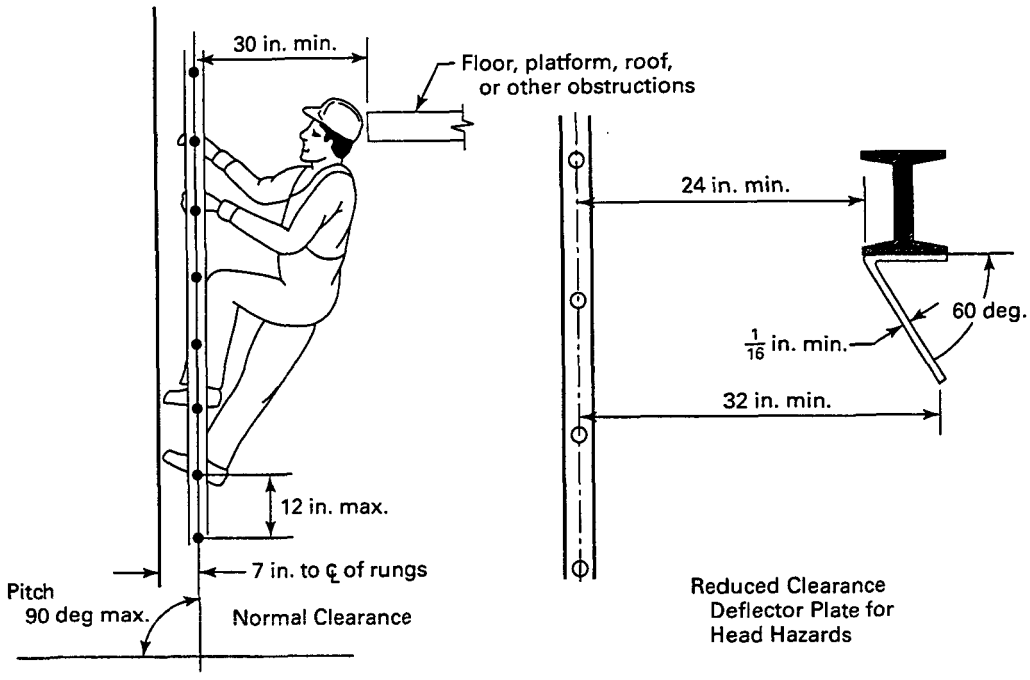

FIG. 6-1 MINIMUM LADDER CLEARANCES

grab bar: an individual handhold placed adjacent to, or as an extension above, a ladder for the purpose of providing safe access/egress for a user of the ladder.

ladder: a device incorporated or employing steps or rungs on which a person may step in ascending or descending, and siderails or grab bars for holding.

ladder, side step: a ladder that requires a person accessing or egressing to or from the ladder to step sideways.

ladder, step through: a ladder that requires a person accessing or egressing at the top to step between the siderails.

ladder support: a device for attaching a ladder to a structure, building, or equipment.

landing or rest platform: a surface that is used when transferring from one section of a ladder to another, or for resting.

length of climb: the total vertical distance a person could climb in traveling between the extreme points of access/egress for a fixed ladder, whether the ladder is of an unbroken length or consists of multiple sections. This total vertical distance is determined by including all spaces between all ladder steps or rungs, and all other vertical intervening spaces between the extreme points of access/egress.

pitch: the included angle between the horizontal and ladder, which is measured on the opposite (back) side of the ladder from the climbing side (See Fig. 6-1).

platform: a surface that is used for working, standing, or transferring from one ladder section to another.

serviceable: capable of performing its intended function within its design parameters.

siderail: the side members of fixed ladder joined at intervals by either rungs or steps.

toeboard: a barrier erected along the exposed edge of a platform to prevent objects from falling, which could create hazards to persons below.

well: a walled enclosure around a fixed ladder, which provides the person climbing the ladder with protection similar to a cage.

6.3 Fixed Ladders

6.3.1 Application. This section applies to new fixed ladders on new or existing steel stacks. Ladders used for steel stack access must conform to ANSI A14.3 (latest edition) Safety Code for Fixed Ladders.

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6.3.2 Materials of Construction. Refer to Section 2 of this Standard for materials of construction.

6.3.3 Live Loads

(a) Live Loads Imposed by Persons

(1) The minimum design live load shall be two loads of 250 lb each concentrated between any two consecutive ladder supports. Each step or rung in the ladder shall be designed for a single concentrated live load of 250 lb minimum.

(2) The number and position of additional concentrated live load units of 250 lb each, determined from anticipated usage of the ladder, shall be considered in the design.

(b) Other Live Loads. The following live load shall be considered in the design, where applicable:

(1) ice on parts of the ladder and appurtenances;

(2) maximum anticipated wind or seismic loading on all parts of the ladder;

(3) anticipated impact loads resulting from the use of climbing protection devices.

(c) Live Load Concentration. All live loads shall be considered to be concentrated at a point or points that will cause the maximum stress in the structural member being considered.

6.3.4 Dead Loads. The weight of the ladder and attached appurtenances shall be considered simultaneously with the live loads in the design of siderails, supports, and fastenings.

6.3.5 Pitch. The pitch of a fixed ladder shall never exceed 90 deg nor be less than 75 deg from the horizontal. The pitch shall not be such that a person's position is below the ladder when climbing. (See definition of pitch in para. 6.2.6 and Fig. 6-1.)

6.3.6 Clearances. The distance from the center line of the rungs to the nearest permanent object on the climbing side of the ladder shall not be less than 36 in. For a pitch of 75 deg, and 30 in., see Fig. 6-1.

(a) The distance from the center line of the rungs to the nearest permanent object on the opposite (back) side shall not be less than 7 in. (See Fig. 6-1)

(b) A clear side-to-side width of a least 15 in. shall be provided each way from the center line of the ladder in the climbing space, except when cages are used. (See Fig. 6-2.)

(c) The distance from the center line of a grab bar to the nearest permanent object in the back of the grab bar shall not be less than 4 in. The grab bars shall not protrude on the climbing side beyond the rungs of the ladder that they serve.

6.3.7 Landing Platforms. When caged ladders are used to ascend to heights exceeding 50 ft (except as provided in para. 6.3.10), landing platforms shall be spaced at intervals of 50 ft or less. Where installation conditions (even for a short, unbroken length) require that adjacent sections be offset, landing platforms shall be provided at each offset. The total depth of platform shall provide a minimum space of 30 in. from the ladder on the climbing side. The width of the platform shall not be less than 30 in. The grating and straight requirements for landing platforms shall be the same as work platforms. (See para. 6.4.3.)

6.3.8 Access/Egress. The siderails of step-through and side step-fixed ladders shall extend at least 42 in. Above the roof, parapet, or landing platform, preferably being gooseneck, unless other convenient and secure hand holds (grab bars) are fixed at such places.

(a) For step-through ladders, the rungs shall be omitted from this extension. For step-through ladders, the step-across distance from the center line of the rung to the nearest edge of the structure, building, or equipment shall not be less than 7 in., or more than 12 in. If the normal step-across distance exceeds 12 in., a landing platform shall be provided to reduce the distance to between 7 in. and 12 in. For these step-through ladders, the same rung spacing used on the ladder shall be used from the landing platform to the first rung below the landing. (See Fig. 6-3.)

(b) For side step or offset fixed ladder sections at landings, the siderails and rungs shall be carried to the next regular rung beyond or above the 42-in. minimum mentioned above. Side step ladders at the point of access/egress to a platform shall have a step-across distance of 15 in. minimum and 20 in. maximum from the center line of the ladder. For side step landings, the platform shall be located at the same level as one of the rungs.

6.3.9 Safety Cages. Except as provided in para. 6.3.10, safety cages shall be provided for all ladders to a maximum unbroken length of 50 ft (See para. 6.3.7.)

(a) Cages shall extend to a minimum of 3 in. to 6 in. above the top of a landing unless other acceptable protection is provided. (See Fig. 6-4.)

(b) Cages shall extend down the ladder to a point not less than 7 ft or more than 8 ft above the base of the ladder with the bottom flared not less than 4 in., or the portion of the cage opposite the ladder shall be carried to the base.

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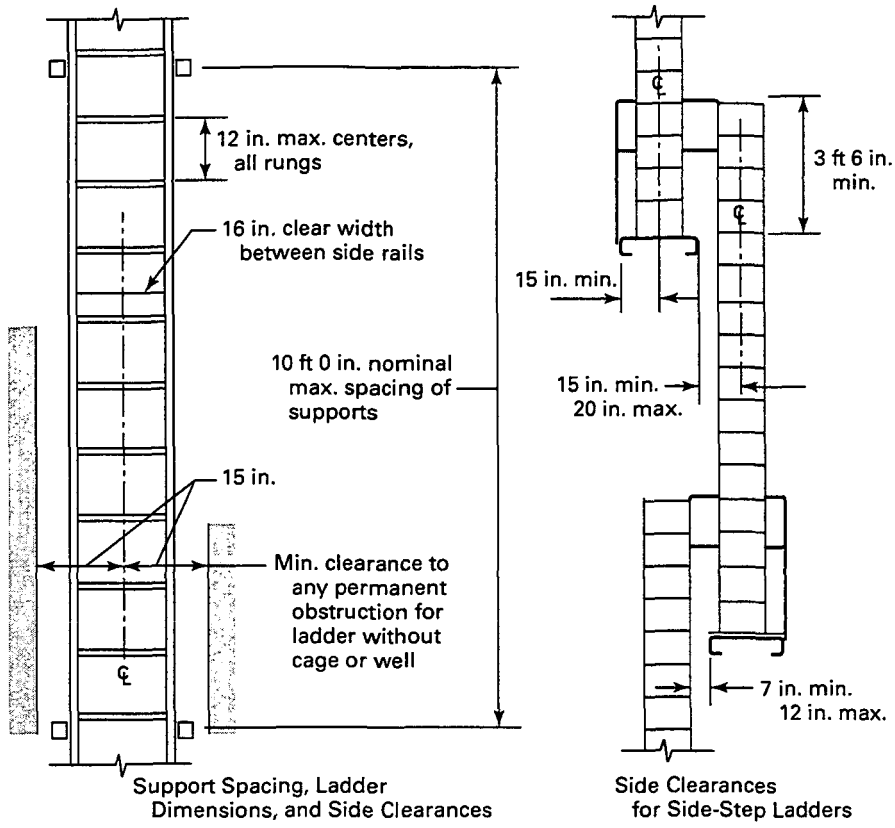

FIG. 6-2 LADDER DIMENSIONS, SUPPORT SPACING, AND SIDE CLEARANCES

(c) Cages shall not extend less than 27 in. or more than 30 in. from the center line of the rungs of the ladder. Cages shall not be less than 27 in. in width. The inside shall be clear of projections. Vertical bars shall be located at maximum spacing of 40 deg around the circumference of the cage. This will give a maximum spacing of approximately $9\frac{1}{2}$ in. center-to-center of the vertical bars. There shall be seven vertical bars located inside the hoops.

(d) Hoop bars shall be $\frac{1}{4}$ x 2 in. steel minimum with a maximum spacing of 4 ft on centers.

(e) Vertical bars shall be sized $\frac{3}{16}$ in. x $1\frac{1}{2}$ in. minimum. Vertical bars shall be welded or bolted together and to the hoops with bolt heads countersunk on the inside.

(f) Where a caged ladder is so located that it could be ascended on the uncased side, a sheet steel baffle shall be erected extending from the ground or floor level to a height of at least 8 ft to prevent access to the uncased side of the ladder.

(g) Climbing protection devices may be used in combination with cages if additional protection is desired.

6.3.10 Climbing Protection Devices. Climbing protection devices may be used on ladders in lieu of cage protection. Landing platforms shall be provided at a maximum of 150-ft intervals in these cases. Climbing protection devices that incorporate friction brakes and sliding attachments shall meet the requirements of ANSI A14.3. Special consideration shall be given to increased possibility of corrosion at the top of stacks resulting from the action of stack gases.

6.3.11 Short Ladders. All stack ladders over 10 ft in height shall be caged, or have a safety device unless the ladder extends less than 15 ft above ground.

6.3.12 Siderails. The siderails shall be of flat bar stock and not be less than $2\frac{1}{2}$ in. x $\frac{3}{8}$ in. If siderails of other cross sections are desired, they shall be at least equal in strength to the above-sized steel bar.

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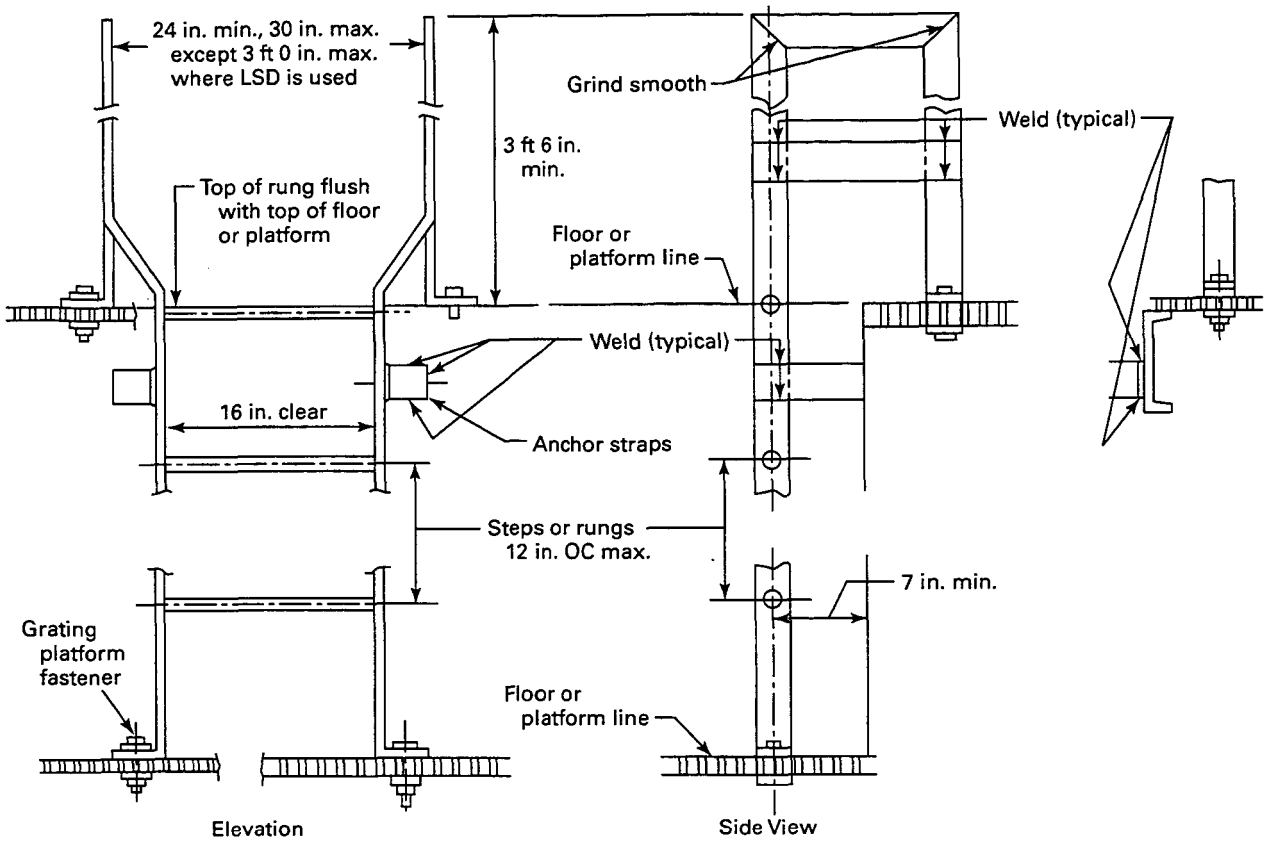

FIG. 6-3 LANDING PLATFORM DIMENSIONS

(a) Rails shall be spaced a minimum of 16 in. (inside) and a maximum of 24 in. (inside) apart.

(b) All splices shall provide smooth transitions with the main siderails so as to afford minimum interference with the gripping surface for the hands of the person using the ladder. Sharp or extensive projections shall not be permitted.

(c) Provisions for expansion due to thermal changes shall be made at the siderail splices, if these provisions are required to prevent buckling or the buildup of stresses in the siderails.

(d) For ladders subject to unusually corrosive atmospheric conditions, corrosion resistant steel of increased thickness should be used. The extent of increased thickness should be determined from experience with corrosion.

(e) Heads of bolts shall be countersunk or of the button type. The heads shall be on the inside of the siderails. Bolts shall not be less than $^{5}/_{8}$ in. in diameter.

(f) With the bolted siderail joints, a minimum of two bolts shall be provided on each side.

(g) Welded siderail splices shall be full penetration butt welds between the rungs and staggered at least 12 in.

6.3.13 Rungs. Rungs shall not be less than $^{3}/_{4}$ in. in diameter. For ladders exposed to unusually corrosive atmospheres, rungs shall be of at least 1 in. solid bars. Spacing of rungs shall not exceed 12 in. center-to-center and shall be spaced uniformly throughout the length of the ladder. Rungs shall be inserted through holes in the siderails and shall be welded completely around the circumference of the rung to the outside of the siderails.

6.3.14 Ladder Support. Ladder supports shall be of steel at least equivalent to the siderails in strength. Ladder supports may be bolted or welded to the siderails, but must be welded to the stack shell. Ladder supports shall not be more than 10 ft apart. Anchorage of ladders must account for the thermal growth of the stack.

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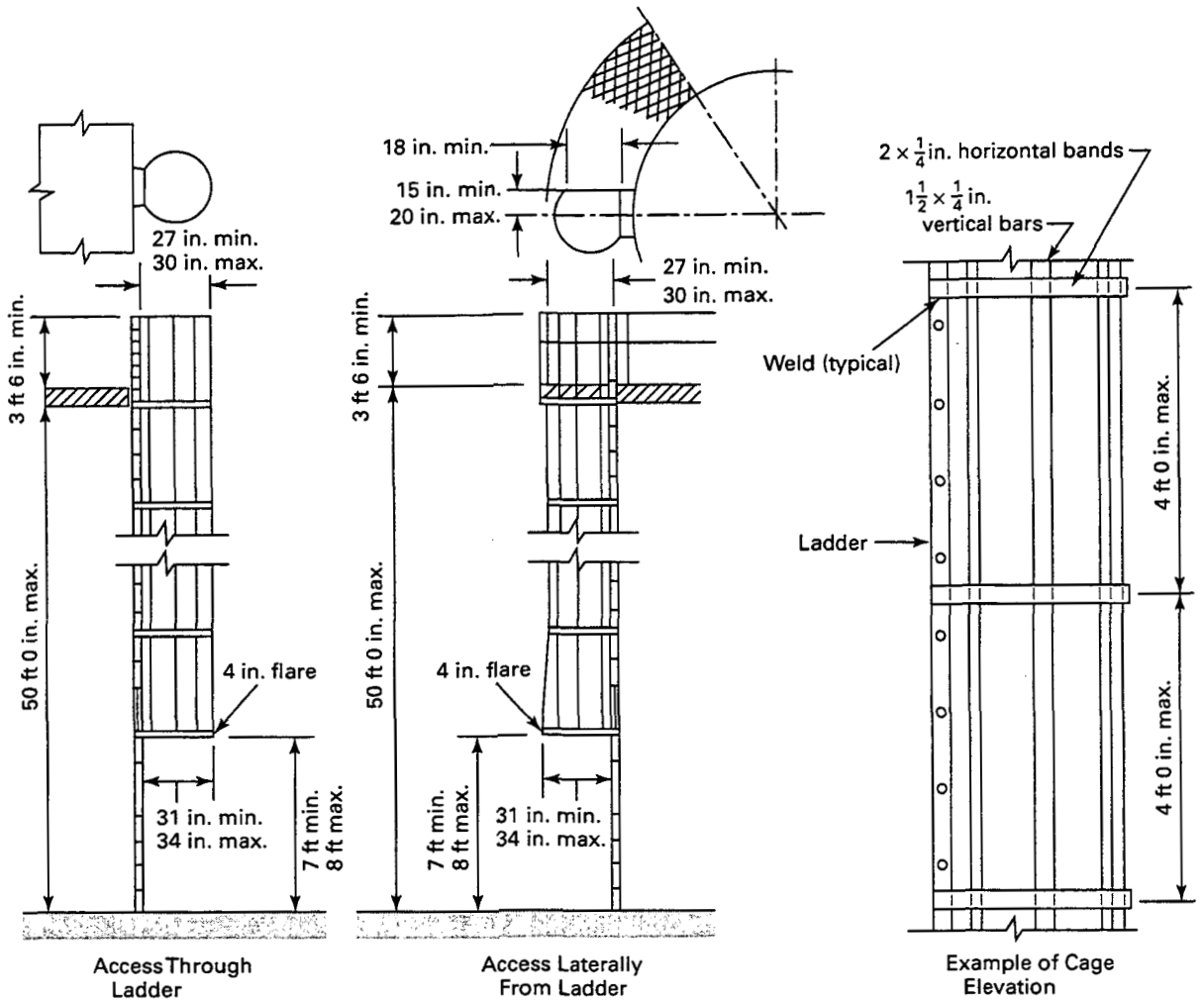

FIG. 6-4 EXAMPLE OF THE GENERAL CONSTRUCTION OF CAGES

6.4 Work Platforms

6.4.1 Where Required. Work platforms shall be provided wherever duties require an employee to work at elevations above grade or building floors adjacent to the stack.

6.4.2 Strength Requirements. Work platforms shall be designed to support the expected loads, including the possible attachment of gin poles, davits, and suspended inspection and maintenance scaffolding.

6.4.3 Surfaces. The flooring should be of the grating type. The space in the grating bars should be such that any one opening is not greater than will permit a ball 1 in. in diameter to pass through. The grating should be of sufficient strength to withstand a live floor loading of 100 lb/sq. ft over the entire platform area. The minimum size of the platform should be the same as the size for landing platforms, as indicated in para. 6.3.7.

6.4.4 Railings. Railings shall be used on all work platforms and shall be of steel construction (see para. 6.3.2). A standard railing shall consist of top rail, intermediate rail, and posts and shall have a vertical height of 42 in. nominal from upper surface of top rail throughout the length of the railing. The intermediate railing shall be approximately halfway between the top rail and the platform. The spacing of the horizontal rails shall be such that a 21-in. diameter ball will not pass between the rails. The ends of the rail shall not overhang the terminal posts, except where such an overhang does not constitute a projection hazard.

(a) The railings shall be of pipe or tubing with

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minimum 1½ in. outside diameter or other cross sections of equivalent strength with the vertical posts spaced not more than 6 ft on centers.

(b) The top and intermediate railings shall be capable of withstanding a force of 200 lb in any direction, and at any location on the railing.

6.4.5 Toe Boards. Toe boards shall be at least 4 in. nominal vertical height from the top edge to the level of the platform. They shall be securely fastened in place with not more than ¼ in. clearance above the platform. They should be made of steel.

6.4.6 Access

(a) Access openings to work platforms shall be guarded.

(b) Where access to work platforms is through the floor, trap doors shall be provided. Access doors shall remain closed except when persons are accessing or leaving the platform. Access doors and hatches should be designed as self-closing.

(c) Where access to work platforms is by way of side-step ladders, the opening shall be guarded by self-closing gates.

6.5 Scaffolding and Hoists Used For Construction of Steel Stacks

6.5.1 General. Scaffolding shall meet the applicable requirements of the current revision of ANSI A10.8, Safety Requirements for Scaffolding.

6.5.2 Lifelines. Lifelines and body belts, or harnesses and their anchorages, shall be used as specified in the current revision of ANSI A10.14, Requirements for Safety Belts, Harnesses, Lanyards, Lifelines, and Drop Lines for Construction and Industrial Use.

6.5.3 Anchorage Points. When scaffolds and hoists are to be used to provide access to steel stacks, appropriate anchorage points shall be provided. Attachments for suspending scaffolds, hoists, and lifelines shall not be bolted or riveted through the stack plate. (See para. 6.3.14.)

6.5.4 Personnel Hoists. Personnel hoists shall meet the requirements of the current revision of ANSI A10.4, Safety Requirements of Personnel Hoists.

6.5.5 Painter's Trolleys Painter's trolleys should not be used for hoisting, lowering, or supporting personnel. Painter's trolleys should be used for hoisting materials only.

6.6 Thermal Protection

6.6.1 Hot Surfaces. Surface of steel stacks (when exposed to personnel) shall be limited to a maximum temperature of 140°F.

6.6.2 Where to Protect. Areas that should be protected are as follows:

(a) 2 ft width x full length of ladders;

(b) Platform grating to 8 ft above grating;

(c) Stack base to 8 ft above base, if hot.

6.6.3 How to Protect. Protection may be provided by insulation and cladding, and/or stand-off mesh. Mesh shall be no larger than 2 in. x 2 in.

6.6.4 Materials. Materials used for anchorage, cladding, and mesh shall be corrosion resistant and designed to resist wind pressures.

7 ELECTRICAL

7.1 Scope

Provisions of this section shall apply to permanent electrical items as related to the stack. They shall not apply to items used during construction or demolition of steel stacks.

7.2 General

7.2.1 Purpose. The purpose of this section is to identify the electrical items commonly used with stacks and to establish a standard as it relates to such items.

7.2.2 Codes, Standards, and Other Documents

(a) National Electrical Code, NEC 96

(b) Lightning Protection Code, ANSI/NFPA 78

(c) Underwriter's Laboratories, Standard UL 96A

(d) FAA, current Advisory Circular AC 70/7460

7.3 Aviation Obstruction Light System

7.3.1 FAA Requirements. It is recommended, immediately following the determination of the location and height of the proposed stack, that the Federal Aviation Administration (FAA) be contacted to determine the FAA's specific requirements for lighting and marking. Aviation warning lighting will be required

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for stack heights 200 ft and higher; and sometimes for shorter stacks, when the stack is near an airport, heliport, or seaport.

Sometimes, however, modifications to the marking/lighting rules are logical and can be acceptable to the FAA. This is generally true in the case of cluster stacks, stacks in line, stacks in a large industrial complex where other tall structures or other stacks are present, etc. The FAA will investigate and rule on the most appropriate marking and/or lighting for each such case upon request.

7.3.2 System Components. When required, an obstruction marking light system shall conform to the requirements of the FAA current Advisory Circular AC 70/7460. A light system may consist of the following:

(a) Flood Lights. Flood lights located at or near the base of the stack are considered nonstandard but may be utilized on short stacks with FAA approval.

(b) Aviation Red Obstruction Lights. Aviation red obstruction lights mounted on the stack at required elevations and at specific positions around the circumference should be as required by the FAA Advisory Circular AC 70/7460. All red obstruction lighting should be exhibited from sunset to sunrise. When the red light system is used, it usually is necessary to paint the stack with an aviation orange and white color pattern for daytime obstruction marking.

(c) Medium Intensity White Obstruction Lights. Omnidirectional medium intensity obstruction lights are recommended for most steel stacks, since the high intensity lights are not normally recommended on structures with heights below 500 ft. The light system intensity must be controlled. The FAA current Advisory Circular AC 70/7460 sets the number and locations. On small diameter stacks, the FAA frequently will allow only two lights, since their light rays are omnidirectional.

(d) High Intensity White Obstruction Lights. If FAA unidirectional high intensity white obstruction lights are required, they should be mounted on the stack at particular elevations and at specific positions around the circumference as required by the FAA current Advisory Circular AC 70/7460. This type of system is used with a light sensitive control device, which faces the north sky to control intensity.

7.3.3 System Access Location. Access to lights for maintenance may be by ladders and platform or by a lowering device which brings the light fixture to an accessible location. Because of stack gas downwash, the location of the access and lights should be as low as the FAA allows.

7.4 Lightning Protection

The lightning protection requirement for metal stacks as covered in the ANSI/NFPA 78, Lightning Protection Code requires two ground terminals located on opposite sides of a stack having a metal thickness of $^{3}/_{16}$ in. (4.8 mm) or greater. No air terminals or down conductors are required. On guyed stacks, metal guy wires are to be grounded at their lower ends if anchored in concrete, or to a masonry building or other nonconductive support.

7.5 Convenience Lighting

Convenience or area lighting on test platforms, monitor platforms, access systems, annular space, etc., may be considered and specified as applicable.

7.6 Convenience Power Outlets

Convenience power outlets are generally useful during stack testing and maintenance of monitoring equipment.

7.7 Instrumentation

7.7.1 Sampling. Instrumentation for monitoring or sampling of stack emissions, based on current Federal EPA regulations, CFR Part 60, shall be mounted on the external surface of the steel stack protected from excessive heat and providing for thermal and other stack movement.

7.7.2 Thermocouples. Thermocouples may be required by the owner at intervals on the stack shell or stack liner for temperature measurement.

8 FABRICATION AND ERECTION

8.1 Purpose

This section is designed to establish a good level of fabrication and erection quality to create a high degree of public safety and confidence in these structures. It establishes the welding requirements for the fabrication and erection of welded steel stacks.

8.2 Scope

This section covers the recommended guidelines applying to the fabrication and erection of steel stacks. It includes, but is not limited to, single-wall, dual-wall, and multi-flue steel stacks; and applies to stacks that are free-standing, self-supported, guy or cable supported, or supported by structural steel braces or framework.

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These guidelines also pertain to shop or field fabrication and to field erection.

8.3 Welding

The American Welding Society Structural Welding Code ANSI/AWS D1.1 (latest edition) or ASME BPV, Section IX shall be used for all welding provisions, workmanship, techniques, welder and inspector qualifications, and inspections. All structural butt welds shall be full penetration welds.

8.4 Welding Inspection and Nondestructive Testing

Welding inspection shall be performed to the extent specified with minimum requirements as follows:

8.4.1 Minimum Weld Inspection

(a) A minimum of one radiograph per each three shop circumferential seams on the stack structural shell, preferably at the vertical weld intersection.

(b) A minimum of one radiograph per each shop circumferential seam on the inner shell(s) of a dual wall or multi-flue stack.

(c) All structural full penetration field welds should be visually inspected.

(d) Shell plate field splice radiographs are not usually feasible due to the design of the field splices.

8.4.2 Types of Welding Inspection. The procedure and technique shall be in accordance with specifications of the specific job and the standards of acceptance shall be according to ASME or AWS Codes.

(a) Radiographic Inspection. This procedure can be performed in the shop on full penetration butt welds.

(b) Magnetic Particle Inspection. This procedure can be used on all welds.

(c) Ultrasonic Inspection. This procedure can be used on all shop butt welds.

(d) Visual Inspection. Visual inspection shall be made for all welds during the welding operation and again after the work is completed to determine satisfactory penetration of weld metal fusion and satisfactory operator performance. After the welding is completed, welds shall be cleaned before the inspector performs the weld inspection. The inspector shall pay particular attention to surface cracking, surface porosity, surface slag inclusion, undercut, overlap, gas pockets, and size of weld. Defective welding shall be corrected according to ASME or AWS Code requirements.

(e) Dye Penetrant Inspection. This procedure shall be used as required to supplement the visual inspection. The standard methods set forth in ANSI/AWS D1.1 (latest edition) shall be used for dye penetrant inspection, and the standard acceptance shall be according to ASME or AWS Codes.

8.5 Tolerances

Unless otherwise specified, the following shall be used as acceptable tolerances:

(a) Misalignment between plates at any butt joint shall not exceed the following limits:

Plate Thickness, in.	Maximum Offset
Up to $\frac{3}{4}$	$\frac{1}{4}$ (t)
$\frac{3}{4}$ to $1\frac{1}{2}$	$\frac{3}{16}$ in.

t = normal thickness of the thinner plate at the joint in inches

(b) Peaking is a localized deviation of stack cylindrical section contour from a true circle at junctions. Peaking of joints and seams shall not exceed $\frac{1}{4}$ in. (6 mm) maximum as measured from an 18 in. (450 mm) long template centered at the weld and cut to the prescribed radius.

(c) At the time of erection, the stack shall be true and plumb to within 2 in. (50 mm) in 100 ft (30 m).

(d) The difference between the maximum and minimum inside diameters at any cylindrical shell cross section along the height shall not exceed 2% of the diameter.

(e) Local dents in plates shall be no deeper than $\frac{1}{2}$ the plate thickness.

8.6 Shop Fabrication and Field Erection

8.6.1 During the assembly of bolted connections:

(a) Drifting, if required, shall not enlarge the holes or distort the members. Holes that must be enlarged shall be reamed.

(b) Bolts shall be tightened using one of the following:

(1) turn-of-the-nut method
(2) load indicating washers
(3) calibrated wrenches

8.6.2 Any required straightening of material shall be done by procedures that will result in the minimum residual stress to the steel.

8.6.3 Anchor bolt straightening or bending by heating is prohibited.

8.6.4 All vertical shop and field plate butt weld seams are to be staggered a minimum of 20 deg. All welded cylindrical sections joined to other cylindrical

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sections by circumferential welds shall have their vertical seams staggered from each other a minimum of 20 deg.

8.6.5 Dimensions and weights of stack sections shall be accurately calculated and compared with crane capabilities at the working radii of cranes to be used during erection. Crane capacities and working radii shall not be exceeded.

8.6.6 Lifting clips, lugs, dogs, brackets, and other items welded to the stack sections, or other parts of the permanent structure and used for erection or fit-up purposes, if not left in place, shall be removed without damaging the base material. Any portion of the weld remaining on the internal surface of the stack subjected to flue gas shall be made flush and ground smooth. If backing is used for welding purposes, they need not be removed.

8.6.7 Erection and scaffolding, ladders, etc. shall be in accordance with latest applicable and/or specified codes.

8.6.8 Anchor bolts should be re-tightened 30 days after stack erection.

8.7 Grouting

Grouting of the stack base ring is recommended when the stack is supported by a concrete foundation or elevated concrete pad.

8.7.1 After the stack is completely erected plumb and the anchor bolts have been torqued, the space between the bottom of the base plate and the top of the foundation shall be grouted. The grout shall be a non-shrink type and shall harden free of bleeding or drying shrinkage when mixed and placed at any consistency (fluid, flowable, plastic, or damp-pack). Steel shims used for plumbing the stack during erection may be best left in place.

8.7.2 Surface areas to be grouted shall be free of all foreign matter and thoroughly wetted down prior to grouting.

8.7.3 The temperatures of the grout, base plate, and foundation during grouting shall be in accordance with the grout manufacturer's recommendations.

8.7.4 If anchor bolts are set in open sleeves, care must be taken to ensure complete filling with grout of sleeve cavity.

8.8 Handling and Storage

8.8.1 Handling during unloading, erecting, or moving any section using a crane, lift, hoist, or manpower should be safely planned.

8.8.2 Protective shipping coverings, if provided, shall remain on their respective stack section areas or locations as long as possible. Components to be set down prior to erection shall be kept off the ground and properly positioned and braced to prevent damage.

8.8.3 All erection aids such as slings, hooks, chokers, beams, lifting lugs, etc., shall be of adequate strength to handle all sections and parts in a safe manner.

8.8.4 The following storage conditions shall be met:

(a) All parts shall be stored in a manner to preclude being kinked, dented, bent, misshapen, or otherwise mismanaged.

(b) All parts shall be stored above ground and so positioned as to minimize water-holding pockets, soiling, contamination, or deterioration of the coating or lining.

(c) Items that could deteriorate or become damaged due to the influence of the elements shall be properly protected.

9 INSPECTION AND MAINTENANCE

9.1 Purpose

The purpose of this section is to identify problems that occur during the service life of steel stacks, and to outline the measures for counteracting such problems through regular inspections and maintenance.

9.2 Scope

The inspection and maintenance provisions of this section apply to the stack shell, flue liners, and appurtenances.

9.3 Common Problems

(a) atmospheric corrosion and weathering on exterior surface

(b) corrosion due to acid condensation in flue gases on internal surfaces

(c) fly ash or particulate collection at the base, false bottom, or roof cap of the stack

(d) moisture condensate at the base of the stack

(e) acid/moisture infiltration of insulation

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(*f*) deformation due to thermal or other loading

(*g*) corrosion of anchor bolts

(*h*) fatigue cracks

(*i*) loss or deterioration of insulation, coating, or linings

(*j*) loosening of anchor bolts

9.4 Inspection

For early detection of the commonly occurring problems, it is recommended that the stack be inspected periodically to enable the user of the stack to take appropriate measures to counteract such problems.

9.4.1 Frequency of Inspection. The frequency of inspections should be based upon climate, construction materials, type of construction, and the nature of use (i.e., fuel type, operating temperature, and operating schedule). This may be specified by the stack manufacturer; however, in the absence of such information, it is recommended that the stacks be inspected annually for the first three years. The results of these inspections should then determine the frequency of future inspections.

9.4.2 Items of Inspection

(*a*) Exterior Inspection

(*1*) *Shell Thickness.* Ultrasonic devices for nondestructive thickness testing or core samples and drill tests for destructive testing may be used to measure the shell thickness. Depending upon the condition of the stack, one shell thickness reading for each portion of the stack height equal to the stack diameter is recommended. A record of the results shall be maintained for monitoring corrosion of the steel shell.

(*2*) *Finish.* Damage, wear, and discontinuity in the exterior finish shall be inspected and all deficiencies should be recorded.

(*3*) *Access System.* All ladders, ladder anchors, cages, safety climb devices, platforms, painter's trolleys, and trolley rails shall be inspected to assure their integrity and safety.

(*4*) *Lightning Protection System.* All components of the lightning protection system, including the grounding connection, shall be inspected for electrical continuity.

(*5*) *Support System.* Any brace, guy wire anchors, guy cables, guy fittings, and other similar items shall be checked. All deficiencies shall be noted and analyzed.

(*6*) Anchor Bolts shall be inspected.

(*7*) *Electrical System.* The presence of any moisture condensation on the inside of the conduit and fittings shall be noted. Corrosion of fittings and conduits shall also be noted. Burned out lamps must be replaced.

(*8*) *Insulation.* Soaking of insulation, due to infiltration of acid in insulated stacks is possible. Wet and acid saturated insulation rapidly accelerates corrosion of the shell leading to major structural damage.

(*b*) Interior Inspection

(*1*) *Shell Thickness.* Ultrasonic devices for nondestructive thickness testing may be used to measure the shell thickness. Depending upon the condition of the stack, one shell thickness reading for each portion of the stack height equal to the stack diameter is recommended. A record of the results shall be maintained for monitoring corrosion of the steel.

(*2*) *Lining.* This component of the stack is the most critical in terms of wear, cracks, spells, and other deficiencies. Such deficiencies are often hidden by overlaying particulate deposits and, therefore, proper care shall be exercised to detect deficiencies. It is recommended that pH readings be taken throughout. pH readings may be taken using litmus paper, reagent(s), or by chemical analysis of representative samples of scrapings from lining surfaces.

(*3*) *Particulate Accumulation.* Accumulation of particulates such as combustion residue, fly ash, etc., on the stack wall and at the base of the stack provides a matrix for acid condensate.

(*c*) *General Items.* Deformation of any component of the stack due to thermal or other loading shall be noted to include stack cap, expansion joints, and test and instrument ports.

9.4.3 Inspection Procedure

(*a*) For thorough inspections, the stack shall be rigged with equipment allowing the inspector to traverse the entire height on the interior and exterior of the chimney. All rigging and scaffolding shall be in compliance with OSHA regulations.

(*b*) The full height of the stack shall be traversed, photographing general interior conditions at regular intervals with specific attention to defective areas.

(*1*) It is recommended that color photographs be taken for use in the report. Instant photographs may be taken as backups.

(*2*) Defective areas that may be found shall be charted and noted.

(*c*) The integrity of the lining shall be judged on a visual basis; supplemented by routine probing to determine hardness, soundness, and/or general conditions.

(*d*) Unlined steel stacks shall receive either nondestructive thickness testing using an acceptable ultrasonic

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device, or destructive thickness testing using drilling or core sampling.

(e) The exterior inspection shall also include a thorough examination of all appurtenance items, such as anchor bolts, cleanout door, ladder, caps, lightning protection system, and any other hardware items.

9.4.4 Inspection Report. The scope of inspection work shall be specified by the stack owner. In the absence of such specifications, it is recommended that the stack inspection report have the following items:

(a) identification and brief description of the stack;

(b) description of the inspection procedures;

(c) color photographs showing typical condition as well as problem areas. Each photograph must be identified as to the location of the photograph as well as the description of what is shown in the photograph;

(d) drawings and/or location charts defining shell thickness, pH readings, and deficiencies;

(e) analysis of deficiencies and problems noted during the inspection;

(f) maintenance and/or repair recommendations.

9.5 Maintenance

9.5.1 Exterior Surface. All wear, corrosion, and other deficiencies in the exterior surfaces shall be repaired as required.

9.5.2 Interior Surface. Periodic removal of particle deposits on the interior surfaces using high-pressure wash or other effective and practical methods is recommended, and other deficiencies in the lining should be repaired.

9.5.3 Anchor Bolts. Areas around the anchor bolts shall be kept clean and free of particle deposits and moisture. Periodic retightening of anchor bolts is recommended.

9.5.4 Drains. All drains and false bottom floors shall be kept clean through periodic maintenance.

9.5.5 Appurtenance. All appurtenances shall be repaired as necessary for safety and intended use.

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MANDATORY APPENDIX I
STRUCTURAL DESIGN
Gust Effect Factor Calculation

The gust effect factor is given by

$$G_f = 0.925\left(\frac{1 + 1.7\, I_{\bar{z}}\sqrt{g_Q^2\, Q^2 + g_R^2\, R^2}}{1 + 1.7\, I_{\bar{z}}\, g_v}\right)$$

where R, the resonant response factor, is given by

$$R = \sqrt{\frac{1}{\beta} R_n R_h R_B\,(0.53 + 0.47\, R_d}$$

$$R_n = \frac{7.47\, N_1}{(1 + 10.3 N_1)^{5/3}}$$

$$N = \frac{n_l L_{\bar{z}}}{\overline{V}_{\bar{z}}}$$

$$R_l = \frac{1}{\eta} - \frac{1}{2\,\eta^2}(1 - e^{-2\eta}) \text{ for } \eta > 0$$

$$1 \text{ for } \eta = 0$$

$(l = h, B, d)$

$R_l = R_h$ setting $\eta = 4.6 n_1 h/\overline{V}_{\bar{z}}$
$R_l = R_B$ setting $\eta = 4.6 n_1 B/\overline{V}_{\bar{z}}$
$R_l = R_d$ setting $\eta = 15.4 n_1 d/\overline{V}_{\bar{z}}$
β = damping ratio

$$\overline{V}_{\bar{z}} = \overline{b}\left(\frac{\bar{z}}{33}\right)^{\overline{\alpha}} V$$

where $\overline{b}$ and $\overline{\alpha}$ are listed in Table I-1.

$$g_R = \sqrt{2\ 1n(3600 n_1)} + \frac{0.577}{\sqrt{2\ 1n(3600 n_1)}}$$

The factors g_Q and g_v may be taken equal to 3.4. V is the 3-sec gust speed in exposure C at the reference height (obtained from Fig. I-1.)

$$I_{\bar{z}} = c\left(\frac{33}{\bar{z}}\right)^{1/6}$$

where $I_{\bar{z}}$ = the intensity of turbulence at height $\bar{z}$, where $\bar{z}$ = the equivalent height of the structure (0.6 h but not less than z_{min} listed for each exposure in Table I-1, c is given in Table I-1 and Q represents the background response. Q is given by

$$Q = \sqrt{\frac{1}{1 + 0.63\left(\frac{B + h}{L_{\bar{z}}}\right)^{0.63}}}$$

where B = stack diameter, h = stack height; and $L_{\bar{z}}$ = the integral length scale of turbulence at the equivalent height

$$L_{\bar{z}} = l(\bar{z}/33)^{\bar{\epsilon}}$$

in which l and $\bar{\epsilon}$ are as listed in Table I-1.

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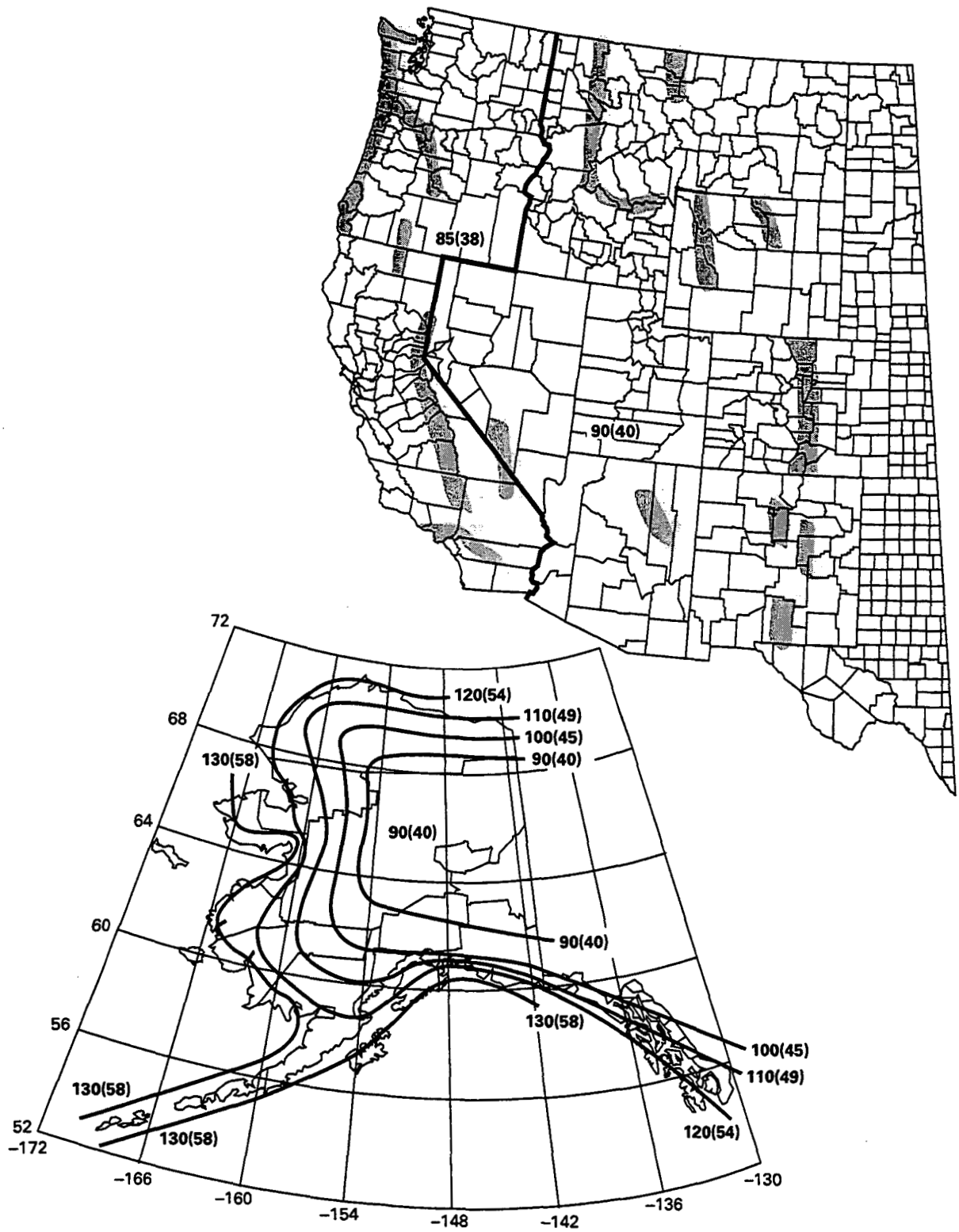

FIG. I-1 BASIC WIND SPEED

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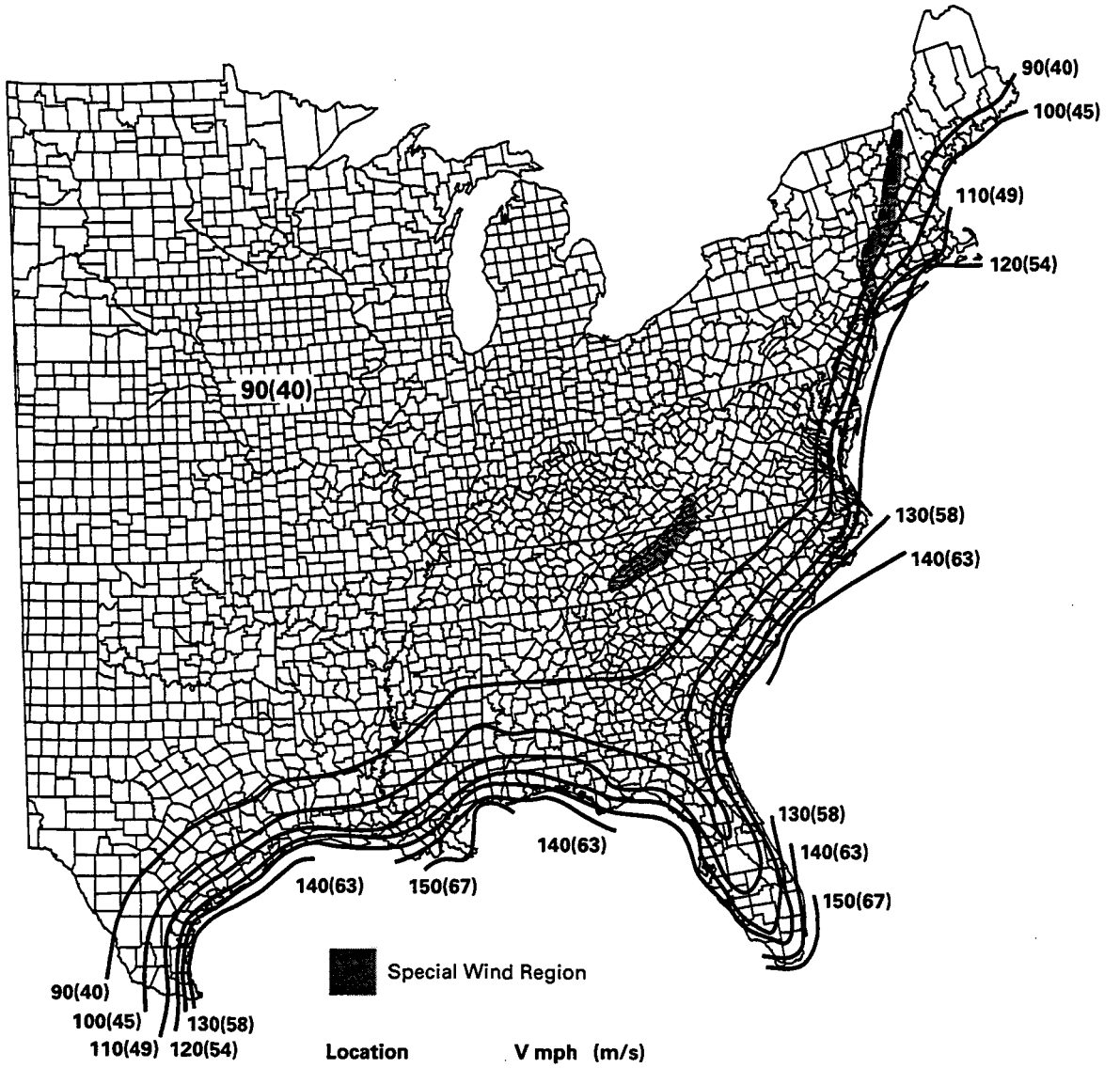

Location	V mph	(m/s)
Hawaii	105	(47)
Puerto Rico	145	(65)
Guam	170	(76)
Virgin Islands	145	(65)
American Samoa	125	(56)

GENERAL NOTES:

(a) Values are nominal design 3-second gust wind speeds in miles per hour (m/s) at 33 ft (10 m) above ground for Exposure C category.

(b) Linear interpolation between wind contours is permitted.

(c) Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.

(d) Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

FIG. I-1 BASIC WIND SPEED (CONT'D)

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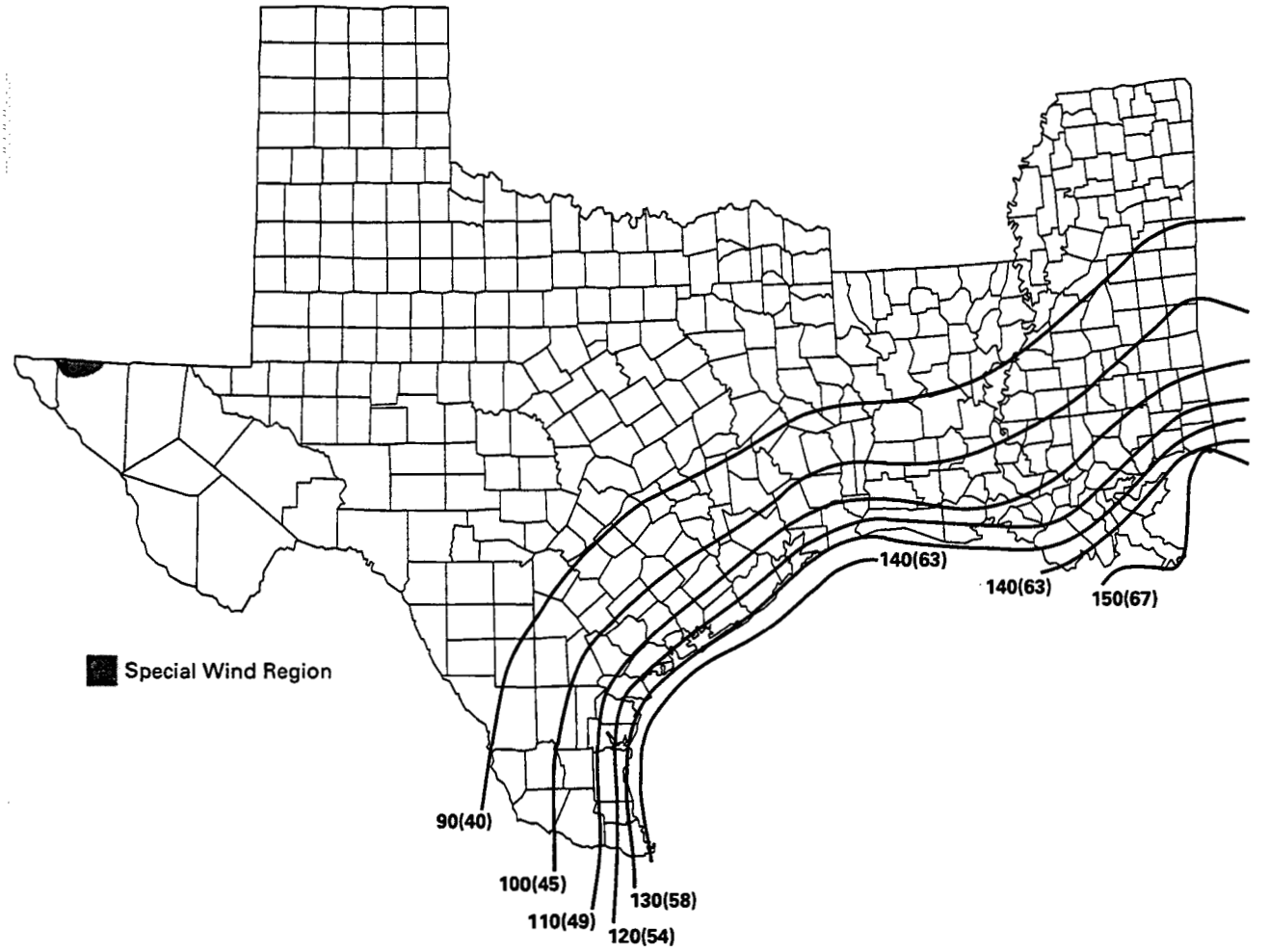

GENERAL NOTES:

(a) Values are nominal design 3-second gust wind speeds in miles per hour (m/s) at 33 ft (10 m) above ground for Exposure C category.

(b) Linear interpolation between wind contours is permitted.

(c) Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.

(d) Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

FIG. I-1a BASIC WIND SPEED – WESTERN GULF OF MEXICO HURRICANE COASTLINE

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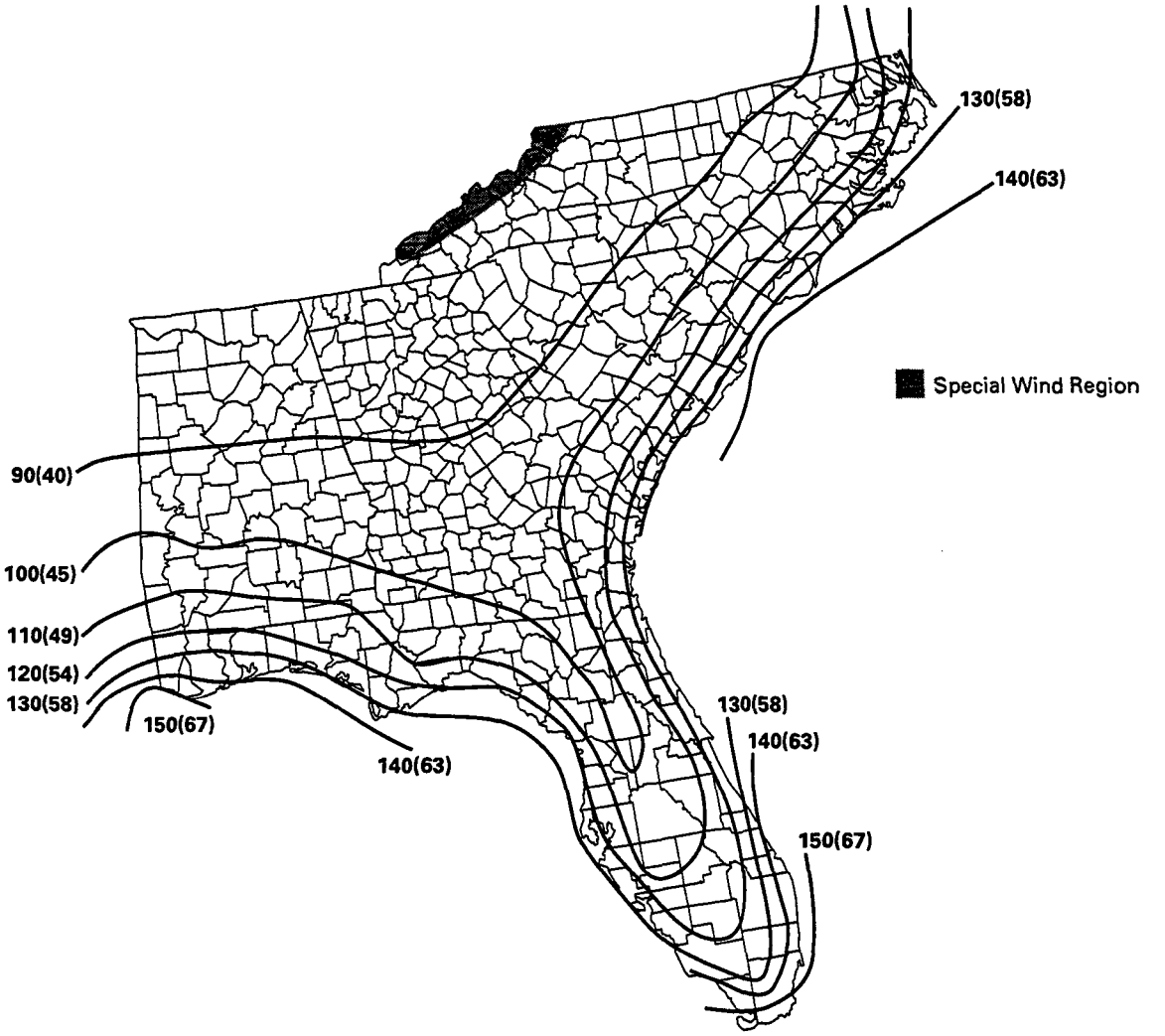

GENERAL NOTES:

(a) Values are nominal design 3-second gust wind speeds in miles per hour (m/s) at 33 ft (10 m) above ground for Exposure C category.

(b) Linear interpolation between wind contours is permitted.

(c) Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.

(d) Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

FIG. I-1b BASIC WIND SPEED – EASTERN GULF OF MEXICO AND SOUTHEASTERN U.S. HURRICANE COASTLINE

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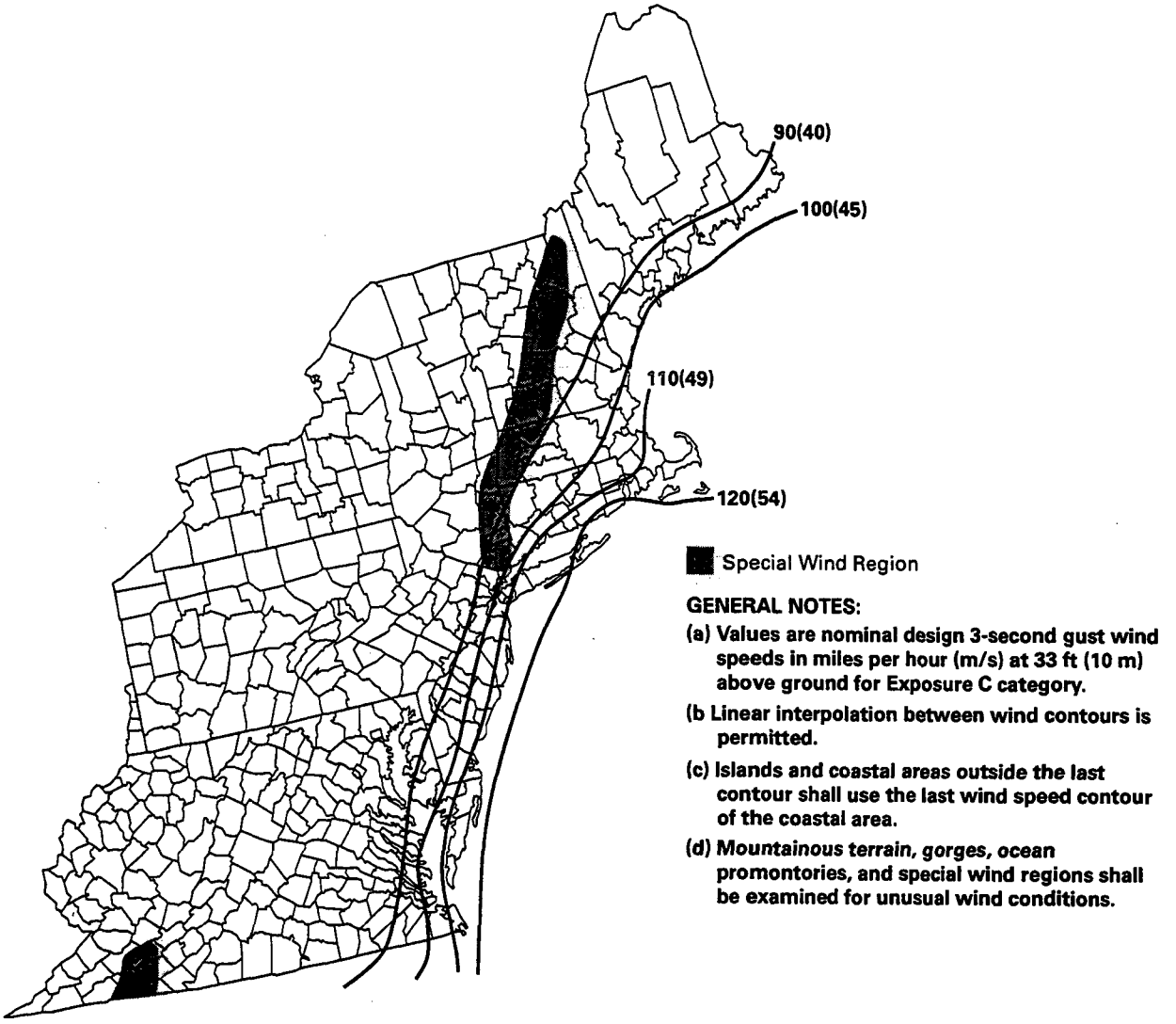

FIG. I-1c BASIC WIND SPEED MID AND NORTHERN ATLANTIC HURRICANE COASTLINE

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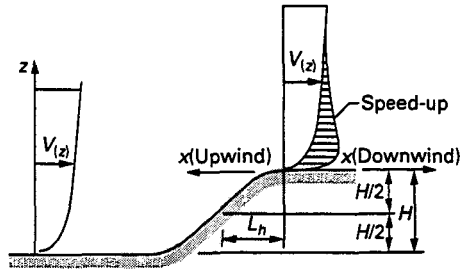

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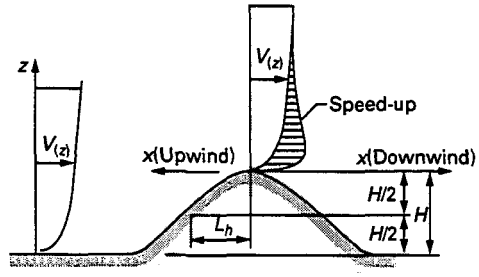

2-D RIDGE OR 3-D AXISYMMETRICAL HILL

Topographic Multipliers for Exposure C (3)

	K_1 Multiplier (2)				K_2 Multiplier (2)			K_3 Multiplier (2)		
H/L_h (1)	2-D Ridge	2-D Escarp.	3-D Axisym. Hill	x/L_h (1)	2-D Escarp.	All Other Cases	z/L_h (1)	2-D Ridge	2-D Escarp.	3-D Axisym. Hill
0.20	0.29	0.17	0.21	0.00	1.00	1.00	0.00	1.00	1.00	1.00
0.25	0.36	0.21	0.26	0.50	0.88	0.67	0.10	0.74	0.78	0.67
0.30	0.43	0.26	0.32	1.00	0.75	0.33	0.20	0.55	0.61	0.45
0.35	0.51	0.30	0.37	1.50	0.63	0.00	0.30	0.41	0.47	0.30
0.40	0.58	0.34	0.42	2.00	0.50	0.00	0.40	0.30	0.37	0.20
0.45	0.65	0.38	0.47	2.50	0.38	0.00	0.50	0.22	0.29	0.14
0.50	0.72	0.43	0.53	3.00	0.25	0.00	0.60	0.17	0.22	0.09
...	...	...	...	3.50	0.13	0.00	0.70	0.12	0.17	0.06
...	...	...	...	4.00	0.00	0.00	0.80	0.09	0.14	0.04
...	...	...	...	...	...	...	0.90	0.07	0.11	0.03
...	...	...	...	...	...	...	1.00	0.05	0.08	0.02
...	...	...	...	...	...	...	1.50	0.01	0.02	0.00
...	...	...	...	...	...	...	2.00	0.00	0.00	0.00

NOTES:
(1) For values of H/L_h, x/L_h and z/L_h other than those shown, linear interpolation is permitted.
(2) For $H/L_h > 0.5$, assume $H/L_h = 0.5$ for evaluating K_1 and substitute $2H$ for L_h for evaluating K_2 and K_3.
(3) Multipliers are based on the assumption that wind approaches the hill or escarpment along the direction of maximum slope.
(4) Notation:

H:	Height of hill or escarpment relative to the upwind terrain, in ft (m).
L_h:	Distance upwind of crest to where the difference in ground elevation is half the height of hill or escarpment, in ft (m).
K_1:	Factor to account for shape of topographic feature and maximum speed-up effect.
K_2:	Factor to account for reduction in speed-up with distance upwind or downwind of crest.
K_3:	Factor to account for reduction in speed-up with height above local terrain.
x:	Distance (upwind or downwind) from the crest to the building site, in ft (m).
z:	Height above local ground level, in ft (m).
μ:	Horizontal attenuation factor.
γ:	Height attenuation factor.

FIG. I-2 TOPOGRAPHIC FACTOR, K_{zt}(4)

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Equations:

$K_{zt} = (1 + K_1 K_2 K_3)^2$

K_1 determined from table below

$K_2 = \left(1 - \frac{|x|}{\mu L_h}\right)$

$K_3 = e^{-\gamma z/L_h}$

Parameters for Speed-Up Over Hills and Escarpments

Hill Shape	$K_1/(H/L_h)$ Exposure B	C	D	γ	μ Upwind of Crest	Downwind of Crest
2-dimensional ridges (or valleys with negative H in $K_1/(H/L_h)$	1.30	1.45	1.55	3	1.5	1.5
2-dimensional escarpments	0.75	0.85	0.95	2.5	1.5	4
3-dimensional axisym. hill	0.95	1.05	1.15	4	1.5	1.5

FIG. I-2 TOPOGRAPHIC FACTOR, K_{zt}(4) (CONT'D)

TABLE I-1 TERRAIN EXPOSURE CONSTANTS

Exposure	α	Z_g (ft)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	l (ft)	$\bar{\epsilon}$	Z_{min} (ft)[1]
A	5.0	1500	1/5	0.64	1/3.0	0.30	0.45	180	1/2.0	60
B	7.0	1200	1/7	0.84	1/4.0	0.45	0.30	320	1/3.0	30
C	9.5	900	1/9.5	1.00	1/6.5	0.65	0.20	500	1/5.0	15
D	11.5	700	1/11.5	1.07	1/9.0	0.80	0.15	650	1/8.0	7

NOTE:
(1) Z_{min} = minimum height used to ensure that the equivalent height $\bar{z}$ is greater of $0.6h$ or Z_{min}. For stacks with $h \le Z_{min}$, $\bar{z}$ shall be taken at Z_{min}.

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TABLE I-2 CLASSIFICATION OF BUILDINGS AND OTHER STRUCTURES FOR FLOOD, WIND, SNOW, AND EARTHQUAKE LOADS

Nature of Occupancy	Category
Buildings and other structures that represent a low hazard to human life in the event of failure including, but not limited to: • Agricultural facilities • Certain temporary facilities • Minor storage facilities	I
All buildings and other structures except those listed in Categories I, III, and IV	II
Buildings and other structures that represent a substantial hazard to human life in the event of failure including, but not limited to: • Buildings and other structures where more than 300 people congregate in one area • Buildings and other structures with day-care facilities with capacity greater than 150 • Buildings and other structures with elementary or secondary school facilities with capacity greater than 150 • Buildings and other structures with a capacity greater than 500 for colleges or adult education facilities • Health care facilities with a capacity of 50 or more resident patients but not having surgery or emergency treatment facilities • Jails and detention facilities • Power generating stations and other public utility facilities not included in Category IV	III
Buildings and other structures containing sufficient quantities of toxic, explosive or other hazardous substances to be dangerous to the public if released including, but not limited to: • Petrochemical facilities • Fuel storage facilities • Manufacturing or storage facilities for hazardous chemicals • Manufacturing or storage facilities for explosives	
Buildings and other structures that are equipped with secondary containment of toxic, explosive or other hazardous substances (including, but not limited to double wall tank, dike of sufficient size to contain a spill, or other means to contain a spill or a blast within the property boundary of the facility and prevent release of harmful quantities of contaminants to the air, soil, ground water, or surface water) or atmosphere (where appropriate) shall be eligible for classification as a Category II structure.	IV
In hurricane prone regions, buildings and other structures that contain toxic, explosive, or other hazardous substances and do not qualify as Category IV structures shall be eligible for classification as Category II structures for wind loads if these structures are operated in accordance with mandatory procedures that are acceptable to the authority having jurisdiction and which effectively diminish the effects of wind on critical structural elements or which alternatively protect against harmful releases during and after hurricanes.	
Buildings and other structures designated as essential facilities including, but not limited to: • Hospitals and other health care facilities having surgery or emergency treatment facilities • Fire, rescue and police stations and emergency vehicle garages • Designated earthquake, hurricane, or other emergency shelters • Communications centers and other facilities required for emergency response • Power generating stations and other public utility facilities required in an emergency • Ancillary structures (including, but not limited to communication towers, fuel storage tanks, cooling towers, electrical substation structures, fire water storage tanks or other structures housing or supporting water or other fire-suppression material or equipment) required for operation of Category IV structures during an emergency • Aviation control towers, air traffic control centers and emergency aircraft hangars • Water storage facilities and pump structures required to maintain water pressure for fire suppression • Buildings and other structures having critical national defense functions	

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TABLE I-3 IMPORTANCE FACTOR, I (WIND LOADS)

Category	Non-Hurricane Prone Regions and Hurricane Prone Regions with V = 85–100 mph and Alaska	Hurricane Prone Regions with V > 100 mph
I	0.87	0.77
II	1.00	1.00
III	1.15	1.15
IV	1.15	1.15

GENERAL NOTE: The building and structure classification categories are listed in Table I-2.

TABLE I-4 VELOCITY PRESSURE EXPOSURE COEFFICIENTS, K_z (1)

Height Above Ground Level, z					
ft	(m) (2)	A	B	C	D
0–15	(0–4.6)	0.32	0.57	0.85	1.03
20	(6.1)	0.36	0.62	0.90	1.08
25	(7.6)	0.39	0.66	0.94	1.12
30	(9.1)	0.42	0.70	0.98	1.16
40	(12.2)	0.47	0.76	1.04	1.22
50	(15.2)	0.52	0.81	1.09	1.27
60	(18)	0.55	0.85	1.13	1.31
70	(21.3)	0.59	0.89	1.17	1.34
80	(24.4)	0.62	0.93	1.21	1.38
90	(27.4)	0.65	0.96	1.24	1.40
100	(30.5)	0.68	0.99	1.26	1.43
120	(36.6)	0.73	1.04	1.31	1.48
140	(42.7)	0.78	1.09	1.36	1.52
160	(48.8)	0.82	1.13	1.39	1.55
180	(54.9)	0.86	1.17	1.43	1.58
200	(61.0)	0.90	1.20	1.46	1.61
250	(76.2)	0.98	1.28	1.53	1.68
300	(91.4)	1.05	1.35	1.59	1.73
350	(106.7)	1.12	1.41	1.64	1.78
400	(121.9)	1.18	1.47	1.69	1.82
450	(137.2)	1.24	1.52	1.73	1.86
500	(152.4)	1.29	1.56	1.77	1.89

NOTES:
(1) Exposure categories are defined in para. 4.3.3.4.
(2) Linear interpolation for intermediate values of height Z is acceptable.

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TABLE I-5 FORCE COEFFICIENTS, C_f (1), (2), (3)

Cross-Section	Type of Surface	h/D = 1	h/D = 7	h/D = 25
Square (wind normal to face)	All	1.3	1.4	2.0
Square (wind along diagonal)	All	1.0	1.1	1.5
Hexagonal or octagonal	All	1.0	1.2	1.4
Round ($D\sqrt{q_z} > 2.5$) ($D\sqrt{q_z} > 5.3$, D in m, q_z in N/m^2)	Moderately smooth	0.5	0.6	0.7
	Rough ($D'/D = 0.02$)	0.7	0.8	0.9
	Very rough ($D'/D = 0.08$)	0.8	1.0	1.2
Round ($D\sqrt{q_z} \le 2.5$) ($D\sqrt{q_z} \le 5.3$, D in m, q_z in N/m^2)	All	0.7	0.8	1.2

NOTES:
(1) The design wind force shall be calculated based on the area of the structure projected on a plane normal to the wind direction. The force shall be assumed to act parallel to the wind direction.
(2) Linear interpolation is permitted for h/D values other than shown.
(3) Notation:

- D: diameter of circular cross-section and least horizontal dimension of square, hexagonal, or octagonal cross-sections at elevation under consideration, in ft (m);
- D': depth of protruding elements such as ribs and spoilers, in ft (m);
- h: height of structure, in ft (m);
- q_z: velocity pressure evaluated at height z above ground, in psf (N/m^2).

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NONMANDATORY APPENDIX A
MECHANICAL DESIGN

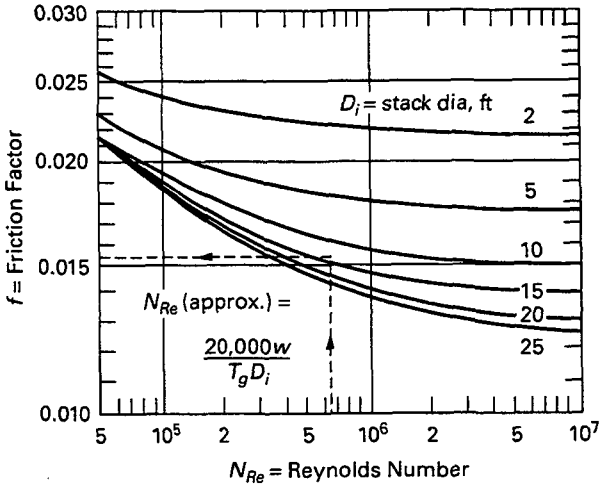

FIG. A-1 FRICTION FACTOR *f* AS RELATED TO REYNOLDS NUMBER AND STACK DIAMETER

TABLE A-1 *K* FACTORS FOR BREECHING ENTRANCE ANGLE

K	= factor depending on breeching entrance angle from vertical
	= 1.0 for 90 deg
	= 0.75 for 60 deg
	= 0.5 for 45 deg
	= 0.2 for 30 deg
	= 0.85 for 45 deg slope on top only

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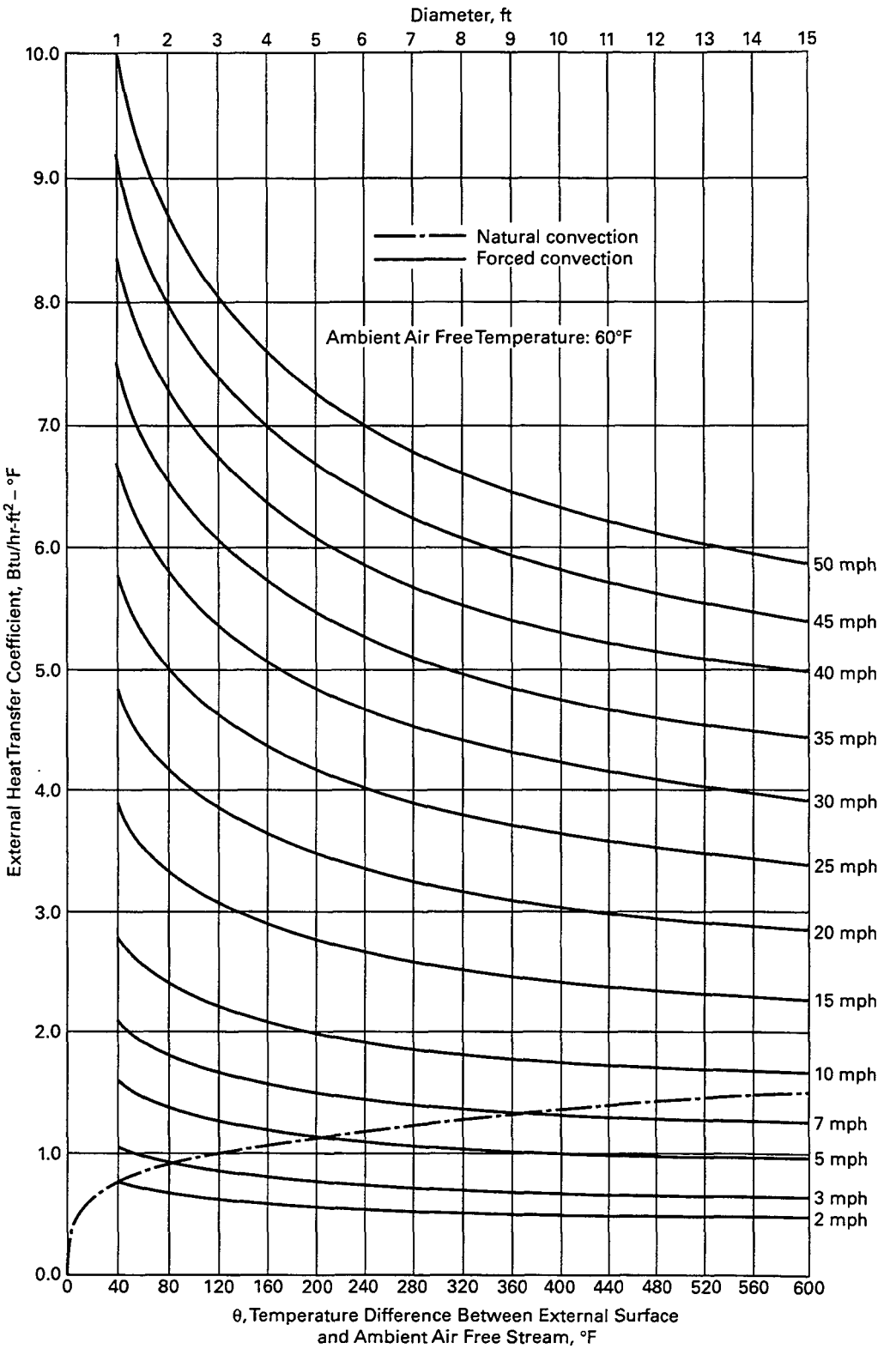

FIG. A-2 EXTERNAL HEAT TRANSFER COEFFICIENT FOR FORCED AND NATURAL CONVECTION

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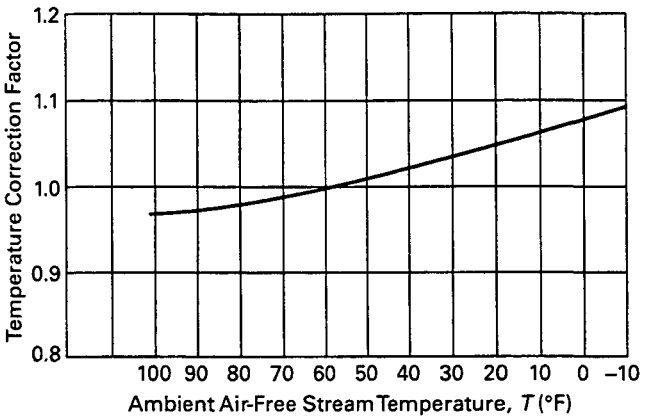

GENERAL NOTE: $h_T = (h_{60°F})$ (Temperature Correction Factor)$_T$, where h_T is the external heat transfer coefficient for forced convection when the ambient air free stream temperature is T(°F); $h_{60°F}$ is the external heat transfer coefficient for forced convection for a T(°F) of 60°F (see Fig. A-2)

FIG. A-3 EFFECT OF A CHANGE IN THE AMBIENT AIR FREE STREAM TEMPERATURE ON THE EXTERNAL HEAT TRANSFER COEFFICIENT FOR FORCED CONVECTION

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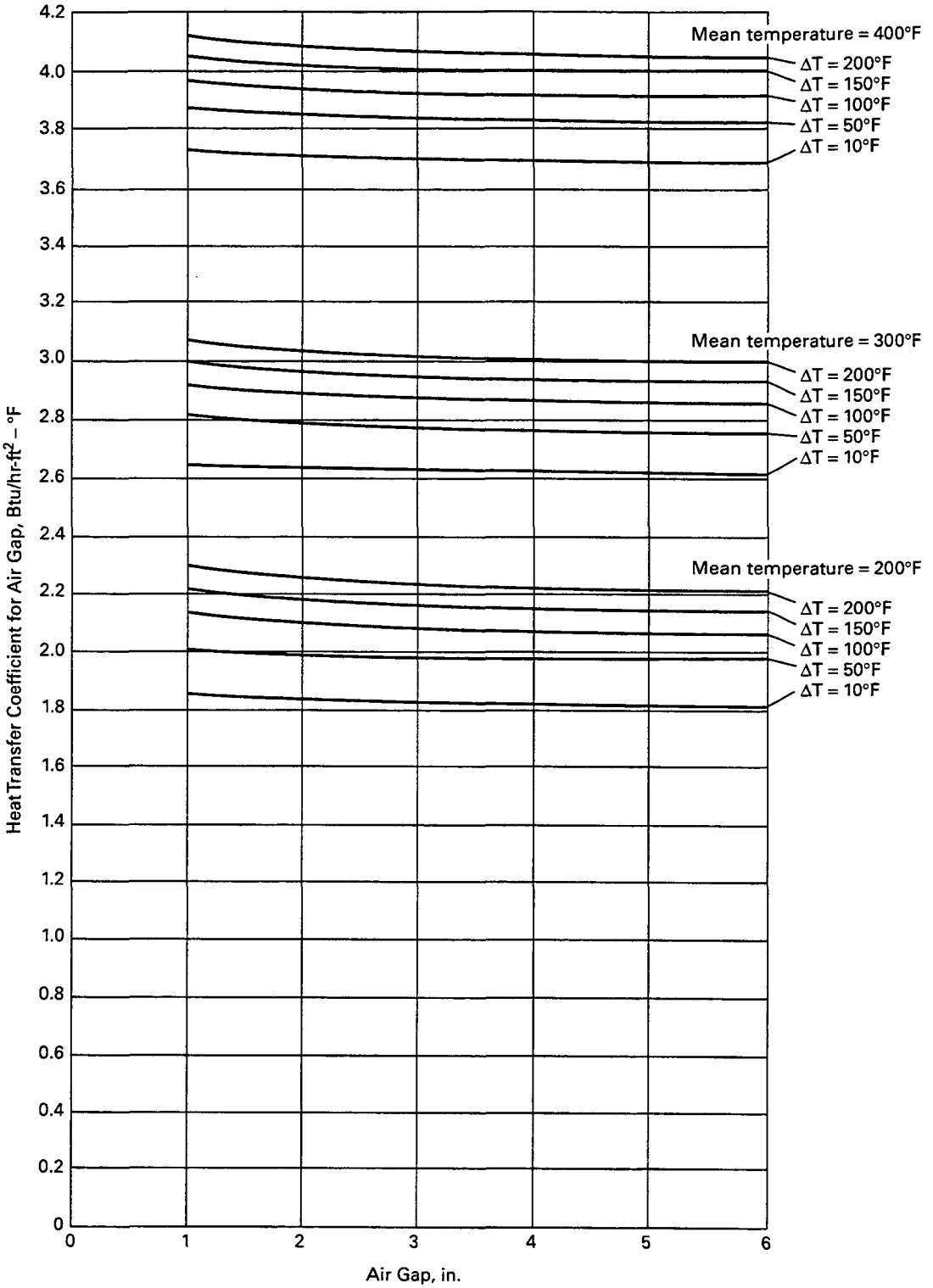

FIG. A-4 HEAT TRANSFER COEFFICIENT FOR THE AIR GAP BETWEEN TWO WALLS OF A DOUBLE-WALLED METAL CHIMNEY

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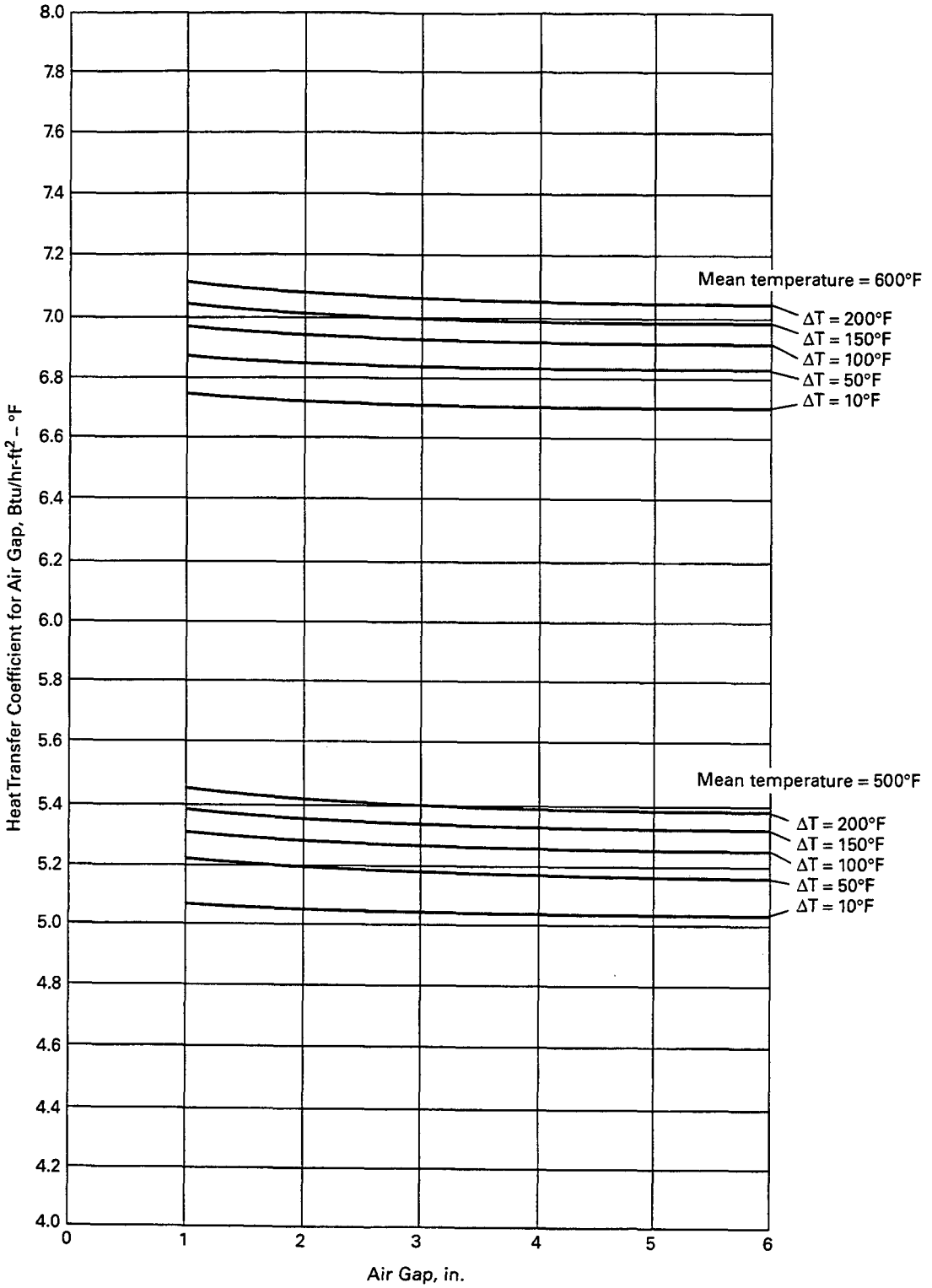

FIG. A-5 HEAT TRANSFER COEFFICIENT FOR THE AIR GAP BETWEEN TWO WALLS OF A DOUBLE-WALLED METAL CHIMNEY

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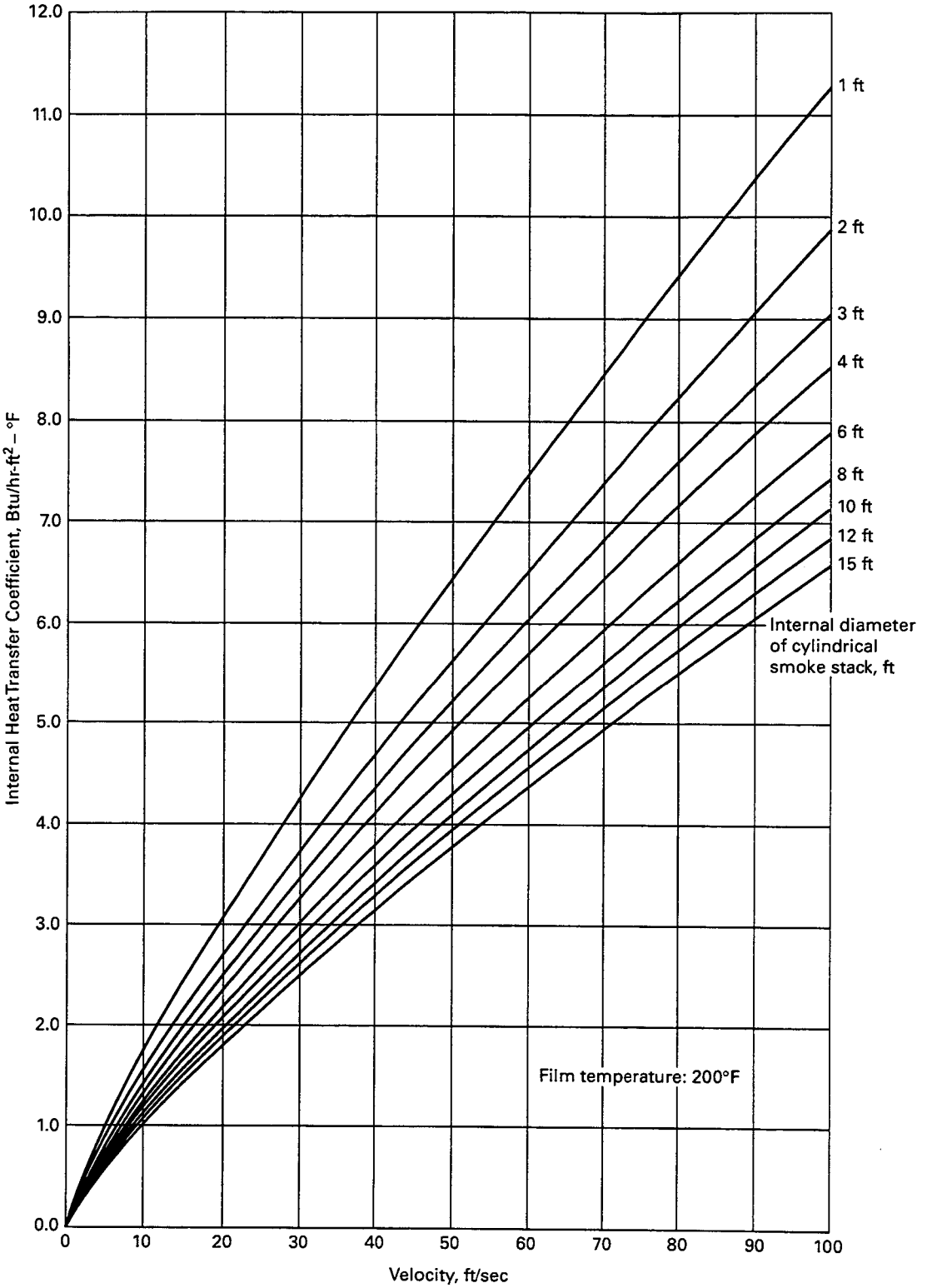

FIG. A-6 INTERNAL HEAT TRANSFER COEFFICIENT (Btu/hr-ft^2°F) VS. VELOCITY (ft/sec) FILM TEMPERATURE: 200°F

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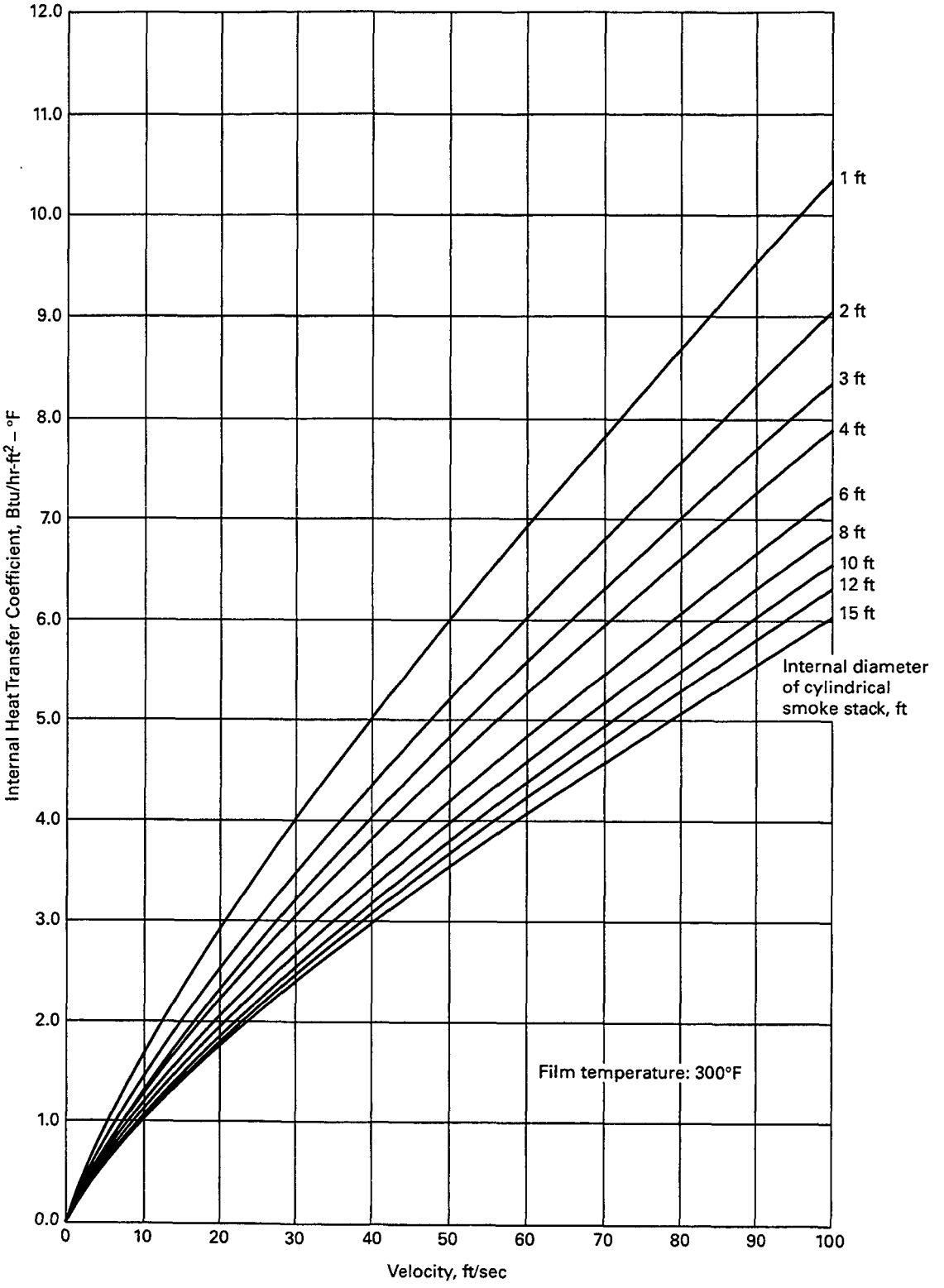

FIG. A-7 INTERNAL HEAT TRANSFER COEFFICIENT (Btu/hr-ft²°F) VS. VELOCITY (ft/sec) FILM TEMPERATURE: 300°F

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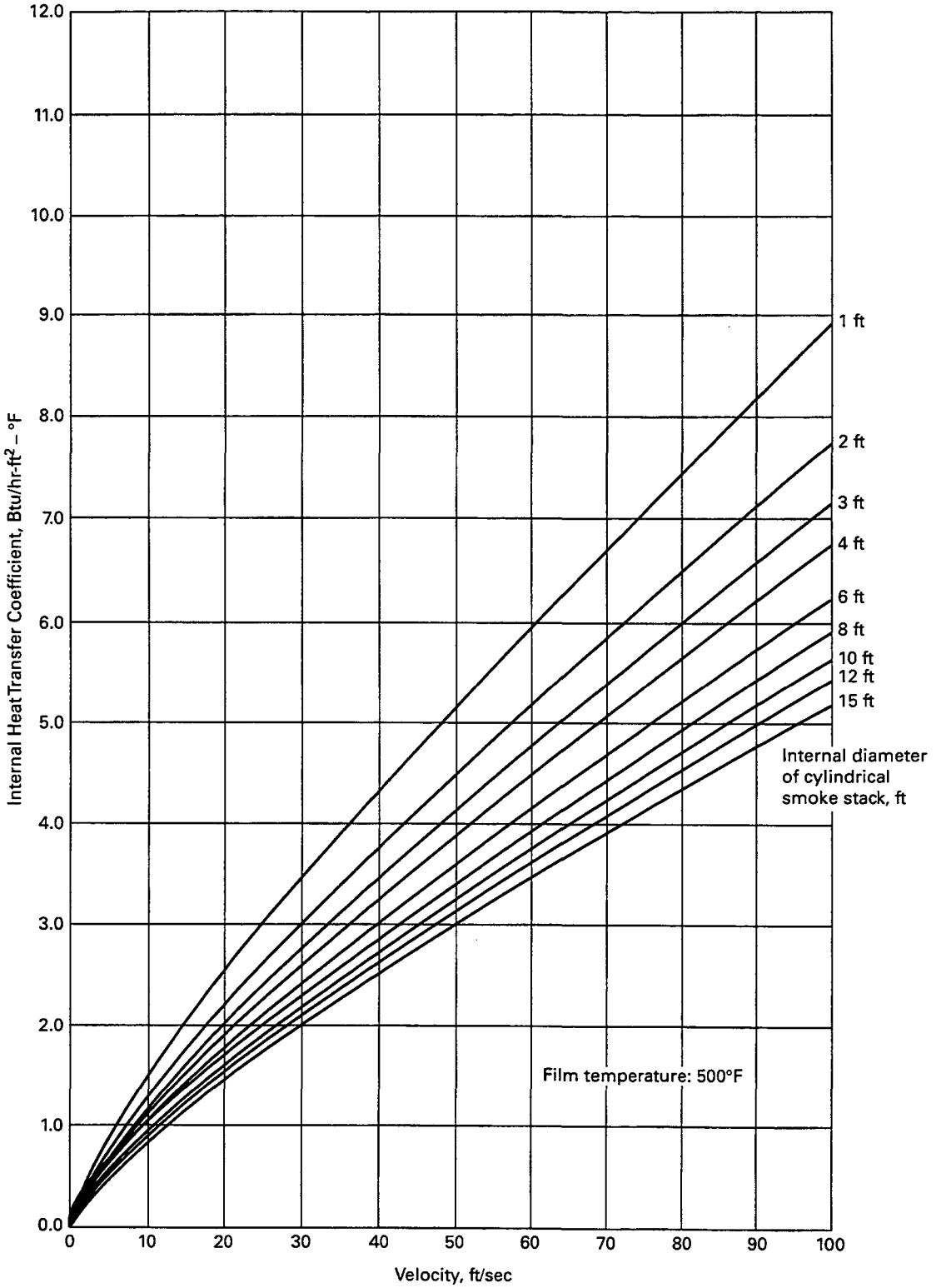

FIG. A-8 INTERNAL HEAT TRANSFER COEFFICIENT (Btu/hr-ft^2°F) VS. VELOCITY (ft/sec) FILM TEMPERATURE: 500°F

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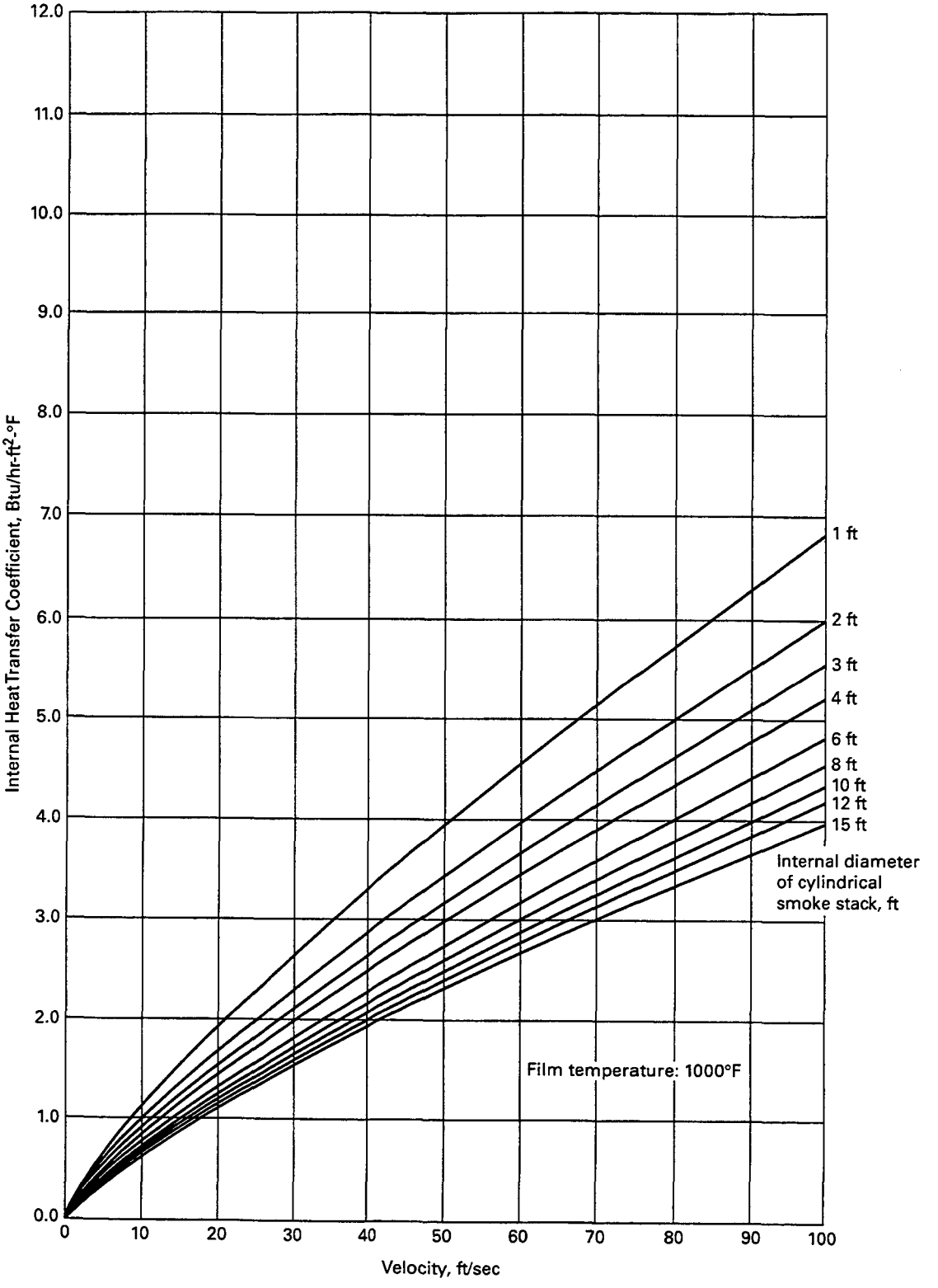

FIG. A-9 INTERNAL HEAT TRANSFER COEFFICIENT (Btu/hr-ft^2°F) VS. VELOCITY (ft/sec) FILM TEMPERATURE: 1000°F

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NONMANDATORY APPENDIX B
MATERIALS FOR AMBIENT AND ELEVATED TEMPERATURE SERVICE

TABLE B-1(a) ASTM A 36 CARBON STEEL

Elements	Chemical Composition, %
Carbon	0.35 Max.
Manganese	0.29/1.06
Phosphorus	0.048 Max.
Sulphur	0.058 Max.
Silicon	0.10 Min

TABLE B-1(b) ASTM A 36 CARBON STEEL

Typical Tensile Properties—Annealed				
Test Temp.	0.2% Offset Yield Strength	Tensile Strength	Elongation	Reduction of Area
°F	1,000 psi	1,000 psi	% in 2 in.	%
80	36.0	64.0	37	60
300	30.2	64.0	25	56
500	27.8	63.8	28	55
700	25.4	57.0	35	63
900	21.5	44.0	42	65
1100	16.3	25.2	50	65
1300	7.7	9.0	71	65

GENERAL NOTES:
(a) Fy = 36 ksi (250 MPa) — Room Temperature Minimum
(b) E = 29,000,000 psi — Room Temperature - decreasing linearly to 25,000,000 psi at 900°F

TABLE B-2(a) ASTM A 387 ALLOY STEEL

Elements	Chemical Composition, % (1)
Carbon	0.15 Max.
Manganese	0.30/0.61
Phosphorus	0.045 Max.
Sulphur	0.045 Max.
Silicon	0.50 Max.
Chromium	0.80/1.25
Molybdenum	0.44/0.65

NOTE:
(1) Chemical composition shown is for Grades 11 and 12, except that the content for Grade 11 is 1.00/1.50 and the Silicon content is 0.50/1.00.

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TABLE B-2(b) ASTM A 387 ALLOY STEEL

Typical Tensile Properties—Annealed				
Test Temp., °F	0.2% Offset Yield Strength, 1,000 psi	Tensile Strength, 1,000 psi	Elongation, % in 2 in.	Reduction of Area, %
80	35.5	72	38	72
300	31.7	71	31	68
500	30.4	70	28	65
700	29.2	68	30	67
900	27.2	64	29	70
1100	22	44.5	35	75
1300	10.5	20	60	80
1500	3	6	65	85

GENERAL NOTES:
(a) Fy = 35 ksi (242 Mpa) — Room Temperature Minimum
(b) E = 30,000,000 psi — Room Temperature decreasing linearly to 25,000,000 psi at 900°F.

TABLE B-2(c) ASTM A 387 ALLOY STEEL

Typical Tensile Properties—Normalized and Tempered				
Test Temp., °F	0.2% Offset Yield Strength, 1,000 psi	Tensile Strength, 1,000 psi	Elongation, % in 2 in.	Reduction of Area, %
80	52.5	80.6	27	60
300	51	79	23	55
500	47	76	22	56
700	41	72	23	58
900	35	67	25	68

TABLE B-3(a) ASTM A 242 TYPE 1/A-606, TYPE 4 HIGH STRENGTH LOW-ALLOY STEEL (WEATHERING TYPE)

Elements	Composition, %
Carbon	0.12 Max.
Manganese	0.20/0.50
Phosphorus	0.07/0.15
Sulphur	0.05 Max.
Silicon	0.25/0.75
Copper	0.25/0.55
Chromium	0.50/1.25
Nickel	0.65 Max.

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TABLE B-3(b) ASTM A 242 TYPE 1/A-606, TYPE 4 HIGH STRENGTH LOW-ALLOY STEEL (WEATHERING TYPE)

Typical Tensile Properties				
Test Temp., °F	0.2% Offset Yield Strength, 1,000 psi	Tensile Strength, 1,000 psi	Elongation, % in 2 in.	Reduction of Area, %
80	54.1	81.3	31	72
200	50.8	76.2	31	70
400	47.6	76.4	27	63
600	41.1	81.3	24	59
800	39.9	76.4	28	61
1000	35.2	52.8	21	34
1200	20.6	27.6	48	60
1400	8.6	10.6	89	94
1600	6.0	9.8	79	91
1900	2.7	5.7	90	99

GENERAL NOTES:
(a) Fy = 50 ksi (345 MPa) — Room Temperature minimum
(b) E = 30,000,000 psi — Room Temperature decreasing linearly to 25,000,000 psi at 900°F
(c) Considerable deviation from the listed properties may occur as a result of the relatively broad chemical composition range shown.

TABLE B-4(a) ASTM A 588, GRADE A A 709 HIGH STRENGTH LOW-ALLOY STEEL

Elements	Composition, %
Carbon	0.10/0.19
Manganese	0.80/1.25
Phosphorus	0.04 Max.
Sulphur	0.05 Max.
Silicon	0.30/0.65
Copper	0.25/0.40
Chromium	0.40/0.65
Vanadium	0.02/0.10

GENERAL NOTE: Acid soluble AL 0.01/0.06% (fine-grain practice).

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TABLE B-4(b) ASTM A 588, GRADE A A 709 HIGH STRENGTH LOW-ALLOY STEEL

Test Temp., °F	0.2% Offset Yield Strength, 1,000 psi	Tensile Strength, 1,000 psi	Elongation, % in 2 in.	Reduction of Area, %
80	55.0	86.7	29	71
200	51.7	81.4	27	69
400	48.4	79.8	24	60
600	46.7	81.5	26	58
800	45.1	71.1	30	71
1000	35.8	52.0	21	29
1200	20.0	30.3	29	39
1400	9.4	11.3	56	70
1600	6.0	10.4	43	48
1900	3.3	6.1	66	75

GENERAL NOTES:
(a) Fy = 50 ksi (345 MPa) — Room Temperature Minimum
(b) E = 30,000,000 psi — Room Temperature decreasing linearly to 25,000,000 psi at 900°F
(c) Considerable deviation from the listed properties may occur as a result of the relatively broad composition range shown.
(d) It should not be used at temperatures above 800°F for load bearing structures because of possible loss of ductility.

TABLE B-5(a) ASTM 240 STAINLESS STEEL TYPE 410

Nominal Chemical Composition, % (Maximum Unless Noted Otherwise)	
Elements	**Composition, %**
Carbon	0.15
Manganese	1.00
Phosphorus	0.040
Sulphur	0.030
Silicon	1.00
Chromium	11.50/13.50
Iron	Bal.

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TABLE B-5(b) ASTM 240 STAINLESS STEEL TYPE 410

Representative Mechanical Properties (Annealed Sheet Unless Noted Otherwise) [Note (1)]					
Test Temperature		Yield Strength		Tensile Strength	
°F	°C	ksi	MPa	ksi	MPa
80	27	45	310	70	483
300	149	36	248	74	510
400	204	135 (1)	931	150	1034
500	260	33	228	70.5	485
600	316	125 (1)	862	145 (1)	1000
700	371	30	207	62.5	431
800	427	115 (1)	793	130 (1)	896
900	482	26.7	184	52.5	362
1000	538	95 (1)	655	100 (1)	589
1100	593	23	159	33	228
1200	649	40 (1)	276	45 (1)	310
1300	704	9.5	66	15.2	105
1400	760	14 (1)	97	18 (1)	124
1500	816	...	...	9	62
1600	871	10 (1)	69	15 (1)	103

GENERAL NOTES:
(a) Fy = 30 ksi (205 MPa) minimum at Room Temperature
(b) E = 29 × 10^6 psi — Room Temperature decreasing linearly to 25 × 10^6 psi at 900°F
NOTE:
(1) Heat Treated

TABLE B-6(a) ASTM A 666, A 240 TYPE 304 STAINLESS STEEL

Nominal Chemical Composition (Maximum Unless Noted Otherwise)	
Elements	Composition, %
Carbon	0.08
Manganese	2.00
Phosphorus	0.045
Sulphur	0.030
Silicon	1.00
Chromium	18.00/20.00
Nickel	8.00/10.50
Iron	Bal.

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TABLE B-6(b) ASTM A 666, A 240 TYPE 304 STAINLESS STEEL

Representative Mechanical Properties (Annealed Sheet Material)					
Test Temperature		*Yield Strength* 0.2% Offset		Tensile Strength	
°F	°C	ksi	MPa	ksi	MPa
80	27	42	290	84	579
300	149	26.4	182	68.4	472
500	260	21.8	150	64.1	442
700	371	19.5	134	61.9	427
900	482	18.1	125	60	414
1100	593	16.4	113	53.2	367
1300	704	13.8	95	35	241
1500	816	9.9	68	18	124
1700	927	...	...	8.9	61
1900	1038	...	...	4.8	33
2000	1093	...	...	3.4	23

GENERAL NOTES:
(a) Fy = 30 ksi (205 MPa) minimum at Room Temperature
(b) E = 28×10^6 psi — Room Temperature decreasing linearly to 20×10^6 psi at 1,300°F

TABLE B-7(a) ASTM A 666, A 240 TYPE 316 STAINLESS STEEL

Nominal Chemical Composition (Maximum Unless Noted Otherwise)	
Elements	**Composition, %**
Carbon	0.08
Manganese	2.00
Phosphorus	0.045
Sulphur	0.030
Silicon	1.00
Chromium	16.00/18.00
Nickel	10.00/14.00
Molybdenum	2.00/3.00
Iron	Bal.

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TABLE B-7(b) ASTM A 666, A 240 TYPE 316 STAINLESS STEEL

Representative Mechanical Properties (Annealed Sheet Material)					
Test Temperature		Yield Strength 0.2% Offset		Tensile Strength	
°F	°C	ksi	MPa	ksi	MPa
80	27	42	290	84	579
300	149	29.2	201	75	517
500	260	25	172	73	503
700	371	23	159	72.5	500
900	482	21.5	148	70.2	484
1100	593	20.3	140	65.5	452
1300	704	19	131	50	345
1500	816	16	110	27	185
1700	927	...	...	11.6	80
1900	1038	...	...	5.6	39
2000	1093	...	...	4	28

GENERAL NOTES:
(a) Fy = 30 ksi (205 MPa) minimum at Room Temperature
(b) E = 28 x 10^6 psi — Room Temperature decreasing linearly to 20 x 10^6 psi at 1,300°F

TABLE B-8(a) ASTM A 240 TYPE 317 STAINLESS STEEL

Chemical Composition	
Elements	Composition, %
Carbon	0.061
Manganese Max.	2.00
Phosphorus Max.	0.04
Sulphur Max.	0.03
Silicon Max.	1.00
Chromium	19.18
Nickel	14.19
Molybdenum	3.57
Iron	Bal.

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TABLE B-8(b) ASTM A 240 TYPE 317 STAINLESS STEEL

Representative Mechanical Properties* (Annealed Material)					
Test Temperatures		Yield Strength 0.2% Offset		Tensile Strength	
°F	°C	ksi	MPa	ksi	MPa
80	27	36.4	251	81	558
300	149	32	221	71.5	493
500	260	30	207	69	475
700	371	26	179	69	475
900	482	21	145	68	469
1100	593	20	138	58	400
1300	704	12.4	85	40	276
1500	816	10.4	72	25	172

GENERAL NOTES:
(a) Fy = 30 ksi minimum at Room Temperature
(b) E = 28 × 10^6 psi — Room Temperature decreasing linearly 20 × 10^6 psi at 1,300°F

TABLE B-9 ALLOY STEEL COMPOSITIONS, STAINLESS STEELS, NICKEL ALLOYS, AND TITANIUM USED FOR STACKS AND CHIMNEY LINERS

Designations			Nominal Chemical Composition (%Weight)								
Alloy	UNS	(ASTM)	C	Cr	Ni	Mo	Cu	N	Ti	Fe	Other
409	S40900	(A 240)	0.08	11	0.5	...	...	...	...	Bal.	0.75 max
410	S41000	(A 240)	0.15	12	0.75	...	...	...	...	Bal.	...
304	S30403	(A 240)	0.03	19	9	...	...	0.10	...	Bal.	...
309	S30900	(A 240)	0.06	23	13	...	...	...	...	Bal.	0.50 Si
310	S31000	(A 240)	0.03	25	20	...	...	...	...	Bal.	0.75 Si
316L	S31603	(A 240)	0.03	17	12	2.25	...	...	...	Bal.	...
317L	S31703	(A 240)	0.03	19	13	3.25	...	...	...	Bal.	...
317LM	S31725	(A 240)	0.03	19	16	4.25	...	...	...	Bal.	...
317LMN	S31726	(A 240)	0.03	19	16	4.	...	0.15	...	Bal.	...
2205	S31803	(A 240)	0.03	22	5.0	3.0	...	0.15	...	Bal.	...
255	S32550	(A 240)	0.03	25	6.0	3.0	2.0	0.15	...	Bal.	...
...	6% Mo (1)	(A 240) (B 688)	0.02	20/24	18/25	6/7.3	0/1	0.2/0.5	...	Bal.	...
625	N06625	(B 443)	0.05	22	Bal.	9.0	...	...	...	...	Cb+Ta
276	N10276	(B 575)	0.02	16	Bal.	16.0	...	...	...	...	W
22, 622	N06022	(B 575)	0.02	22	Bal.	13	...	...	...	...	W
59	N06059	(B 575)	0.02	23	59	16	...	...	...	...	...
686	N06686	(B 575)	0.01	21	57	16	...	...	...	...	W
...	Titanium R50250	(B 265)	0.08	...	...	...	...	...	Bal.	0.12	Residuals

NOTE:
(1) Because the 6% Molybdenum super austenitic stainless steels are proprietary, it is necessary to show a range of compositions.

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TABLE B-10 THERMAL COEFFICIENTS OF EXPANSION

ASTM Alloy Designation	Average Coefficient of Linear Thermal Expansion (in./in./°F × 10^{-6}) From 32°F				
	400°F (204°C)	600°F (316°C)	800°F (427°C)	1,000°F (538°C)	1,200°F (649°C)
ASTM A 36	6.8	7.2	7.7	8.0	8.2
ASTM A 242	6.9	7.0	7.2	7.5	7.6
ASTM A 588	6.9	7.0	7.2	7.5	7.6
ASTM A 387, GR 11, 12	6.8	7.2	7.5	7.8	8.1
ASTM A 176, Type 409	5.8	6.1	6.4	6.6	6.8
ASTM A 176, Type 410	5.8	6.1	6.4	6.6	6.8
ASTM A 240, Type 304	9.6	9.8	10.1	10.3	10.5
ASTM A 240, Type 316	9.6	9.8	10.1	10.3	10.5
ASTM A 240, Type 309	8.8	9.3	9.5	9.7	9.9
ASTM A 240, Type 310	8.1	8.3	6.7	9.0	9.0
ASTM B 686, 6% Mo	8.9	9.3	9.8	10.0	...
ASTM B 443, Alloy 625	7.3	7.4	7.6	7.8	8.2
ASTM B 575, Alloy C-276	6.2	6.7	7.3	7.4	7.8

TABLE B-11 MAXIMUM NON-SCALING TEMPERATURE

ASTM Type or Grade [Note (1)]	Temp., Max., °F (°C)
A 36	800° (427°)
A 242, Type 1	950° (510°)
A 387, Gr. 11, 12	1,050° (566°)
A 176, Type 409	1,300° (704°)
A 176, Type 410	1,300° (704°)
A 240, Type 304	1,650° (899°)
A 240, Type 316	1,650° (899°)
A 240, Type 317	1,650° (899°)
A 240, Type 309	1,900° (1 038°)
A 240, Type 310	2,000° (1 093°)

NOTE:
(1) Manufacturers of types or grades not listed should be consulted for recommendations.

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NONMANDATORY APPENDIX C
LININGS AND COATINGS

TABLE C-1 SUGGESTED SUITABILITY OF LININGS FOR STEEL STACKS TO WITHSTAND CHEMICAL AND TEMPERATURE ENVIRONMENTS OF FLUE GASES

Lining Classification UNS No.	Type (ASTM)	Chemical Environment			Thermal Environment		
		Mild	Moderate	Severe	Mild	Moderate	Severe
Organic Resin	Polyester	X	X	...	X	...	...
	Novolac phenolic epoxy (1)	X	X	X	X	X	X (2)
	Novolac epoxy (1)	X	X	X	X	X	...
	Epoxy	X	X	...	X	...	...
	Vinyl ester	X	X	X	X	...	...
	Urethanes	X	X	...	X	...	...
Organic Elastomers	Natural rubber	X	X	...	X	...	...
	Neoprene	X	X	...	X	...	...
	Chlorobutyl	X	X	...	X	...	...
	Fluoroelastomer	X	X	X	X	X	...
Inorganic Monolitic Concrete	Potassium Silicate	X	X	X	X	X	X
	Calcium Aluminate	X	X	...	X	X	X
	Refractory	X	...	...	X	X	X
	Insulating	...	...	...	X	X	X
Inorganic Masonry	Borosilicate glass block	X	X	X	X	X	X
	Firebrick and refractory mortar	X	X	...	X	X	X
	Acid resistant brick and chemically-resistant mortar	X	X	X	X	X	X
	Insulating brick and refractory mortar	...	...	...	X	X	X
UNS 40900	Stainless Steel (A 240) (3)	X	...	...	X	X	X
UNS 41000	Stainless Steel (A 240) (3)	X	...	...	X	X	X
UNS 30403	Stainless Steel (A 240) (3)	X	X	...	X	X	X
UNS S31603	Stainless Steel (A 240) (3)	X	X	...	X	X	X
UNS S31703	Stainless Steel (A 240)	X	X	...	X	X	X
UNS S31725	Stainless Steel (A 240)	X	X	...	X	X	X
UNS S31726	Stainless Steel (A 240)	X	X	...	X	X	X
UNS S31803	Stainless Steel (A 240)	X	X	X	X	X	X
UNS S32550	Stainless Steel (A 240)	X	X	X	X	X	X
6% Mo	Stainless Steel (A 240)	X	X	X	X	X	X
UNS N06625	Nickel-based alloy (B 443)	X	X	XX (4)	X	X	X
UNS N10276	Nickel-based alloy (B 575)	X	X	XX (4)	X	X	X
UNS N06022	Nickel-based alloy (B 575)	X	X	XX (4)	X	X	X
UNS N06059	Nickel-based alloy (B 575)	X	X	XX (4)	X	X	X
UNS N06686	Nickel-based alloy (B 575)	X	X	XX (4)	X	X	X
UNS R50250	Titanium (B 246)	X	X	XX (4)	X	X	X

GENERAL NOTE: Materials suppliers shall be consulted with respect to specific recommendations on usage.

NOTES:
(1) Can be used in very severe chemical environments
(2) Coating may darken surface and convert to organic carbon at higher temperatures.
(3) There is usually no significant price advantage to the use of these alloys as linings in place of solid alloys.
(4) Most resistant of the alloys.

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TABLE C-2 SUGGESTED STACK COATING CHARACTERISTICS AND CLASSIFICATIONS

Generic Maximum Type	Cure Mechanism	Acid	Salt	Weather	Dry Heat
Alkyd	Air oxidation	Poor	Fair	Excellent	250°F (121°C)
Chlorinated rubber	Solvent evaporation	Excellent	Excellent	Good	150°F (66°C)
Catalyzed epoxy	Chemical crosslinking	Excellent	Excellent	Good	250°F–300°F (121°C–149°C)
Novolac phenolic epoxy	Chemical crosslinking	Excellent	Excellent	Excellent	325°F (163°C)
Novolac epoxy	Chemical crosslinking	Excellent	Excellent	Excellent	250°F–300°F (121°C–149°C)
Aliphatic polyurethane	Chemical crosslinking	Very good	Excellent	Excellent	180°F–250°F (82°C–121°C)
Aluminum Silicone	Solvent/heat	Poor	Good	Good	1,000°F (538°C)
Coal-tar epoxy	Solvent evaporation	Very good	Excellent	Poor	160°F–250°F (71°C–121°C)
Vinyl	Solvent evaporation	Excellent	Excellent	Very good	150°F (66°C)
Inorganic zinc	Hydrolysis	Excellent (1)	Excellent	Excellent	750°F–1,000°F (2) (399°C–538°C)
Organic zinc-rich	Chemical crosslinking	Very good (1)	Very good	Very good	300°F (149°C) (2)
Inorganic silicate	Chemical reaction	Very good	Excellent	Excellent	...

NOTES:
(1) Indicated results based on primer being top coated.
(2) Indicated results based on limitation of top coat in the system.

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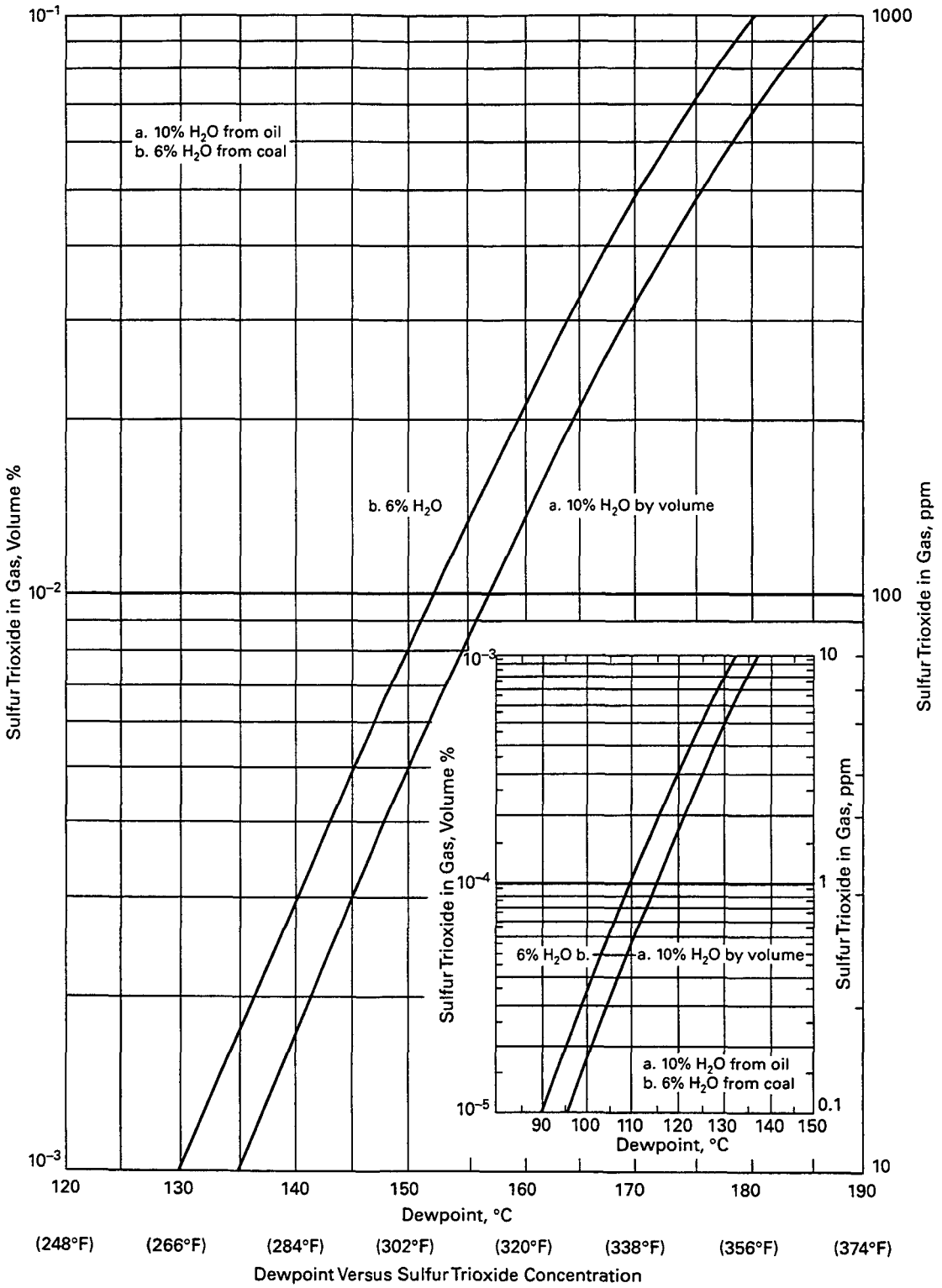

FIG. C-1 DEWPOINT IN STACK GASES

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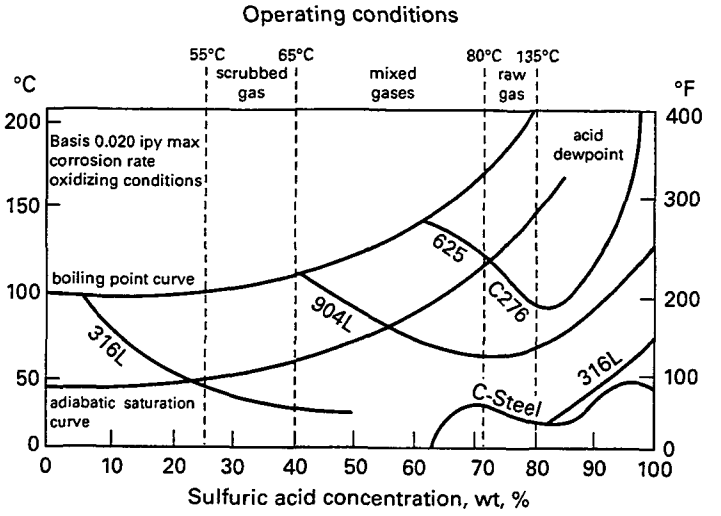

FIG. C-2 SULFURIC ACID SATURATION CURVE

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STRUCTURAL DESIGN

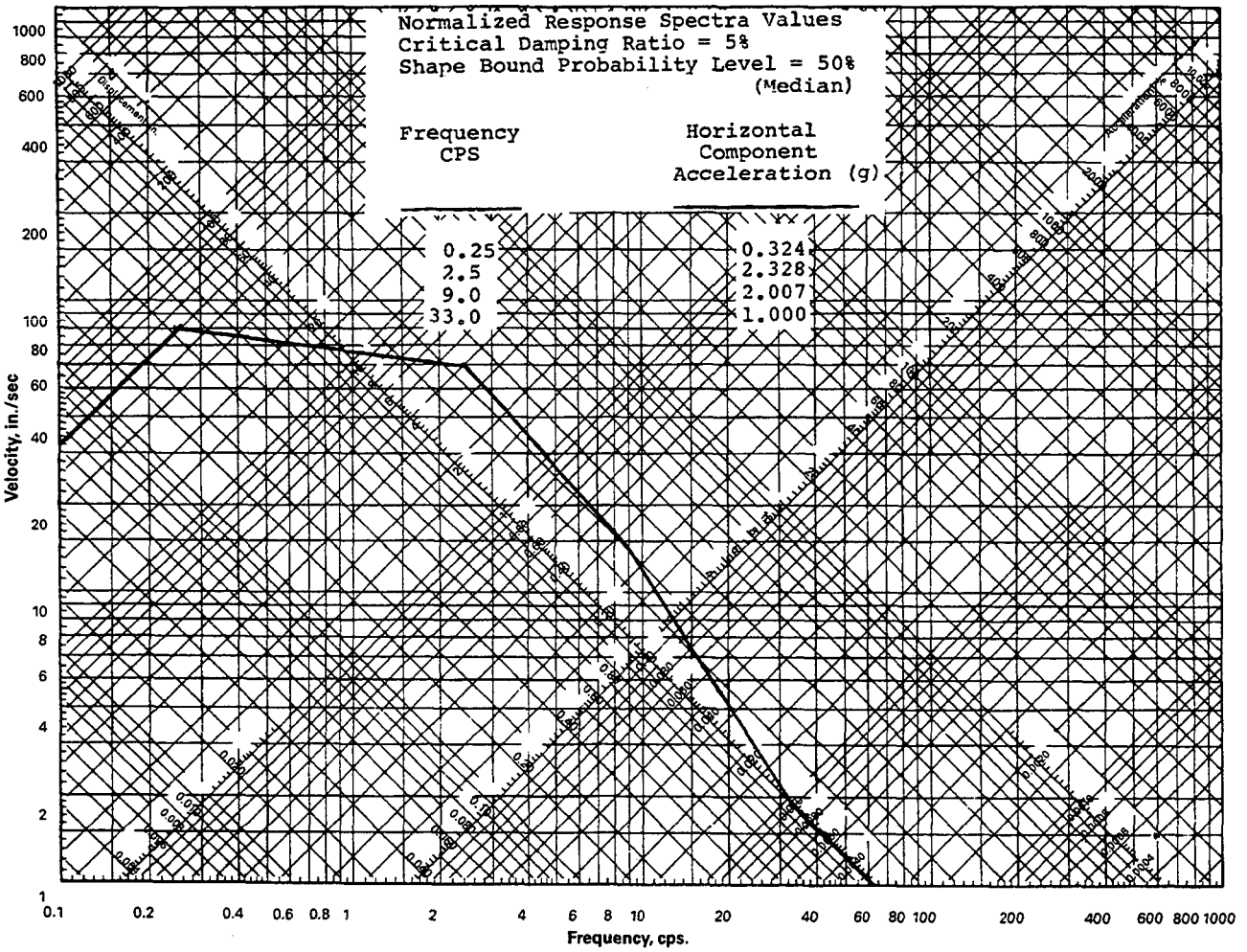

FIG. D-1 NORMALIZED RESPONSE SPECTRUM VALUES

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TABLE D-1 SPECIAL VALUES FOR MAXIMUM GROUND ACCELERATION OF 1.0g

Frequency, Hz	Displacement spectrum, in.	Velocity spectrum, in./sec	Acceleration spectrum, g
$f \le 0.25$	50.7	$318.6f$	$5.186f^2$
$0.25 \le f \le 2.5$	$\frac{10.39}{f^{1.1436}}$	$\frac{65.26}{f^{0.1436}}$	$1.062f^{0.8564}$
$2.5 \le f \le 9$	$\frac{25.32}{f^{2.1158}}$	$\frac{159.1}{f^{1.1158}}$	$\frac{2.589}{f^{0.1158}}$
$9 \le f \le 33$	$\frac{63.87}{f^{2.5369}}$	$\frac{401.3}{f^{1.5369}}$	$\frac{6.533}{f^{0.5369}}$
$f > 33$	$\frac{9.768}{f^2}$	$\frac{61.37}{f}$	1.00

TABLE D-2 RESPONSE SPECTRUM SCALING RATIO VERSUS A_v

A_v, Effective peak velocity-related accelerations	Scaling ratio
0.05	0.04
0.08	0.06
0.15	0.11
0.20	0.15
0.30	0.23
0.40	0.30

GENERAL NOTE: Linear interpolation may be used in between A_v coefficients not given.

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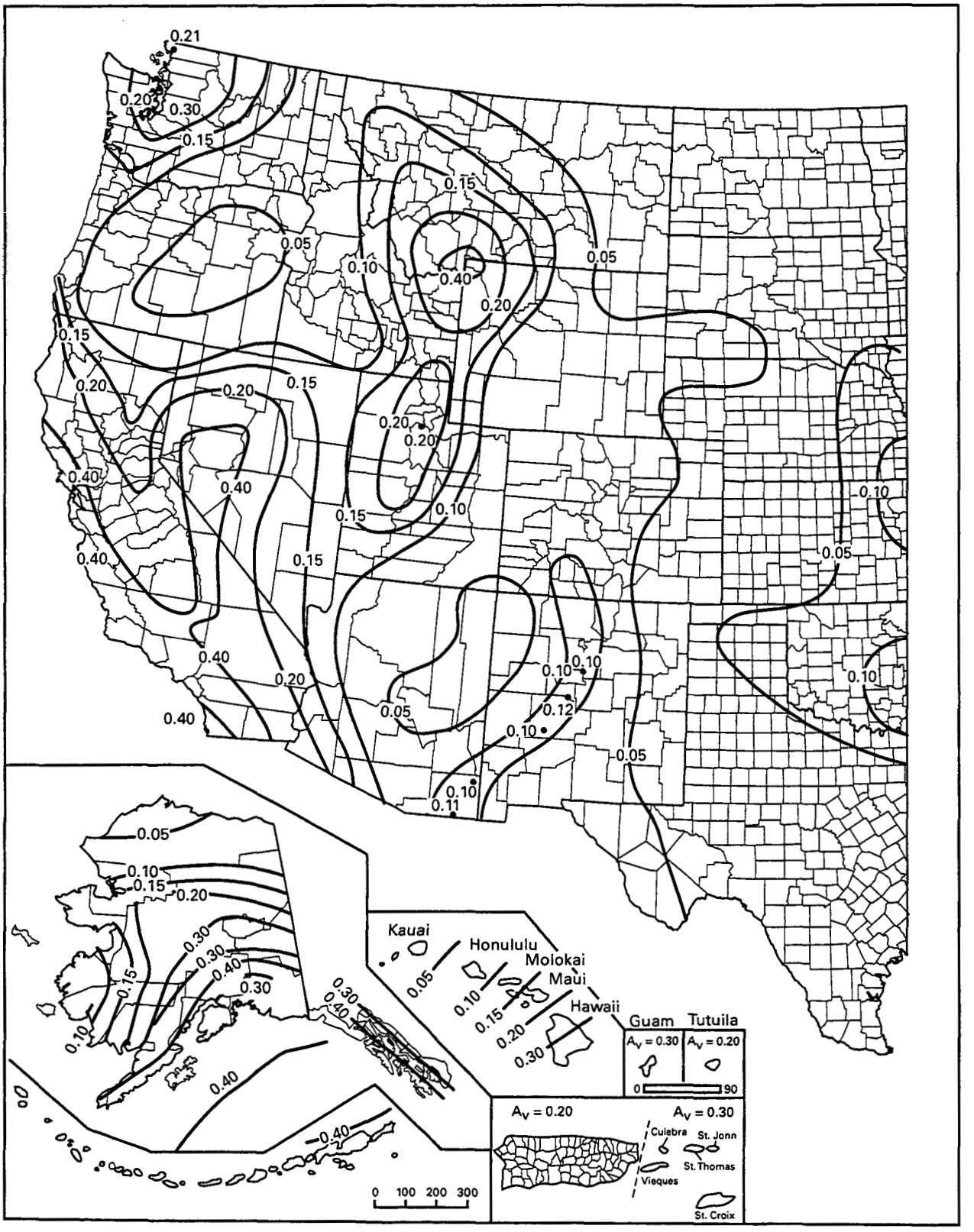

FIG. D-2 SEISMIC ZONE MAP

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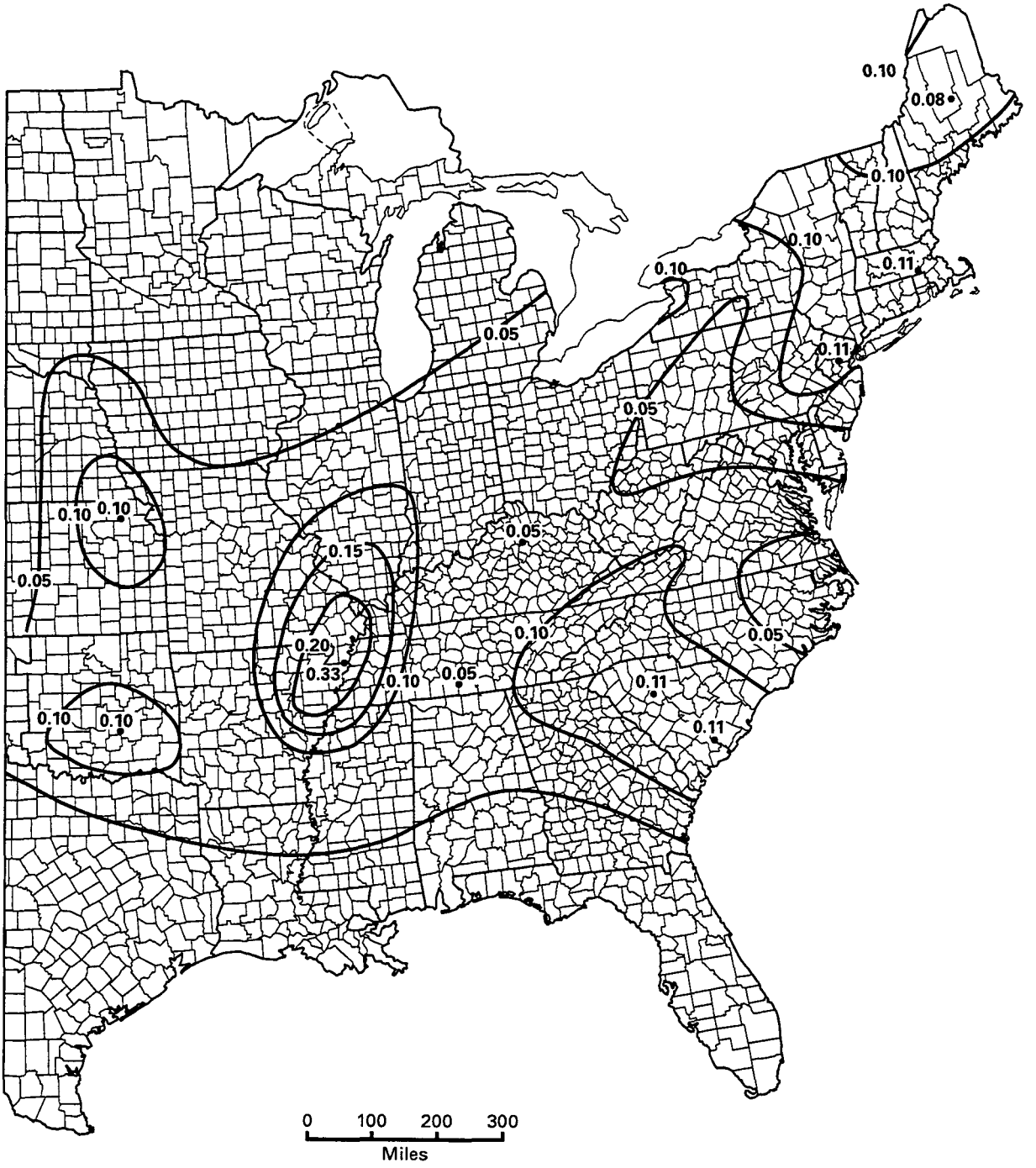

FIG. D-2a SEISMIC ZONE MAP

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TABLE D-3 ALLOWABLE CREEP STRESS OF CARBON STEEL AT ELEVATED TEMPERATURE

	Allowable Creep Stresses (in ksi) (1)							
	Temperature (°F)							
Type of Steel (2)	750	800	850	900	950	1000	1050	1100
A 36 (5) A 53 Gd B (5)	14.3 (3)	‡ 10.3 (3)	·	·	·	·	·	·
A 242 Type I (6) A 618 Gr 1 (6)	··	12-17	8-13	5-9	‡	‡	·	·
A 588 Gr A (6) A 588 Gr B (6)	··	12-17	‡ 8-13	‡ 5-9	‡	‡	·	·
A 387 Gr 11 (7) A 335 Gr P11 (7)	··	··	··	15.7 (3)	10.7 (3)	7.1 (4)	4.4 (4)	2.7 (4)
A 387 Gr 12 (7) A 335 Gr P12 (7)	··	··	··	18.0 (3)	11-3 (3)	7.3 (3)	4.5 (4)	2.5 (4)

·· Indicates that the creep value does not govern—normal allowable stresses based on F_y govern.
· Indicates that the use of this steel is not recommended at this temperature.
‡ Indicates that the use of this steel at this temperature is only recommended for non-critical applications.
() Indicates reference to notes.

NOTES:
(1) The values presented in this table are allowable stresses based on the criteria presented in para. 3.3.5 with a design life of 100,000 hr. The appropriated factor of safety has been incorporated in these values.
(2) Creep and rupture properties are highly dependent upon the exact chemical composition of the steel. The values indicated in the table are intended to be used only as a reference. Values used in design should be obtained from test data reflecting the precise chemical composition of the steel to be used in the ductwork fabrication.
(3) The allowable stress value at this temperature is governed by the creep rupture strength.
(4) The allowable stress value at this temperature is governed by the creep rate.
(5) Creep and rupture properties for this steel are derived from ASTM DS-11S1.
(6) Creep and rupture properties for this steel are derived from various United States Steel Corporation publications, including *Steels for Elevated Temperature Service.*
(7) Creep and rupture properties for this steel are derived from ASTM DS-50. These values differ from some of the ASME values because ASME limits the allowable stress to 0.25 F_y, which is a limitation for boilers, not ducts.
(8) A range of values is presented for A 242, A 588, and A 618 steels because of the potentially large variation in chemistry, which can drastically effect the steel's properties. The lower bound value should be used unless data indicate otherwise.

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TABLE D-4 CREEP AND RUPTURE PROPERTIES OF TYPE 410 STAINLESS STEEL

Test Temperature		Stress for a Creep Rate of 0.0001% per hr 1% in 10,000 hr		Stress for a Creep Rate of 0.00001% per hr 1% in 100,000 hr		Stress for Rupture in 1,000 hr		Stress for Rupture in 10,000 hr	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
900	482	24	165	13.6	94	34	234	22	152
1000	538	9	62	7.4	51	19.4	134	13	90
1100	593	4.2	29	3.6	25	10	69	6.8	47
1200	649	2	14	1.7	12	4.8	33	2.8	19
1300	704	0.8	6	0.8	4	2.5	17	1.2	8
1400	760	...	...	...	...	1.2	8	0.6	4

TABLE D-5 CREEP AND RUPTURE PROPERTIES OF TYPE 304 STAINLESS STEEL

Test Temperature		Stress for a Creep Rate of 0.0001% per hr 1% in 10,000 hr		Stress for a Creep Rate of 0.00001% per hr 1% in 100,000 hr		Stress for Rupture in 1,000 hr		Stress for Rupture in 10,000 hr	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000	538	25.5	176	17.9	123	49.8	343	36	248
1100	593	16.5	114	11.1	77	31	214	22.2	153
1200	649	10.8	74	7.2	50	19	131	13.8	95
1300	704	7	48	4.5	31	11.9	82	8.5	59
1400	760	4.6	32	2.9	20	7.7	53	5.3	37
1500	816	3	21	1.8	12	4.7	32	3.3	23

TABLE D-6 CREEP AND RUPTURE PROPERTIES OF TYPE 316 STAINLESS STEEL

Test Temperature		Stress for a Creep Rate of 0.0001% per hr 1% in 10,000 hr		Stress for a Creep Rate of 0.00001% per hr 1% in 100,000 hr		Stress for Rupture in 1,000 hr		Stress for Rupture in 10,000 hr	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000	538	35.5	245	20.1	139	50	345	43	296
1100	593	22.5	155	12.4	85	34	234	26.5	183
1200	649	14.2	98	7.9	54	23	159	16.2	112
1300	704	8.9	61	4.8	33	15.4	106	9.9	66
1400	760	5.6	39	3	21	10.3	71	6	41
1500	816	3.6	25	1.9	13	6.7	46	3.7	26

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TABLE D-7 CREEP AND RUPTURE PROPERTIES OF TYPE 317 STAINLESS STEEL

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per hr 1% in 10,000 hr		0.00001% per hr 1% in 100,000 hr		1,000 hr		10,000 hr	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000	538	24	165	16	110	...	...	...	...
1100	593	17.3	119	14.7	101	34	234	28	193
1200	649	12.7	88	8.7	60	24	165	13.3	92
1300	704	7.3	50	4.7	32	16.7	115	10.7	74
1400	760	4.3	30	2.3	16	10.3	71	6.7	46
1500	816	2.7	19	2	14	6.7	46	3.3	23

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NONMANDATORY APPENDIX E
EXAMPLE CALCULATIONS

E-1 VELOCITY PRESSURE (q_z)

$$(q_z) = 0.00256 \times V^2 \times I$$

		Stack 1	Stack 2	Stack 3	
3-Second Gust Speed	V	90	100	110	mph
Importance Factor	I	1.00	1.00	1.00	(unitless)
Stack Height	h	80.00	160.00	240.00	ft
Top Outside Diameter	D	5.000	10.000	15.000	ft
Exposure Category		C	C	C	C
First Mode Frequency	η_1	2.60	1.30	0.90	Hz
Plate Thickness	t	0.250	0.3125	0.375	in.
Damping Value	β	0.006	0.006	0.006	(unitless)
Slenderness Ratio	h/D	16.0	16.0	16.0	
Force Coefficient	c_f	0.65	0.65	0.65	Table I-5
Gust Effect Factor	G_f	0.95	1.01	1.05	See Mandatory Appendix I
Velocity Pressure	q_z	20.74	25.60	30.98	psf

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EXAMPLE CALCULATION E-2 GUST EFFECT FACTOR (G_f)

$$G_f = 0.925\left(\frac{1 + 1.7 I_{\bar{z}} g_Q^2 Q^2 + g_R^2 R^2}{1 + 1.7\, I_{\bar{z}}\, g_v}\right)$$

		Stack 1	Stack 2	Stack 3	
3-Second Gust Speed	V	90	100	110	mph
Importance Factor	I	1.00	1.00	1.00	(unitless)
Stack Height	h	80.00	160.00	240.00	ft
Top Outside Diameter	D	5.000	10.000	15.000	ft
Exposure Category		C	C	C	...
First Mode Frequency	η_1	2.60	1.30	0.90	Hz
Plate Thickness	t	0.250	0.3125	0.375	in.
Damping Value	β	0.006	0.006	0.006	(unitless)
Stack Width	B	5.000	10.000	15.000	ft
Turbulence Intensity Factor	c	0.20	0.20	0.20	Table I-1
Integral Length Scale Factor	l	500	500	500	ft (Table I-1)
Integral Length Scale Power Law Exponent	$\bar{\epsilon}$	0.2	0.2	0.2	Table I-1
Equivalent Height	$\bar{z}$	48.00	96.00	144.00	ft
Intensity Turbulence	$I_{\bar{z}}$	0.188	0.167	0.156	...
Integral Length Scale of Turbulence	$L_{\bar{z}}$	538.91	619.04	671.34	ft
Background Response	Q	0.914	0.884	0.863	...
Mean Hourly Wind Speed Factor	$\bar{b}$	0.65	0.65	0.65	Table I-1
Mean Hourly Wind Speed Law Exponent	$\bar{a}$	0.154	0.154	0.154	Table I-1
Mean Hourly Wind Speed	$\bar{V}_{\bar{z}}$	90.89	112.35	131.55	...
Reduced Frequency	N_1	15.42	7.16	4.59	...
...	R_n	0.0245	0.0403	0.0535	...
...	η_h	10.53	8.52	7.55	...
...	η_b	0.658	0.532	0.472	...
...	η_d	2.20	1.78	1.58	...
...	R_h	0.0905	0.1105	0.1236	...
...	R_B	0.6747	0.7226	0.7475	...
...	R_d	0.3522	0.4082	0.4410	...
Resonant Response Factor	R	0.4160	0.6221	0.7794	...
Peak Factor of Resonant Response	g_R	4.411	4.252	4.164	...
Peak Factor for Wind Response	g_v	3.4	3.4	3.4	...
Peak Factor for Background Response	g_Q	3.4	3.4	3.4	...
Gust Effect Factor	G_f	**0.95**	**1.01**	**1.05**	**(unitless)**

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EXAMPLE CALCULATION E-3 ALONG WIND LOADS

Wind design based upon ASCE 7-1998, as applicable for steel stack design used as an Example of the design method for ASME STS-1-2000

Height $H = 140$ ft true: $= -1$

Top $\frac{1}{3}$ Ht Mean OS Diameter (ft): $D = 8.00$

Top $\frac{1}{3}$ Ht Mean Thickness (in): $t = 0.3125$ false: $= 0$

3-sec gust Velocity (mph) from (Fig I-1) $V = 100$

Importance Factor (Table I-2) $I_{factor} = 1.00$

Exposure: C

First Mode Frequency (Hz): $n_1 = 1.3246$

Density of air (slugs/ft^3): $\rho = 0.00238$
$32.2\rho = 0.08$ lb/ft3

Structural Damping (unlined): $\beta_s = 0.004$

Shape factor (Table I-4): $C_f = 0.6583$

Spacing between stacks: $A = 20D$

Strouhal Number:
$$S_t = \text{if}\left[\frac{A}{D} > 15,\ 0.2,\ 0.16 + \frac{1}{300}\left(\frac{A}{D} - 3\right)\right]$$
$$= 0.20$$

Average Diameter for Top $\frac{1}{3}$ Ht (ft): $D_{bar} = D$

Vortex Shedding Elevation Range (ft): $z_1 = H,\ z_2 = 0$

For Exposure C, From Table I-1:
$$\alpha_{bar} = \frac{1}{6.5}$$
$$b_{bar} = 0.65$$
$$c = 0.2$$
$$I_{ft} = 500$$
$$\epsilon = \frac{1}{5}$$

Number of Sections:
$$k = 1...15$$
$$I = 500$$
$$Z_{min} = 15$$
$$\alpha = 9.5$$
$$z_g = 900$$

k	Z_k	El_k	odk	ht_k	$mass_k$	Φ_k
1	140	135	8	10	320	1.000
2	130	125	8	10	320	0.9022
3	120	115	8	10	320	0.8044
4	110	105	8	10	320	0.7072
5	100	95	8	10	320	0.6113
6	90	85	8	10	320	0.5176
7	80	75	8	10	320	0.4272
8	70	65	8	10	320	0.3413
9	60	55	8	10	320	0.2616
10	50	45	8	10	320	0.1894
11	40	35	8	10	320	0.1263
12	30	25	8	10	320	0.0742
13	20	15	8	10	320	0.0346
14	10	5	8	10	320	0.0092
15	0	0	8	0	160	0.0

Equivalent Height of Stack: $0.6H$ but $> Z_{min}$
$$z_{bar} = 0.6H$$
$$= \text{if}(z_{bar} < z_{min}, z_{min}, z_{bar})$$
$$= 84.00 \text{ ft}$$

Mean Hourly Wind Speed:
$$V_{bar\ zbar} = b_{bar}\frac{44}{30}V_R\left(\frac{z_{bar}}{33}\right)^{\alpha bar}$$
$$= 110.07 \text{ ft/sec}$$

Top $\frac{1}{3}$ Ht Mass (lb/ft):
$$m_{avg} = \pi D\frac{t}{12}490 = 320.70$$

$$mq = \frac{m_{avg}}{32.2\rho D^2} = 65.39$$

$$vD = \frac{V_{bar\ zbar}}{n_1 D} = 10.39$$

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Aerodynamic Damping: $\beta_a = \frac{C_f \rho \overline{D}\,\overline{V}_z}{4\pi m_a n_1} = 0.00869$

Total Damping: $\beta = \beta_s + \beta_a = 0.00816$

Intensity Turbulence (4A-?): $I_{zbar} = c\left(\frac{33}{z_{bar}}\right)^{\nu 6} = 0.171$

Integral Length of Turbulence (4A-?): $L_{zbar} = l\left(\frac{z_{bar}}{33}\right)^{\epsilon} = 602.73$

Background Response (4A.?): $Q = \sqrt{\frac{1}{1 + 0.63 \cdot \left(\frac{D+H}{L_{zbar}}\right)^{0.63}}} = 0.891$

Resonance Response Factor (4A-?): $N_1 = \frac{n_1 L_{zbar}}{V_{bar\ zbar}} = 7.25$

$R_n = \frac{7.465 N_1}{(1 + 10.302 N_1)^{5/3}} = 0.04$

Resonance Response Factors: $\eta_h = 4.6 n_1 \frac{H}{V_{bar\ zbar}} = 7.75$

$R_h = \text{if}\left\{\eta_h > 0, \frac{1}{\eta_h} - \frac{1}{2\eta_h^2}[1 - \exp(-2\eta_h)], 0\right\}$

$= 0.12$

$\eta_b = 4.6 n_1 \frac{D}{V_{bar\ zbar}} = 0.44$

$R_b = \text{if}\left\{\eta_b > 0, \frac{1}{\eta_b} - \frac{1}{2\eta_b^2}[1 - \exp(-2 \cdot \eta_b)], 0\right\} = 0.76$

$\eta_d = 15.4 n_1 \frac{D}{V_{bar\ zbar}} = 1.48$

$R_d = \text{if}\left\{\eta_d > 0, \frac{1}{\eta_d} - \frac{1}{2\eta_d^2}[(1 - \exp(-2\eta_d)], 0\right\} = 0.46$

$R = \sqrt{\frac{1}{\beta}[R_n R_h R_b (0.53 + 0.47 R_d)]} = 0.38$

$g_r = \sqrt{\ln(3600 n_1)} + \frac{0.577}{\sqrt{2 \ln(3600 n_1)}} = 4.26$

The following values may be assumed: $g_Q = 3.4$, $g_v = 3.4$

Gust Factor: $G = 0.925\left(\frac{1 + 1.7 I_{zbar}\sqrt{g_Q^2 Q^2 + g_r^2 R^2}}{1 + 1.7 I_{zbar} g_v}\right) = 0.9302$

Basic Pressure (psf): $q_z = 0.00256 V^2 I = 25.60$ psi

Velocity Pressure Coef: $K_k = 2.01 \text{ if } \left[El_k > 15, \left(\frac{El_k}{z_g}\right), \left(\frac{15}{z_g}\right)\right]^{2/\alpha}$

$W_{b_k} = \frac{(C_f q K_k o d_k)}{1 + 6.8 I_{zbar}}$

K_k	W_{b_k}
1.348	83.99
1.326	82.64
1.303	81.20
1.279	79.66
1.252	78.00
1.223	76.20
1.191	74.21
1.156	72.01
1.116	69.52
1.070	66.65
1.015	63.21
0.945	58.89
0.849	52.89
0.849	52.89
0.849	

(lb/vertical ft)

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$$M_{barO} = \sum_k w_{b_k} ht_k \frac{1}{1000} EI_k$$

M_{barO} = 749.4 ft-Kip base moment mean component

$$w_{D.H} = \frac{3M_{barO}}{H^2}$$

$$[G(1 + 6.8I_{zbar}) - 1]1000$$

$$w_{d_k} = w_{D.H}\left(\frac{EI_k}{H}\right)$$

$w_{D.H}$ = 132.04 lb/vertical ft

$$M_{barD} = \sum_k (w_{d_k})\, ht_k \frac{1}{1000} EI_k$$

M_{barD} = 759.0 ft-Kip base moment fluctuating component

AlongWind_M = $M_{bar\,O} + M_{bar\,D}$

AlongWind_M = 1508.4 ft-Kip

w_{d_k}
127.32
117.89
108.46
99.03
89.60
80.16
70.73
61.30
51.87
42.44
33.01
23.58
14.15
4.72
0.00

(lb/vertical ft)

EXAMPLE CALCULATION E-4 EARTHQUAKE RESPONSE

For a lumped mass system, such as shown in Example 1, the response spectra analysis is as follows:

(a) The displacement u_{jn} of the jth mass in the nth mode of vibration is given by

$$u_{jn} = \Gamma_n u_n^o a_{rn} \tag{1}$$

where

Γ_n = participation factor of the nth mode

$$\sum_n = \frac{\sum_{j=1}^{N} M_j a_{jn}}{\sum_{j=1}^{N} M_j a_{jn}^2} \tag{2}$$

N = number of masses
M_j = the jth mass of stack
u_n^o = design response spectra value for the nth mode frequency
a_{jn} = the nth mode shape value of the jth mass

For the horizontal excitation, the bending moment M_{in} and shear force V_{in} at the ith mass location and in the nth mode of vibration can be obtained, as

$$V_{in} = \sum_{j=1}^{N} M_j \omega_n^2 u_{jn} \tag{3}$$

$$M_{in} = \sum_{j=1}^{N} M_j \omega_n^2 u_{jn}(h_j - h_i) \tag{4}$$

(a) The overturning moment is

$$M_{A,n} = \sum_{j=1}^{N} (M_j \omega_n^2 u_{jn} h_j) + I_A \omega_n^2 \theta_{A,n} \tag{5}$$

where

ω = natural circular frequency of the nth mode of stack, in radians per second
I_A = mass moment of inertia of footing about point A
$\theta_{A,n}$ = the nth mode rotation of footing of stack

In the general case, when a stack is supported at many places, the shear forces V_{in} and bending moments M_{in} along a stack can be obtained by static analysis due to inertia loads

$$F_j = M_j \omega_n^2 u_{jn}\,, j = 1 \text{ to } N \tag{6}$$

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Total shear force V_i and bending moments M_i at the ith location are calculated from the modal values V_{in} and M_{in} using expressions

$$V_i = \left(\sum_{n=1}^{N} V_{in}^2 \right)^{1/2} \quad (7)$$

$$M_i = \left(\sum_{n=1}^{N} M_{in}^2 \right)^{1/2} \quad (8)$$

where

N = number of governing modes, i.e., modes which contribute 10% or more to the responses.

EXAMPLE CALCULATION E-4 EARTHQUAKE RESPONSE SPECTRUM EXAMPLE

A single wall steel stack, which has a height of 210 ft, outside diameter of 12 ft, and thickness of 0.50 in., which is located with $A_v = 0.30$ has the following modal properties and response spectrum earthquake SRSS values.

	Modal Properties				
	1	2	3	4	5
Frequency (cycle/sec)	0.883	5.373	14.429	26.740	41.371
Time Period (sec)	1.132	0.186	0.069	0.037	0.024
Participation Factor	1.6008	−0.9801	0.4572	−0.414	0.2089
Scaled displacement (ft)	0.2994	0.018	0.0018	0.0004	0.0001

Mode Shape (ft):

Elev (ft)	1	2	3	4	5	SRSS
210	1.0000	1.0000	1.0000	1.0000	1.0000	0.4796
196	0.9087	0.6833	0.4818	0.2706	0.0541	0.4357
182	0.8175	0.3695	−0.0118	−0.3630	−0.6344	0.3919
168	0.7266	0.0699	−0.4099	−0.6960	−0.6823	0.3483
154	0.6367	−0.2009	−0.6437	−0.6201	−0.1261	0.3052
140	0.5485	−0.4279	−0.6734	−0.2032	0.5582	0.2630
126	0.4629	−0.5979	−0.5039	0.3311	0.8113	0.2221
112	0.3808	−0.7016	−0.1867	0.7080	0.4251	0.1829
98	0.3033	−0.7353	0.1921	0.7344	−0.2956	0.1460
84	0.2317	−0.7017	0.5333	0.3929	−0.7776	0.1118
70	0.1673	−0.6101	0.7507	−0.1517	−0.6350	0.0809
56	0.1113	−0.4762	0.7944	−0.6366	0.0249	0.0540
42	0.0652	−0.3213	0.6656	−0.8358	0.6915	0.0318
28	0.0303	−0.1712	0.4192	−0.6794	0.8665	0.0148
14	0.0081	−0.0541	0.1550	−0.3020	0.4816	0.0040
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Moment (ft-Kips)

Elev(ft)	1	2	3	4	5	SRSS
210	0	0	0	0	0	0
196	72	2661	19186	65894	157732	62
182	274	8958	56860	167448	332516	213
168	594	17222	94081	221161	307182	426
154	1019	25858	115574	183151	66594	677
140	1535	33425	112369	63421	−213779	948
126	2130	38715	83326	−83092	−318044	1231
112	2791	40823	34947	−185969	−166383	1521
98	3507	39197	−20594	−195537	119371	1819
84	4267	33658	−68763	−108314	311865	2131
70	5060	24384	−96467	30687	259070	2465
56	5877	11863	−95364	149693	5951	2826
42	6710	−3191	−63777	184799	−239327	3217
28	7553	−19956	−6651	109762	−266473	3637
14	8400	−37632	66561	−54813	−20266	4081

GENERAL NOTE: Shear calculation method similar with base shear = 37 kips

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E-5 VORTEX SHEDDING DESIGN (THIS METHODOLOGY IS NOT AN EXAMPLE)

The steel stack response to vortex induced wind loads is based upon dimensions, modal properties for the vibration mode being considered, the structural damping, β_s and aerodynamic damping, β_a.

It should be noted that the structural damping for vortex shedding is in accordance with para. 5.2(b). This is not the same value of damping used for seismic loads.

For the vortex shedding response, when V_c is in the vicinity ±30% of $V_{z_{cr}}$ the aerodynamic damping is negative and shall be included.

Response is highly sensitive to small changes in damping β_s where values of A_2 are near 1.

GENERAL THEORY

The root-mean-square motion at the point of maximum displacement is given by,

$$\frac{\tilde{a}_M}{\overline{D}} = \frac{C_1 C_M}{m_r \sqrt{\lambda(\beta_s + \beta_a)^{1/2}}}$$

$$\beta_a = -\frac{C_2}{m_r}\left[1 - 4\left(\frac{\tilde{a}_M}{\overline{D}}\right)^2\right]$$

$$\lambda = H/\overline{D}$$

$$m_r = m_e / \rho \overline{D}^2 g$$

$$m_e = \int_o^H m(z)\,\phi^2(z)dz \Big/ \int_o^H \phi^2(z)dz$$

C_2 = 0.6 (for parallel stacks only)

$$C_M = \phi(z_M)\frac{\left(\frac{1}{H}\int_O^H \phi^2(z)dz\right)^{1/2}}{\frac{1}{H}\int_O^H \phi^2(z)dz}$$

$\phi(z_M)$ = Value of $\phi(z)$ at maximum deflection $z_M = H$ for cantilever mode

$C_M \doteq$ 2.0 for the fundamental mode of vibration

C_1 = 0.12 for an isolated steel stack

$$C_1 = \frac{0.12}{(5S)^2}\alpha \text{ for a grouped steel stack}$$

For a group of two or more identical steel stacks, the amplification factor α and Strouhal Number S are given as,

$$\alpha = 1.50 - \frac{(A/\overline{D} - 3)}{24},\ 3 < \frac{A}{\overline{D}} < 15$$

$$\alpha = 1.0 \text{ for } \frac{A}{\overline{D}} \geq 15$$

$$S = 0.16 + \frac{1}{300}\left(\frac{A}{\overline{D}} - 3\right) \text{ for } \frac{A}{\overline{D}} < 15$$

$$S = 0.20 \text{ for } \frac{A}{\overline{D}} \geq 15$$

For $\frac{A}{\overline{D}} < 3$ or for groups of identical steel stacks or non-identical steel stack groups, interference effects shall be established by reference to model test, or other studies of similar arrangements.

E-6 COMPUTATION OF VORTEX-INDUCED RESPONSE (THIS METHODOLOGY IS NOT AN EXAMPLE)

Evaluation of Loads Due to Vortex Shedding

The equation defining $\tilde{a}_M/\overline{D}$ can be written as,

$$\frac{\tilde{a}_M}{\overline{D}} = \frac{A_1}{\left\{1 - A_2^2\left[1 - 4\left(\frac{\tilde{a}_M}{\overline{D}}\right)^2\right]\right\}^{1/2}}$$

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$$A_1 = C_1 C_M / m_r \sqrt{\beta_s \lambda}$$

$$A_2 = C_2 / m_r \beta_s$$

For $m_r \beta_s > 0.8$

$$\frac{\tilde{a}_M}{\overline{D}} \doteq \frac{A_1}{\left[1 - \left(\frac{C_2}{m_r \beta_S}\right)\right]^{1/2}}$$

For $m_r \beta_s < 0.4$

$$\frac{\tilde{a}_M}{\overline{D}} \doteq 0.5 \left(1 - \frac{m_r \beta_s}{C_2}\right)^{1/2}$$

Practical Application

The general solution may be reduced to the following formulas of vortex shedding and then used to determine equivalent static loads. For any values of $m_r \beta_s$,

$$\hat{a}_M = \overline{D} \left(\frac{-(1 - A_2) + \sqrt{(1 - A_2)^2 + 16 A_1^2 A_2}}{8 A_2} \right)^{1/2}$$

The peak values for vortex shedding response are:

$$\hat{a} = \hat{g}\, \tilde{a}_M \quad \text{and} \quad a_s = g_s\, \tilde{a}_M$$

where $\hat{a}$ is the maximum value and is used to calculate peak loads and stresses while a_s defines equivalent constant amplitude for fatigue calculations. The values of $\hat{g}$ and g_s are determined from the following:

For $m_r \beta_s > 0.8$, $\hat{g} = 4.0$ and $g_s = 2.0$
For $m_r \beta_s < 0.4$, $\hat{g} = 1.6$ and $g_s = 1.5$

Linear interpolation is used for $0.4 < m_r \beta_s < 0.8$.

Equivalent Static Loads

The equivalent static loads corresponding the displacement, $\hat{a}_M$, are given by:

$$\hat{w}(z) = \hat{a}\, (2\pi n_1)^2\, \phi\, (z)\, m(z)/g_c$$
$$w_s(z) = a_s\, (2\pi n_1)^2\, \phi\, (z)\, m(z)/g_c$$

The number of cycles in 50 years at the equivalent constant amplitude a_s is given by:

$$N/n_1 = 10^{10} \left(\frac{V_c \sqrt{I}}{V_{z_{cr}}} \right)^2 \exp \left[-15 \left(\frac{V_c \sqrt{I}}{V_{z_{cr}}} \right)^2 \right]$$

V_c and $V_{z_{cr}}$ are evaluated at the same height.

Variable Diameter Stacks

For variable diameter stacks, the preceding method may be used with the following modifications to account for the range of possible critical diameters. The previous method is used with the following changes in formulas.

The peak response is determined by varying the range of height being considered for any mean diameter, $\overline{D}$ for a portion of the steel stack where the diameter varies 15% from this mean diameter. The peak response is determined by iterations over the full height of the stack.

$$\lambda = \frac{z_2 - z_1}{\overline{D}}$$

$$C_M = \phi\,(z_M) \frac{\left(\frac{1}{H} \int_{z_1}^{z_2} \phi^2\,(z)\, dz \right)^{1/2}}{\frac{1}{H} \int_0^H \phi^2\,(z)\, dz}$$

$$R = \frac{\left(\int_{z_1}^{z_2} \phi^2\,(z)\, dz \right)}{\int_0^H \phi^2\,(z)\, dz}$$

R = 1.0 for nearly parallel
C_2 = 0.6 R

The limits change to:
$m_r \beta_s > 0.8\ R$
$m_r \beta_s < 0.4\ R$

Symbols and Definitions

A = center-to-center stack spacing for interference effects (ft)

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A_1 = constant
A_2 = constant
$\hat{a}$ = maximum value amplitude for static equivalent design loads (ft)
a_s = maximum value amplitude for static equivalent fatigue loads (ft)
$\tilde{a}_M$ = r. m. s. dynamic displacement at $z = z_m$ (ft)
C_1 = constant for grouped/isolated stacks
C_2 = constant
C_M = mode shape constant
$\overline{D}$ = mean diameter for the segment z_1 to z_2, or for stacks with less than +/–10% variation over the top $\frac{1}{3}$ the value of $\overline{D}$ is the average over the top $\frac{1}{3}$ (ft)
H = height of steel stack (ft)
$\hat{g}$ = constant for maximum static equiv. loads
g = gravitational acceleration (32.2 ft/sec^2)
g_c = gravitational constant (32.2 lbm-ft/ft-lb/lbf-sec^2)
g_s = constant for fatigue static equiv. loads
m_e = equivalent uniform mass per unit length (lbm/ft)
$m(z)$ = mass per unit length at height z (lbm/ft)
m_r = dimensionless mass
n_1 = natural frequency of mode (Hz)
R = constant for tapered stacks
S = strouhal number
V_c = critical speed for the segment z_1 to $z_2 = 5n_1\overline{D}$ (ft/sec)
$V_{z_{cr}}$ = mean hourly design speed (50-year return period) at the critical height z_{cr} used for evaluating the critical wind velocity (ft/sec)
z = height z under consideration (ft)
z_{cr} = $\frac{1}{2}(z_1 + z_2)$ or, for stacks with less than +/–10% variation over the top third, $z_{cr} = \frac{5}{6} H$ (ft)
z_M = height at maximum modal shape displacement (H for mode 1) (ft)
z_1, z_2 = upper and lower limits of a section of the stack over which the diameter changes by 30% (i.e., $\overline{D}$ ±15%) (ft)

For tapered stacks, vortex shedding loads shall be evaluated over all ranges of height for the distance of +/–15% of mean diameter of that height. For a strongly tapered stack, the range z_1 to z_2, is not necessarily near the top. A larger response can be lower where the diameter is larger.

a = amplification factor
β_a = aerodynamic damping
β_s = structural damping
λ = aspect ratio
ρ = air density (0.00238) (lbm-sec^2/ft^4)
$\phi(z)$ = normalized mode shape at height z (ft)
$\phi(z_M)$ = max normalized modal displacement $\phi(z)$ for mode at $z = z_M$, for the first mode $z = H$ (ft)
$\hat{\omega}(z)$ = equivalent static load (lbf/ft)
$\omega_s(z)$ = equivalent fatigue load (lbf/ft)

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ASME Technical Paper, 65WA/FU5

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4 LIST OF ABBREVIATIONS OF ENGINEERING SOCIETIES AND INDUSTRIAL ASSOCIATIONS

(1) ACI American Concrete Institute
(2) AISC American Institute of Steel Constructions
(3) ANSI American National Standards Institute
(4) ASCE American Society of Civil Engineers
(5) ASME American Society of Mechanical Engineers
(6) ASTM American Society of Testing and Materials
(7) AWS American Welding Society
(8) CICIND International Committee on Industrial Chimneys
(9) EPA Environmental Protection Agency
(10) FAA Federal Aviation Administration
(11) NFPA National Fire Protection Association
(12) OSHA Occupational Safety and Health Administration
(13) SSPC Steel Structure Painting Council
(14) UBC Uniform Building Code
(15) UL Underwriters Laboratory
(16) SMACNA Sheet Metal And Air Conditioning Controllers National Association

CONVERSION FACTORS INCH-POUND TO SI (METRIC)

LENGTH

To Convert From	To	Multiply By
in.	mm	25.4
in.	cm	2.54
ft	m	0.3048
yd	m	0.9144
mile (statue)	km	1.609

KINEMATIC VISCOSITY (THERMAL DIFFUSIVITY)

To Convert From	To	Multiply By
in./sec	m^2/sec	0.0006451
in./sec	stokes	6.4521

AREA

To Convert From	To	Multiply By
sq. in.	mm^2	645.16
sq. in.	cm^2	6.451
sq. ft	m^2	0.0929
sq. in.	m^2	0.0006451
sq. yd	m^2	0.8361
sq. mile (statue)	m^2	2,590,000

FORCE

To Convert From	To	Multiply By
kgf	N	9.807
kip-force	N	4448
lbf	N	4.448

VOLUME (capacity)

To Convert From	To	Multiply By
ounce	cm^3	29.57
gal	m^3	0.003785
cu. in.	cm^3	16.4
cu. ft	m^3	0.02832
cu. yd	m^3	0.7646

FORCE/LENGTH

To Convert From	To	Multiply By
lbf/in.	N/m	175.13
lbf/ft	N/m	14.59

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PRESSURE OR STRESS (FORCE PER AREA)

To Convert From	To	Multiply By
kgf/m^2	Pa	9.807
ksi	MPa	6.895
N/m^2	Pa	1.000
ksf	kPa	47.88
psf	Pa	47.88
psi	kPa	6.895

TEMPERATURES

To Convert From	To	Multiply By
°F	°C	$t_c = (t_f - 32)/1.8$
°C	°F	$t_f = 1.8t_c + 32$
K	°C	$t_c = t_k - 273.15$

BENDING MOMENT (torque)

To Convert From	To	Multiply By
in./lbf	Nm	0.1130
ft/lbf	Nm	1.356
m/kgf	Nm	9.807

HEAT

To Convert From	To	Multiply By
BTU/lbm	J/kg	2326
BTU in./h sq. ft	W/m•K	0.1442
BTU/h sq. ft°F	W/m^2•K	5.678
BTU/lbm°F	J/kg-°C	4184
BTU/lbm°F	^{K}cal/kg–°C	1.0

MASS

To Convert From	To	Multiply By
ounce-mass (avoirdupois)	g	28.34
ounce-mass (avoirdupois)	kg	0.0283
pound-mass (avoirdupois)	kg	0.4536
ton (metric)	Mg	1.000
ton (short, 2,000 lbm)	Mg	0.9072

VELOCITY

To Convert From	To	Multiply By
in./sec	m/s	0.0254
ft/sec	m/s	0.305
ft/min	m/s	0.00508
mph	km/h	1.609
km/h	m/s	0.278

MASS PER AREA

To Convert From	To	Multiply By
psf	kg/m^2	4.88
lbm/sq. yd	kg/m^2	0.034

ACCELERATION

To Convert From	To	Multiply By
ft/sec^2	m/s^2	0.3048
$in./sec^2$	m/s^2	0.0254
freefall, standard	m/s^2	9.807

MASS PER VOLUME

To Convert From	To	Multiply By
lbm/cu. in.	kg/m^3	27,680
lbm/cu. ft	kg/m^3	16.02
lbm/cu. yd	kg/m^3	0.5933
lbm/gal (U.S. liquid)	kg/m^3	119.83

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