ASME STS-1–2021

(Revision of ASME STS-1–2016)

Steel Stacks

AN AMERICAN NATIONAL STANDARD

The American Society of
Mechanical Engineers

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The American Society of Mechanical Engineers
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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 Standard 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 the mechanical design of stacks. In the last several decades, much research has been done and many papers written on the subject. While investigation and research continued, it was the feeling of these persons that some formal guidelines needed to be established. Therefore, in April of 1979, a group composed 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 3 yr, 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 clarification. 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.

The 2006 edition included changes and improvements to the Environmental Protection Agency regulation concerning emissions that have created a strong emphasis on the mechanical design of steel stacks, made necessary changes found through practical experience with the previous edition, expanded formulas as necessary, and provided both revised and new sections for steel stack design, fabrication, and erection. It revised sections on appurtenances to meet today's requirements for these items. A new section provided the fundamental concepts for guyed stacks. Revisions to the section on the physical properties of steel at elevated temperatures were made to match information available through a comprehensive review of current technical literature. Sections on vibration included minor changes but yielded a more workable standard. Also, a detailed example was included to provide a method for determining the magnitude of across wind loads. One method was included to address fatigue due to vibration. Fatigue can be a significant issue in steel stack design and needs to be considered in the design. Methods to determine across wind load and seismic loads were provided in the nonmandatory appendices. If fatigue requires close examination, the engineer is cautioned to review this issue with other design standards if necessary. There are several standards among them that can be helpful: AISC, CICIND, or ASME.

This Standard is available for public review on a continuing basis. This provides an opportunity for additional public review input from industry, academia, regulatory agencies, and the public-at-large.

ASME STS-1–2011 was approved as an American National Standard on March 11, 2011. ASME STS-1–2016 was approved as an American National Standard on September 23, 2016. ASME STS-1–2021 was approved by ANSI as an American National Standard on October 19, 2021.

ASME STS COMMITTEE
Steel Stacks

(The following is the roster of the Committee at the time of approval of this Standard.)

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General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions or a case, and attending Committee meetings. Correspondence should be addressed to:

Secretary, STS Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
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This Standard is always open for comment, and the Committee welcomes proposals for revisions. 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 proposal, including any pertinent documentation.

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Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the STS Standards Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the STS Standards Committee.

Requests for interpretation should preferably be submitted through the online Interpretation Submittal Form. The form is accessible at http://go.asme.org/InterpretationRequest. Upon submittal of the form, the Inquirer will receive an automatic e-mail confirming receipt.

If the Inquirer is unable to use the online form, he/she may mail the request to the Secretary of the STS Standards Committee at the above address. The request for an interpretation should be clear and unambiguous. It is further recommended that the Inquirer submit his/her request in the following format:

Subject: Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.

Edition: Cite the applicable edition of the Standard for which the interpretation is being requested.

Question: Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. Please provide a condensed and precise question, composed in such a way that a "yes" or "no" reply is acceptable.

Proposed Reply(ies): Provide a proposed reply(ies) in the form of "Yes" or "No," with explanation as needed. If entering replies to more than one question, please number the questions and replies.

Background Information: Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in the format described above may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Standard requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

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INTRODUCTION

The following Standard applies to steel stacks; i.e., 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 that 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 nonflammable 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 (BPVC). 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.

ASME STS-1–2021
SUMMARY OF CHANGES

Following approval by the ASME STS Committee and ASME, and after public review, ASME STS-1–2021 was approved by the American National Standards Institute on October 19, 2021.

Throughout this Standard, variable *d* has been revised to $\overline{D}$. In addition, ASME STS-1–2021 includes the following changes identified by a margin note, **(21)**.

Page	*Location*	*Change*
2	1.5.2	Revised
5	2.2.1	Subparagraph (b) revised, and subpara. (f) added
5	2.2.2	First paragraph revised
5	2.2.3	Subparagraph (a)(4) added
6	2.2.6	Subparagraphs (a) and (b) revised
6	2.2.7	Subparagraphs (e)(2) and (f) revised
6	2.2.8	Revised
7	3.2	Subparagraph (b) revised
7	3.2.1	Subparagraph (f) revised
7	3.2.2	Subparagraph (c) revised
8	3.2.4.1	First paragraph revised
8	3.2.4.2	Subparagraph (a)(1) revised, and subpara. (a)(6) added
10	3.3.1	(1) Subparagraph (h) revised (2) Subparagraph (j) added and subsequent subparagraphs redesignated
11	3.3.2	Subparagraph (c) added and subsequent subparagraphs redesignated
13	4.3.3.1	Revised
14	4.3.3.2	Revised in its entirety
14	4.3.3.3	Revised
14	4.3.3.4	First paragraph revised
15	4.3.5	Last paragraph revised
15	4.3.9	Added
15	4.4	(1) In para. 4.4.1, sentence below eq. (4-8) revised, and last nomenclature added (2) In para. 4.4.2, sentence below eq. (4-11) revised (3) In para. 4.4.3, eq. (4-12) revised (4) In para. 4.4.4, last sentence added (5) In para. 4.4.5, eqs. (4-15), (4-16), and (4-17) revised (6) In para. 4.4.5(a), nomenclature deleted (7) Former para. 4.4.6 and Table 4.4.6-1 deleted and subsequent paragraphs and table redesignated
18	4.6.2	Subparagraph (c) revised
18	4.8.1	Last sentence added
20	4.13	Added and subsequent paragraphs redesignated

Page	*Location*	*Change*
21	4.14	(1) Definitions of I and q_p deleted (2) Definitions of M, P, V, $w(z)$, $\overline{w}(z)$, and $w_{D(z)}$ revised
22	5.2.1.1	Revised
22	5.2.1.3	Equation (5-1) revised
22	5.2.2	First line of paragraph below eq. (5-6) revised
24	5.4	Definitions of V, V_R, and $V_{z_{cr}}$, and ρ revised
25	6.2.6	Definitions of *fall protection*, *guardrail system*, *ladder safety system*, *lower level*, *opening*, *single length of climb*, and *unprotected sides and edges* added
25	6.3	(1) Paragraph 6.3.1 revised (2) Paragraph 6.3.7 added, former para. 6.3.11 deleted, and former paras. 6.3.7 through 6.3.14 redesignated
34	8.6.1	Revised
36	9.4.2	Subparagraph (b)(2) revised
36	9.4.3	Subparagraphs (c) and (e) revised
37	9.4.4	Subparagraph (d) revised
37	9.5.3	Revised
37	10	Updated
40	Mandatory Appendix I	(1) Figures I-1 through I-1c deleted (2) Table I-2 revised in its entirety (3) Former Table I-3 deleted and subsequent tables redesignated (4) Table I-3 (former Table I-4) revised
45	Nonmandatory Appendix A	Titles of Figures A-6 through A-9 editorially revised
74	Table B-15	Note (1) added and subsequent note renumbered
81	Nonmandatory Appendix D	Column headings in Tables D-3 through D-7 editorially revised
87	Nonmandatory Appendix E	Revised in its entirety

STEEL STACKS

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 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. Equations 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 equations 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 2,400 ft/min and 3,600 ft/min are most common. Stacks venting saturated gases sometimes limit maximum stack velocities between 1,800 ft/min and 2,400 ft/min to reduce entrained or condensed moisture from leaving the stack exit. Tests by EPRI give different ranges for each type of 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:

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

where

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

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

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

(a) Entrance loss

$$FL_{en} = 0.003\,KdV^2 \qquad (1\text{-}2)$$

(b) Friction loss

$$FL_f = \left(\frac{2.76}{B}\right)(F)(T_g)\left(\frac{H_E}{Di^5}\right)\left(\frac{W}{10^5}\right)^2 \qquad (1\text{-}3)$$

(c) Exit loss

$$FL_{ex} = \left(\frac{2.76}{B}\right)\left(\frac{T_g}{D_t^{\,4}}\right)\left(\frac{W}{10^5}\right)^2 \qquad (1\text{-}4)$$

where

B = barometric pressure; mercury absolute, in.
d = gas density, lb/ft^3
D_i = inside diameter(s) of stack section, ft
D_t = inside diameter of stack at outlet, ft
F = friction factor based on Reynolds number (see Nonmandatory Appendix A, Figure A-1)
FL_{en} = stack entrance loss; water gage, in.
FL_{ex} = stack exit loss; water gage, in.
FL_f = stack friction loss; water gage, in.
H_E = stack height above centerline of inlet, ft
K = breeching inlet angle factor (see Nonmandatory Appendix A, Table A-1)
T_g = average absolute temperature of gas, °R
V = gas velocity at inlet, ft/sec
W = mass flow rate of gas, lb/hr

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

(d) Total loss

$$FL_{\text{total}} = FL_{en} + FL_f + FL_{ex}\ \text{water gage, in.} \qquad (1\text{-}5)$$

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.

1.4.3 Approximate Stack Draft Losses and Size. See Nonmandatory Appendix A, Figures A-10 through A-13.

1.5 Heat Loss (See Nonmandatory Appendix A, Figures A-2 Through 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. (21)

(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. To design an appropriate lining system, the following information is needed:

(1) normal operating temperature
(2) upset (maximum) operating temperature
(3) chemical composition of flue gas
(4) operating conditions, cyclical service
(5) flue gas velocity

Once defined, a lining system can be selected, and the appropriate thickness determined. Lining reinforcing and attachments to stack shell should be per lining 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 equation:

Heat transferred through the stack wall

$$Q = U \times A \times t_s \tag{1-6}$$

Heat loss in flowing gas entering versus leaving

$$Q = W \times C_p \times t_g \tag{1-7}$$

Combining eqs. (1-6) and (1-7)

$$U \times A \times t_s = W \times C_p \times t_g \tag{1-8}$$

$$t_s = \left(\frac{t_{\text{in}} + t_{\text{out}}}{2}\right) - t_{\text{amb}} \tag{1-9}$$

$$t_g = t_{\text{in}} - t_{\text{out}} \tag{1-10}$$

$$U \times A \times \left(\frac{t_{\text{in}} + t_{\text{out}}}{2}\right) - t_{\text{amb}} = W \times C_p \times (t_{\text{in}} - t_{\text{out}}) \tag{1-11}$$

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_a} + \frac{1}{h_{\text{ins}}} + \frac{1}{h_l} + \frac{1}{h_o} \tag{1-12}$$

Heat loss through the stack wall section

$$Q/A = U \times t_s \tag{1-13}$$

Heat loss through each component of the stack wall section

$$Q/A = h \times t_h \tag{1-14}$$

where

A = stack mean surface area, ft^2
C_p = specific heat of gas, Btu/lb, °F
h_a = airspace coefficient, Btu/hr-ft^2, °F
h_i = internal film coefficient, Btu/hr-ft^2, °F
h_{ins} = insulation coefficient, Btu/hr-ft^2, °F
h_l = lining coefficient, Btu/hr-ft^2, °F
h_o = external film coefficient, Btu/hr-ft^2, °F
t_g = gas temperature entering minus gas temperature leaving, °F
t_h = temperature drop through the h component of the stack wall, °F
t_s = average gas temperature minus ambient temperature, °F
U = overall heat transfer coefficient
W = gas flow, lb/hr

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 used 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 multiflue 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) Lighting requirements are established by Federal Aviation Administration (FAA) directives. Access platforms to service lights are recommended for corrosion-resistant construction. See sections 6 and 7.

(h) 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.

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

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

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

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

(m) 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.

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

(o) 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.

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

1.8 Symbols for Section 1

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

1.9 Definitions for Section 1

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.

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

EPRI: Electric Power Research Institute.

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.

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.

(21) ### 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. Approval shall include confirmation that steels used meet all requirements.

(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.

(f) Galvanic corrosion shall be considered.

(21) **2.2.2 Shell and Base Plates.** For more information on this subject, see Nonmandatory Appendix B, Tables B-1 through B-11. Additional materials or material grades may be applicable.

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

(1) carbon steels conforming to ASTM A36, ASTM A283, or ASTM A529

(2) high-strength, low-alloy steels conforming to ASTM A242, ASTM A572, or ASTM A588

(3) stainless steels conforming to ASTM A666

(4) stainless chromium-nickel steel clad plate conforming to ASTM A264 and nickel-base alloy clad steel conforming to ASTM A265 may be considered for use as shell plate

(5) metals listed in 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 A285, ASTM A515, and ASTM A516; alloy steels such as ASTM A387; and stainless steels such as ASTM A240 may be substituted for structural quality materials as appropriate.

(c) Carbon steels such as ASTM A516, Grades 55 through 70 and low-alloy steels such as ASTM A517, Grades A through T and ASTM A537 are usually specified for service temperatures as low as −50°F (−46°C). Nickel-containing alloy steels such as ASTM A203, 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 used and the conditions encountered. Section 3 should be consulted and used 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 (21)

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

(1) carbon steels conforming to ASTM A36, ASTM A283, or ASTM A529

(2) high-strength, low-alloy steels conforming to ASTM A242, ASTM A572, or ASTM A588

(3) stainless steels conforming to the ASTM A240 or ASTM A666 or nickel-containing alloys having compositions similar to those of the shell plate

(4) materials from paras. 2.2.2(b) and 2.2.2(c) may be considered

(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 used 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 ASTM A474

(2) zinc-coated (galvanized) steel wire strand conforming to ASTM A475 and ASTM A586

(3) zinc-coated (galvanized) steel wire rope conforming to ASTM A603

(4) stainless steel wire strand conforming to ASTM A368

(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 ASTM A307

(2) carbon steel bolts for general applications conforming to ASTM A449

(3) alloy steel bolts, studs, and threaded fasteners conforming to ASTM A354

(4) alloy steel bolts and studs with enhanced impact properties conforming to ASTM A687

(5) carbon steel conforming to ASTM A36

(6) high-strength, low-alloy steels conforming to ASTM F1554

(7) Alloy steel and stainless steel conforming to ASTM A193, Grade B7

(b) Material for washers shall conform to ASTM F436 and correspond to the anchor bolt material.

(c) Material for nuts shall conform to ASTM A563 and correspond to the anchor bolt material.

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

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

(21) **2.2.6 Bolts, Washers, and Nuts**

(a) Unless otherwise specified, carbon and high-strength steel bolts conforming to ASTM A307, ASTM F3125 (A325), or ASTM A449 will be used.

(b) High-strength alloy steel bolts may be required, and these should conform to ASTM A354 or ASTM F3125 (A490).

(c) For high-temperature applications, bolt material should conform to ASTM A193, Grades B7, B8, or B8M covering alloy and stainless steels. Stainless steel bolts are also covered under ASTM F593.

(d) Unless otherwise specified, nuts should conform to ASTM A563. 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 ASTM F436. 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 used as appropriate.

(21) **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 ASTM A569 and ASTM A570

(3) high-strength, low-alloy sheet and strip conforming to ASTM A606 and ASTM A607

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

(1) materials under (a).

(2) stainless steels conforming to ASTM A666.

(3) aluminum conforming to ASTM B221. 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 ASTM A36 or ASTM A20

(2) high-strength, low-alloy steel conforming to ASTM A242, ASTM A588, or ASTM A618

(3) aluminum conforming to ASTM B221

(4) stainless steels conforming to ASTM A666 and ASTM A554

(d) Access Doors and 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) 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 ASTM A240 or higher alloyed, corrosion-resistant materials should be considered. Refer to para. 3.4 on corrosion.

(f) 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. The designer may consider making the drain pipe from corrosion-resistant material such as Type 304 or Type 316 stainless steel conforming to ASTM A240 or ASTM A666, nickel alloy, or plastic.

2.2.8 Welding Electrodes (21)

(a) AWS D1.1/D1.1M is usually specified for structural welding of steel stacks constructed from carbon or low-alloy steels. AWS D1.6/D1.6M should be specified for structural welding of stainless steel stacks. As an alternative, ASME BPVC, Section IX may be specified.

(b) AWS provides electrode specifications based on the material type and the welding process to be used. With each specification they include the appropriate electrode classification. Please refer to the appropriate sections of AWS.

(c) The electrode classification provides the electrode type, minimum tensile strength, welding position, type of coating, the correct polarity or current to use, as well as the type of shielding gas. There are also supplemental designators such as improved toughness and diffusible hydrogen included in some electrode classifications.

(d) Welding electrodes with a minimum tensile strength of 70 ksi are to be used for carbon steel applications in steel stack construction.

(e) 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.

(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

Section 3 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.

(21) 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 whether a lining should be used, a complete thermal analysis of the entire system from heat source to stack inlet and to stack outlet should be performed giving primary consideration to the stack wall surface temperatures noting temperature changes from the inlet point of the flue gas to the top of the stack. 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.

(21) **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 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 (28°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, hydrofluoric, and sulfurous acids.

(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 nonstabilized grades of stainless steel susceptible to intergranular corrosion. The temperature range for this effect is 800°F (427°C) to 1,650°F (899°C). Typical chemically stabilized stainless steels include 321 and 347 while limited use of low carbon grades 304L and 316L may offer some resistance to intergranular corrosion for short periods.

3.2.2 Other Critical Temperatures (21)

(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 1 sec. Reversible injury occurs at 154°F (68°C) for 1 sec, and the threshold of pain is about 140°F (60°C) for 1-sec contact.

(b) *400°F (204°C).* Average coefficients of linear thermal expansion for carbon, alloy, stainless steels, and nickel alloys are shown in Nonmandatory 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 A36, creep becomes a design consideration at temperatures above 750°F (400°C). Creep is defined as the time-dependent permanent deformation that occurs after the application of a load to a metal in or above the creep temperature range. ASTM A242 and ASTM A588 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 A242 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 ASTM A588 at 800°F (427°C) and above because of relatively low ductility. ASTM A387 provides additional alternatives to ASTM A36 between 750°F (400°C) and 1,100°F (593°C).

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

(e) 1,050°F (565°C). The temperature at which creep becomes important for chromium-nickel austenitic stainless steels.

(f) 1,150°F (620°C) to 2,000°F (1 093°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-17 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, Tables C-1 and C-2.

(21) **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 their products can perform up to 500°F (260°C). However, it is important to clarify temperature limitations on such linings in regard to both dry and wet flue gas conditions because the temperature limitations of an organic coating system will often vary significantly depending on whether the flue gas is wet or dry. The condition of the stack wall, wet or dry, must also be taken into consideration because a wet surface can have the same effect as wet flue gas. Oftentimes, 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 are comprised of chemical resinous compounds based on carbon chains or rings and also contain 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. Fluoropolymer, natural rubber, butyl rubber, urethane asphalt, etc. linings are based on natural or synthetic polymers that, 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 (21)

(a) Inorganic Cementitious Concrete Monolithics. These linings are comprised of materials other than hydrocarbons and their derivatives. These protective barriers are comprised of inert mixtures of chemically inert, solid aggregate fillers 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 RP 936. Included are the following:

(1) Acid-Resistant Concrete. These linings are based on silicate chemical setting cements and use chemically inert fillers. They are particularly suited for severe chemical environments and mild/moderate temperature. Lightweight versions of these concretes that are suited for severe chemical environments and will resist temperatures up to 1,600°F (871°C) are available.

(2) Acid-Alkali-Resistant Concrete. These linings are generally based on a combined silicate, chemically resistant cement, with inert aggregate fillers. They are 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, using inert refractory-type aggregate fillers. They are suitable for mild chemical environments and severe temperature environments.

(4) Insulating Concrete for Temperatures to 1,650°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; and a perlite or vermiculite aggregate filler combined with a high alumina cement binder. They are suited for application where temperature is the main environmental condition to be addressed.

(5) Insulating Concrete for Temperatures up to 2,200°F (1 204°C). Linings are based on high-temperature insulating aggregate fillers using a high alumina hydraulic setting cement binder. They are particularly suited where the temperature environment and insulation characteristics of the lining are important.

(6) Geopolymer Concretes. These linings are a relatively new class of cementitious linings based on environmentally friendly (Green Technology) combinations of pozzolans, industrial waste by-products (e.g., fly ash or slag), and aluminosilicates that will provide a wide range of both chemical resistance and temperature resistance up to 2,100°F (1 100°C). The high strength and density of geopolymers also provide excellent abrasion resistance.

(b) Inorganic Masonry. These linings are 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 and 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 2,200°F (1 204°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 C279 or ASTM C980.

(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.

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 gage, $^{1}/_{4}$ 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 standpoint of developing the passive or protective film that 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 G48 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 Standard, 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 A242 and ASTM A588, 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.

(21) **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. It tends to exhibit 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 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 6-month period, even in normal rural or mild industrial environments or marine exposures.

(f) Coal-Tar Epoxy Coating. This coating is 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, are normally black in color, and require an SSPC-PC5 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-SP10 minimum surface preparation with a surface profile of 1 mil to 2 mil to obtain total adhesion.

(h) Epoxy Coating System. These coatings provide good resistance to industrial fumes and marine atmosphere exposures. These coatings exhibit hardness, excellent toughness and some degree of flexibility and will range from high solids content to 100% 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, and toughness and are of 100% solids content. They have a higher temperature resistance than an epoxy system and better chemical resistance.

(j) Two-Component Vinyl Ester and Polyester Systems. These styrene-based systems provide a wider range of chemical resistance and higher temperature resistance than epoxies and Novolak epoxies; however, they are moisture sensitive during application and curing and tend to be rigid when cured. The styrene odors associated with these systems can also be problematic to workers involved in the application and to other workers in the general area. Similar to epoxies, these systems will chalk under weathering while retaining their chemical resistance.

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

(l) 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 marine environments in salt water. It is normally limited to 160°F (71°C) performance temperature.

(m) 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.

(n) 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.

(o) 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 are nothing more than very mild fume conditions. They do not exhibit properties as good as vinyl or chlorinated rubbers with respect to chemical resistance.

(21) **3.3.2 Important Coating Considerations**

(a) environment (rural, industrial, and marine)
(b) exposure to temperature
(c) chemical exposure
(d) weathering
(e) aesthetic color retention
(f) durability
(g) surface preparation
(h) cost
(i) coating manufacturer's recommendation

3.3.3 Curing Methods

(a) air oxidation (alkyds and 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 the coating dry-film thickness will be. 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 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 ASTM A153 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 A242 or A588 steel.

(k) Because of potential corrosion problems with stack rain-caps, stainless steels conforming to ASTM A240 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.

3.3.6 Variations of Formulations. Due to the great number of variations of formulations by coating manufacturers, this Standard 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 recommended 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 parts per million) 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 (28°C), above the acid dew point estimated in Nonmandatory Appendix C, Figure C-1, 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 Nonmandatory Appendix C, Figure C-2.

(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 acids, 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 (28°C) above the acid dew point is determined from Nonmandatory Appendix C, Figures C-1 and C-2.

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 and hydrofluoric acids. 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 and sulfurous acid dew points. 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)

(-b) elementary chlorine: 0.1% by weight (1 300 mg/m^3 at 20°C and 1 bar pressure)

(-c) hydrogen chloride: 0.1% by weight (1 300 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.

(c) There are numerous ASTM standards covering thermal insulating materials and their properties. These standards should be consulted and used 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 ASTM A463
(2) galvanized steel conforming to ASTM A527
(3) stainless steel conforming to ASTM A666
(4) aluminum conforming to ASTM B209

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

4 STRUCTURAL DESIGN

4.1 Scope

Section 4 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 this 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, 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. False bottom plates shall be designed for a minimum live load of 150 psf.

4.3.3 Wind Load. The wind load shall be calculated in accordance with procedures outlined in this section. It is the designer's responsibility to calculate any applicable wind load not specified in this section, including all external attachments. The design shall also consider wind loads due to interference effects as stated in para. 4.3.3.8.

4.3.3.1 Design Wind Force. The design load distribution is given by (21)

$$w(z) = \overline{w}(z) + w_D(z) \tag{4-1}$$

where

$$\overline{w}(z) = \frac{C_f q_z D}{12(1 + 6.8 I_{\bar{z}})} \tag{4-2}$$

and

$$w_D(z) = \frac{3zM_0}{h^3}[G_f(1 + 6.8I_{\bar{z}}) - 1] \tag{4-3}$$

The velocity pressure, q_z, shall be calculated by

$$q_z = 0.00256\, V^2 K_{zt} K_z \tag{4-4}$$

where the basic wind speed, V, is based on a 3-sec gust velocity and is selected in accordance with the provisions of ASCE 7 and paras. 4.3.3.2 through 4.3.3.5, the Risk Category set forth in Mandatory Appendix I, Table I-2, and the velocity pressure exposure coefficient, K_z, is given in Mandatory Appendix I, Table I-3 in accordance with the provisions of paras. 4.3.3.6 and 4.3.3.8. The provisions of para. 4.3.3.6 shall be used to determine K_{zt} where applicable, but K_{zt} shall be not 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. Values for the force coefficient, C_f, can be found in Mandatory Appendix I, Table I-4. Interference effects on the force coefficient, C_f, described in para. 4.3.3.8 shall be considered.

(21) **4.3.3.2 Determination of Basic Wind Speed.** The basic wind speed, V, used in calculating the velocity pressure in eq. (4-4), is based on ultimate strength load conditions. Refer to Mandatory Appendix I, Table I-2 to determine the Risk Category of the stack structure. The basic wind speed can be found in ASCE 7 based on the applicable Risk Category. The ultimate wind speed mean recurrence intervals are as follows:

(a) Risk Category I: 300 yr
(b) Risk Category II: 700 yr
(c) Risk Category III: 1,700 yr
(d) Risk Category IV: 3,000 yr

(21) **4.3.3.3 Special Wind Regions.** The basic wind speed shall be increased where records or experience indicate that the wind speeds are higher. Mountainous terrain, gorges, and special regions shown in ASCE 7 shall be examined for unusual wind conditions. The authority having jurisdiction shall, if necessary, adjust the values given in ASCE 7 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. 4.3.3.4.

(21) **4.3.3.4 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 ASCE 7 when the following applies:

(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

4.3.3.5 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 B. This includes 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.

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

(c) Exposure D. This includes flat, unobstructed areas exposed to wind flowing over open water for a distance of at least 1 mi. 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.

4.3.3.6 Wind Speed Over Hills and Escarpments. The provisions of this paragraph shall apply to isolated hills or escarpments located in Exposure B, C, or D where the upwind terrain is free of such topographic features for a distance equal to $50H_H$ or 1 mi, 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 Mandatory Appendix I, Figure I-1 by using factor K_{zt}

$$K_{zt} = (1 + K_1 K_2 K_3)^2 \tag{4-6}$$

where K_1, K_2, and K_3 are given in Mandatory Appendix I, Figure I-1. The effect of wind speed-up shall be not required to be considered when $H_H/L_h < 0.2$ or when $H_H < 15$ ft for Exposure D, 30 ft for Exposure C, or <60 ft for all other exposures.

4.3.3.7 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.

4.3.3.8 Force Coefficient Interference Effect. For grouped or clustered stacks having a center-to-center distance of 3 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 containing high mass distribution are governed by seismic loads.

(21) **4.3.5 Earthquake Response.** The steel stack response to earthquakes 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 in Nonmandatory Appendix D, Table D-2 or the published value for the location. Using the value of A_v, the response spectrum scaling ratio is found in Nonmandatory Appendix D, Table D-2. 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 ten elements and five 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 E.

4.3.6 Thermal Loads. Nonuniform 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 nonuniform temperatures along its height is restrained from lateral movements. The thermal stresses should be considered in applicable stack and liner designs.

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 nonuniform 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.

4.3.7 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.

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

4.3.9 Load Factors. The following load factors shall be applied to the dead, wind, seismic, and thermal loads for use in the allowable stress calculations in para. 4.4. (21)

Load Type	Load Factor
Dead	1.0 (use 0.6 when resisting uplift)
Wind	0.6
Seismic	0.7
Thermal	1.0

As per para. 4.3.2, live load need not be considered in combination with wind or seismic.

4.4 Allowable Stresses (21)

The following equations for determining allowable stresses are applicable for circular stacks and liners provided that eq. (4-7) is satisfied:

$$\frac{t}{D} \leq \frac{10F_y}{E} \tag{4-7}$$

An increase in allowable shell stresses due to wind or seismic loads shall be not 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, 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 eq. (4-7), the following four load cases must be satisfied.

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}.

$$\frac{P}{A} \leq S_{cl} \tag{4-8}$$

where P is factored and

$$S_{cl} = \frac{EtY}{4D(\text{F.S.})} \tag{4-9}$$

when

$$\frac{t}{D} \leq \frac{2.8F_y}{E}$$

or

$$S_{cl} = \frac{F_y(1 - 0.3K_s)Y}{(\text{F.S.})} \tag{4-10}$$

when

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

and

$$Y = 1$$

when

$$\frac{L_e}{r} \leq 60$$

and

$$F_y \leq 50\,\text{ksi}$$

and

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

when

$$\frac{L_e}{r} > 60$$

and

$$F_y \leq 50\,\text{ksi}$$

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

F.S. = Factor of Safety = 1.5.
During construction 1.33 may be used.

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}.

$$\frac{P}{A} + \frac{MD}{2I_{\text{section}}} \leq S_{bl} \tag{4-11}$$

where S_{bl} = (S_{cl}) is given in para. 4.4.1, eqs. (4-9) and (4-10), and P and M are factored.

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

$$f_c = \frac{0.6q_zD}{288t} \tag{4-12}$$

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

$$S_{cc} = \frac{1.30EK\left(\frac{t}{D}\right)^{1.5}}{(\text{F.S.})\left(\frac{l_s}{D}\right)} \tag{4-13}$$

when

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

when

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

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

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

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 equation:

$$\frac{\left(\frac{P}{A}\right) + \frac{MD}{2I_{\text{section}}}}{S_{bl}} + \left(\frac{f_c}{S_{cc}}\right)^2 \leq 1.0 \tag{4-14}$$

where P and M are factored

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

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

$$I_{s+p} \geq \frac{0.6q_zl_sD^3(\text{F.S.})}{3{,}456E} \tag{4-15}$$

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

$$A_{s+p} \geq \frac{0.6 q_z l_s D}{288 S_{ccs}} \tag{4-16}$$

Circumferential compression in the stiffeners shall not exceed

$$S_{ccs} = \left(\frac{EI}{D^2}\right)\left(\frac{1}{A_{s+p}}\right)\left(\frac{1}{\text{F.S.}}\right)$$

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 × 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:

$$S_{s+p} \geq \frac{0.6 q_z D^2 l_s (\text{F.S.})}{1{,}830 F_y} \tag{4-17}$$

where

q_z = external wind pressure

4.4.6 Minimum Fabricated Plate Thickness and Maximum Stiffener Spacing. Table 4.4.6-1 shows the minimum plate thickness to be used in the fabrication of steel stacks and liners and maximum stiffener spacing.

4.4.7 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 A36, 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 creep design life should be selected based on the expected service life and 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 ASME BPVC, Section II. 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 ASME BPVC, Section I, 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

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

4.5 Deflections

4.5.1 Lateral Deflection. The maximum deflection shall be calculated and the foundation rotation or movement shall be considered in evaluating deflection. The resulting additional stresses caused by P-Delta effect, and other secondary effects shall be considered for stacks with lateral deflections greater than 12 in. per 100 ft of height. The calculated maximum deflection shall also be considered in evaluating the required clearance for the equipment and structures near 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. Once the deflected outer shell makes contact to the plumbed liners due to wind load, both the outer shell and liners deflect together as a combined section. The outer stack shall be designed to carry all the stresses without any help from liners. However, the liners shall be designed to carry the stresses caused by lateral deflection.

4.5.3 Attachments and/or Contact Points. The design and detailing of attachments and/or contact points to shell and/or liner shall take into account vertical movements and lateral deflections. The lack of proper detailing can put unplanned loads and stresses in the system.

Table 4.4.6-1
Minimum Fabricated Plate Thickness and Maximum Stiffener Spacing

Inside Diameter, D, ft	Minimum Fabricated Plate Thickness, in.	Maximum Stiffener Spacing, ft [Note (1)]
$D \leq 3.5$	0.125	5D
$3.5 < D \leq 8.5$	0.1875	3D
$8.5 < D \leq 18.0$	0.1875	2D
$D > 18.0$	0.25	1½D

NOTE: (1) Equal to or greater if the requirements of paras. 4.3.7 and 4.4.5 are satisfied.

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.

(21) **4.6.2 Flanged Shell Connections.** Generally welded stack splice connections are preferred over bolted splice connections as they provide continuity between stack sections. If bolted shell connections are used the designer should consider the following recommendations:

(a) Bolts are to be designed for both the tension caused by bending moment plus any additional prying force caused by bolt eccentricity and flexure in the connection.

(b) It is recommended that bolt spacing not exceed 6 in. on-center. The designer may consider closer spacing to minimize flange thickness and reduce the risk for leaks.

(c) All bolts shall be tightened in accordance with AISC standards via one of the methods described in para. 8.6.1.

(d) To prevent exhaust gasses from leaking between the flange connection the splice should receive an internal seal weld or be caulked with a suitable grade sealant suitable for both exhaust temperature and flue gas composition.

(e) Flange fabrication tolerances of adjoining sections are such that both the inner and outer surfaces are in contact once the connection is complete for the full circumference of the splice.

(f) Bolts shall be inspected during all routine stack inspections.

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

(21) **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:

$$F_b = \frac{4M_b}{ND_{bc}} - \frac{P}{N} \quad (4\text{-}18)$$

where P and M are factored.

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.

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 False Bottom

False bottom shall be designed to resist all anticipated loads that can be applied. These loads include pressure, live load (see para. 4.3.2), and personnel load. False bottoms can be either sloped or conical in shape. Sloped false bottoms shall have a slope of not less than 5 deg. Sloped false bottoms can be designed as diaphragms or stiffened with beams underneath the false bottom. The Designer is cautioned to ensure that diaphragms or conical false bottoms be designed with a properly sized compression ring to resist the loads at the false bottom to stack junction. The Designer is cautioned to include corrosion allowance in accordance with the process gas that is flowing in the stack. Failures can occur in false bottoms due to heavy ash buildup and subsequent corrosion.

4.10 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 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.

4.11 Guyed Stacks

In a guyed stack, externally applied loads (wind, seismic forces, etc.) are carried by the stack shell as well as by guys in tension. The term "guy wire" refers to wire rope or

Table 4.11.1.3-1
Cable Selection Criteria

Cable Type	Lateral Deflection	Thermal Expansion	Construction
Structural bridge strand	Due to high stiffness, offers good resistance to lateral movement	Due to high stiffness, thermal expansion introduces large stresses into the cables, stack, and foundation	Requires guy fittings for both ends to be installed in shop. Consequently, length adjustment in the field is limited to turnbuckle allowance.
Wire rope	Relatively high flexibility leads to larger deflection	Flexibility is more forgiving for thermal expansion, offering less stress in cables, stack, and foundation	Flexibility allows cable to be supplied longer than required and field adjusted

structural bridge strand. Sometimes it is also referred to as a "stay."

4.11.1 Guy Wire. In design and selection of guy wires, the factors as stated in paras. 4.11.1.1 through 4.11.1.5 should be considered.

4.11.1.1 Guy Wire Spacing and Position. Guy wires are to be equally spaced in plan. A stack may be guyed at one or more levels through its height. A minimum of three cables (at 120 deg from each other around the circumference) is recommended at each level. An angle of 45 deg to 60 deg between the guy and horizontal axis of the stack is typical.

4.11.1.2 Guy Wire Anchorage. Guy cables shall be attached to a fixed and stable structure or foundation often referred to as a dead man. Each set of guy wire anchors should be at the same relative elevation above ground.

4.11.1.3 Guy Wire Material. Guy wires shall be galvanized or protected from corrosion by other suitable means, such as plastic coating or using stainless steel cable strands. The fittings required in the assembly of guy wires shall be galvanized. See Table 4.11.1.3-1 for cable selection criteria, and refer to para. 2.2.4 for more details.

4.11.1.4 Guy Wire Pretensioning/Site Tensioning. Guyed stacks move laterally due to wind. With adequate initial tension in the guys (pretensioning), this movement is reduced. The pretension force as well as the procedure for pretensioning shall be established by the designer. To avoid stretching of the cables during construction, which may alter the design condition, use of prestretched cable is recommended. In the case of hot stacks (over 400°F), the pretension is usually less so that the cable is more forgiving as the stack grows. However, the lateral deflection of the stack will increase due to this reduction in pretension. Consequently, the guyed stack must be analyzed in both hot and cold conditions. A turnbuckle or take-up, typically provided at the guy- wire-to-deadman connection, allows adjustment to the cable to set the pretension. The effect of temperature causing differential thermal expansion in stack and guys shall be considered. The effect of ice on guys shall also be considered. Refer to ASCE 7, Section 10.0 for additional information. The breaking strength (B.S.) of the cables should be based on a minimum factor of safety of 3. The efficiency of the fittings shall also be considered. For detailed information, such as material, size, and strength, refer to the cable manufacturer.

4.11.1.5 Guy Wire Inspection and Maintenance. The guy wires should be inspected frequently. This may comprise visual inspection of the cable or electromagnetic measurement, which estimates the lost metal thickness. For inspection frequency, refer to para. 9.4.1. The pretension of the cables should also be periodically checked and verified. It is recommended that the guy wires be lubricated and tension verified every 5 yr.

4.11.2 Analysis of Guy Wire Stacks. After height and stability considerations, the guy wire levels as well as the number and angle of the guy wires shall be established by the designer. Analysis of a multilevel guy wire stack is very complex due to many variable support conditions. Therefore, timesaving computer modeling for structural analysis is essential. In computer modeling, the following parameters must be considered:

(a) nonlinear cable effects
(b) wind/seismic loads in different directions
(c) thermal expansion of the stack
(d) vortex shedding of guyed stacks

4.11.3 Guy Wire Attachment to Stack. Commercial-rated capacity of the cable shall be used for design of guy wire attachment assembly, including the lug. The stack shell shall be reinforced at the attachment level by using continuous ring and stiffeners as needed.

4.12 Braced and Tower-Supported Stacks

In addition to freestanding stacks on typical ground-based foundation or guyed stacks, a stack may also be supported vertically or laterally at different elevations due to structural reasons surrounding physical constraints and even safety reasons. Understanding advantages and structural characteristics of stack support options are prerequisites for analysis and design of braced or tower-supported stacks.

4.12.1 Types of Supports. There are two types of stack supports: vertical and lateral or braced. Vertical supports may be above ground. Examples of this kind of support would be a stack supported on a steel frame within a structural tower or a stack supported on a floor or on top of a building. Considerations for stacks supported on other structures are discussed in para. 4.12.3.2. Examples of a laterally supported stack would be a stack braced against a building or by a structural tower. A stack may be braced at more than one location. Design considerations for this type of stack are discussed in para. 4.12.3.1. It is very important that any catwalk connecting any building to a stack be of a sliding connection type, where it does not permit any horizontal load transfer between the stack and connecting structure. Otherwise, redistribution of forces and stresses shall be considered in modeling and analysis of the stack. Refer to para. 4.12.3 for further discussion on analysis.

4.12.2 Advantages of Vertically Supported and Braced Stacks. Stacks supported above ground usually have the option of receiving exhaust duct attachment from below, as well as from the sides. A braced stack will require a smaller foundation as compared with a free-standing stack with the same height, since some of the wind load will be transferred to the adjacent bracing structure. Due to the same load transfer, a braced stack also has fewer shell stresses as compared with a free-standing stack, therefore requiring thinner shell or smaller diameter. For multiplatform and tall stacks, sometimes access to the platform can be provided by catwalks from the adjacent building rather than a ladder from ground level. In the case of the tower-supported stacks, the tower also has the advantage of providing an easy and safe framework for staircases and test platforms.

4.12.3 Analysis. The stack should be analyzed based on a model considering rigidity of the supporting structure and connecting component between the stack and supporting structure. Stiffeners are required around the perimeter of the stack to resist the local stresses due to wind or seismic reaction at bracing level.

4.12.3.1 Stacks Supported by Other Structures. Stacks may be laterally supported by other structures, such as towers and buildings. No credit for shielding provided by the bracing building shall be considered when computing design wind. The bracing assembly should allow vertical movement due to thermal expansion. Stacks may also be vertically supported by other structures. For proper analysis, structural interaction between the stack and its supporting structure should be considered.

4.12.3.2 Stacks Supported on Top of Other Structures. Sometimes short and light stacks are supported on top of equipment directly below them. In this case, special attention shall be given to ensure proper base attachment and load transfer to the supporting equipment. When possible, the designer may consider placement of an independent structural frame to support the stack and using an expansion joint under the stack to connect the stack to the equipment without any load transfer between them. Where feasible, a stack may also be supported on a building roof or supported on a floor penetrating, and braced at, the roof. In either case, the base support condition shall be evaluated.

4.13 Stacks with Refractory-Concrete Lining (21)

In stacks subject to high operation temperatures, refractory-concrete lining is often used as a protective barrier for the shell plate and all internal components exposed to high heat. Chemical compositions, classifications, and characteristics of different types of linings are described in section 3 and Nonmandatory Appendix C, Tables C-1 and C-2. Structural effects of refractory-concrete linings shall be considered in the design of steel stacks.

4.13.1 Maintenance and Inspection Considerations. Brick and castable are two general types of concrete refractory used in steel stacks. For inspection of refractory linings, see para. 9.4.3(c).

4.13.2 Structural Considerations. Although refractory-concrete lining is heavy and thick compared to the stack shell plates, the strength of the refractory-concrete shall not be considered in the design of the shell plate.

4.13.2.1 Dead Load. The weight of refractory-concrete lining is generally much greater than stack shell plates. The additional weight shall be considered in the design of shell plates and the stack structural components.

4.13.2.2 P-Delta Effect. Stresses due to P-Delta effect shall be added to the stresses calculated for wind or seismic loads since P-Delta loads are much greater in refractory-concrete lined stacks than unlined stacks.

4.13.2.3 Frequency. Although the strength of refractory-concrete lining is not considered in the design of stack shell plates, it will affect the natural frequency and therefore, the structural character of the stack.

4.13.2.4 Seismic. Seismic force on any structure is a function of its mass. Therefore, the heavy weight of refractory-concrete lining can substantially increase the seismic forces on the stack and its components. See para. 4.3.4 for additional seismic considerations.

(21) ## 4.14 Symbols and Definitions for Section 4

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), ft

B.S. = breaking strength

$\bar{b}$ = coefficient given in Mandatory Appendix I, Table I-1

c = coefficient given in Mandatory Appendix I, Table I-1

C_f = force coefficient given in Mandatory Appendix I, Table I-4

D = diameter of stack at elevation under consideration, in.

D_{bc} = diameter of anchor bolt circle, 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 Mandatory Appendix I, Figure I-1, ft

h = height of stack, ft

$I_{section}$ = 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 = circumferential stress coeffecient

K_z = velocity pressure exposure coefficient evaluated at height z

K_{zt} = topographic factor for along wind pressure calculation

K_1, K_2, K_3 = topographic multipliers given in Mandatory Appendix I, Figure I-1

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 hill crest or escarpment in Mandatory Appendix I, Figure I-1 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 = factored 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

P = factored dead load of stack above elevation under consideration, lb

Q = background response factor

q_z = external wind pressure on stack shell at elevation under consideration, psf

R = resonant response factor

R_B, R_h, R_d = resonance response factors used in Mandatory Appendix I

R_n = value obtained from equation in Mandatory Appendix I

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

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-sec gust speed at 33 ft above ground in exposure category C, mph

$\overline{V}_{\bar{z}}$ = mean hourly wind speed, ft/sec

$w(z)$ = total along-wind unfactored load on stack per unit height, lbf/ft

$\overline{w}(z)$ = mean along-wind unfactored load on stack per unit length, lbf/ft

$w_{D(z)}$ = fluctuating along-wind load on stack per unit height, lbf/ft

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 Mandatory Appendix I, Table I-1

β = total damping value

$\bar{\varepsilon}$ = coefficients given in Mandatory Appendix I, Table I-1
η = coefficient used to calculate the resonant response factor

5 DYNAMIC WIND LOADS

5.1 Scope

Section 5 considers the dynamic wind load effects on steel stacks. Since steel stacks are lightweight, flexible structures with low inherent structural damping, 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.

(21) **5.2.1.1 Frequencies.** Stack frequencies and corresponding mode shapes are a function of the stack configuration, distribution of self-weight and added dead load, and the vertical and lateral support conditions. The frequencies and mode shapes shall be calculated using a suitable mathematical modeling method.

5.2.1.2 Mathematical Modeling. Appropriate detailed calculation methods shall be used for dynamic analysis of more complex configurations. These configurations include, but are not limited to stacks with variable diameters and thickness, stacks with inner liners, guyed or laterally supported stacks, derrick-supported stacks, multiple-flue 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 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 that disrupt vortex formation, although the last may, in fact, reduce the damping.

For wind loads, the structural damping values, β_s, shown in Table 5.2.1.2-1 have been observed for steel stacks. Damping values other than those shown in Table 5.2.1.2-1 may be used for support conditions that have inherently large damping or use 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.

5.2.1.3 Aerodynamic Damping. Aerodynamic damping shall also be considered. The aerodynamic damping value, β_a, is calculated as follows: (21)

(a) For along wind response

$$\beta_a = \frac{C_f \rho \bar{D} \overline{V_{\bar{z}}}}{4\pi m_a n_1 \sqrt{1.6}} \tag{5-1}$$

(b) For a crosswind motion response, the effects of the aerodynamic damping are included in the procedures described in Nonmandatory Appendix E.

The total damping shall be as follows:

$$\beta = \beta_s + \beta_a \tag{5-2}$$

5.2.2 Wind Responses (21)

(a) *Vortex Shedding.* Across wind loads for plumb or nearly plumb (less than ±10% diameter variation over the top one-third) stacks, the mean hourly speed at five-sixth 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

$$V_c = n_1 \bar{D}/S \tag{5-4}$$

(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 long wind loads.

(2) Vortex shedding loads shall be calculated for all modes of vibration where $V_{z_{cr}} < V_c < 1.2V_{z_{cr}}$. 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 $V_c > 1.2V_{z_{cr}}$, then response vortex shedding can be ignored.

Table 5.2.1.2-1
Representative Structural Damping Values, β_s

Support Type Welded Stack	Damping Value: Rigid Support [Note (1)]	Damping Value: Elastic Support [Note (2)]
Unlined	0.002	0.004
Lined [Note (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 100 pcf density liner material for stack to be considered lined for the use of this table.

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 $\overline{V}_{\overline{z}}/\sqrt{1.6}$, the unlined stack should be reinforced with ring stiffeners meeting the requirements of Table 4.4.6-1. 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, $\bar{D}$, of the obstructed stack is less than 15, the Strouhal number, S, shall be determined from eq. (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 $1.2V_{z_{cr}}$ for wind directions near the line of the stacks.

(1) For $A/\overline{D} \leq 15$

$$S = 0.16 + \frac{1}{300}\left(\frac{A}{\overline{D}} - 3\right) \tag{5-8}$$

(2) For $A/\overline{D} > 15$

$$S = 0.20$$

(3) 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, damping, 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.

5.3.1.1 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 one-tenth diameter from the aerodynamic diameter. Strakes of adequate structural thickness should be provided on the top one-third 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 × 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.

5.3.1.2 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.

5.3.2.1 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.

5.3.2.2 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.

5.3.2.3 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 $1.2V_{z_{cr}}$ or lower the critical velocity to an acceptable level.

(21) 5.4 Symbols and Definitions for Section 5

A = horizontal distance between stacks centerlines, ft

$\bar{b}$ = coefficient given in Mandatory Appendix I, Table I-1

C_f = force coefficient given in Mandatory Appendix I, Table I-4

D = diameter of stack at elevation under consideration, ft

$\overline{D}$ = mean diameter for the segment z_1 to z_2 or for stacks ±10% variation over the top one-third the value of $\overline{D}$ is the average over the top one-third, ft

f_0 = ovalling natural frequency of the stack, Hz

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 one-third 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-sec gust speed at 33 ft above ground in exposure category C, mph

V_c = critical wind speed for vortex shedding, ft/sec

V_R = service level basic wind speed, mph = $V/\sqrt{1.6}$

$\overline{V}_{\overline{z}}$ = mean hourly wind speed, ft/sec

$V_{z_{cr}}$ = mean hourly wind speed at z_{cr}, ft/sec

v_{co} = ovalling critical wind velocity, ft/sec

z_{cr} = elevation equal to five-sixth stack height, ft

$\bar{\alpha}$ = coefficients given in Mandatory Appendix I, Table I-1

β = total damping value

β_a = aerodynamic damping value

β_s = structural damping value

π = pi (3.141593)

ρ = density of air, lbm/ft^3

σ_a = allowable tensile stress in stack stiffener, psi

6 ACCESS AND SAFETY

6.1 Scope

Section 6 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 this 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 be in accordance with AWS D1.1/D1.1M or ASME BPVC, Section IX.

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

(21) #### 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 Figure 6.2.6-1).

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.

fall protection: any equipment, device, or system that prevents a person from falling from an elevation or mitigates the effect of such a fall.

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.

guardrail system: a barrier erected along an unprotected or exposed side, edge, or other area of a walking-working surface to prevent employees from falling to a lower level.

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

ladder safety system: an assembly of components whose function is to arrest the fall of a user, including the carrier and its associate attachment elements (brackets, fasteners, etc.), safety sleeve, full body harness and connectors, wherein the carrier is permanently attached to the climbing face of the ladder or immediately adjacent to the structure. A cage is not a ladder safety device.

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.

lower level: a surface or area to which a person could fall. Such surfaces or areas include, but are not limited to, ground levels, floors, roofs, equipment, and similar surfaces and structures, or portions thereof. The lower level shall be of sufficient size and strength such that a person cannot fall beyond this surface.

opening: a gap or open space in a wall, walking-working surface, or similar surface that is at least 30 in. high and at least 18 in. wide, through which a person can fall to a lower level.

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 Figure 6.2.6-2).

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.

single length of climb: the vertical distance travelled on a ladder from a lower level to the top of a landing or platform in which the person must exit the ladder.

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

unprotected sides and edges: any side or edge of a walking-working surface (except an entrance and other points of access) where there is no wall, or guardrail system to protect a person from falling to a lower level.

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 (21)

6.3.1 Application. This section applies to new fixed ladders, permanently attached to the stack or structure, on new or existing steel stacks. Ladders used for steel stack access must conform to ANSI A14.3.

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.

Figure 6.2.6-1
Example of the General Construction of Cages

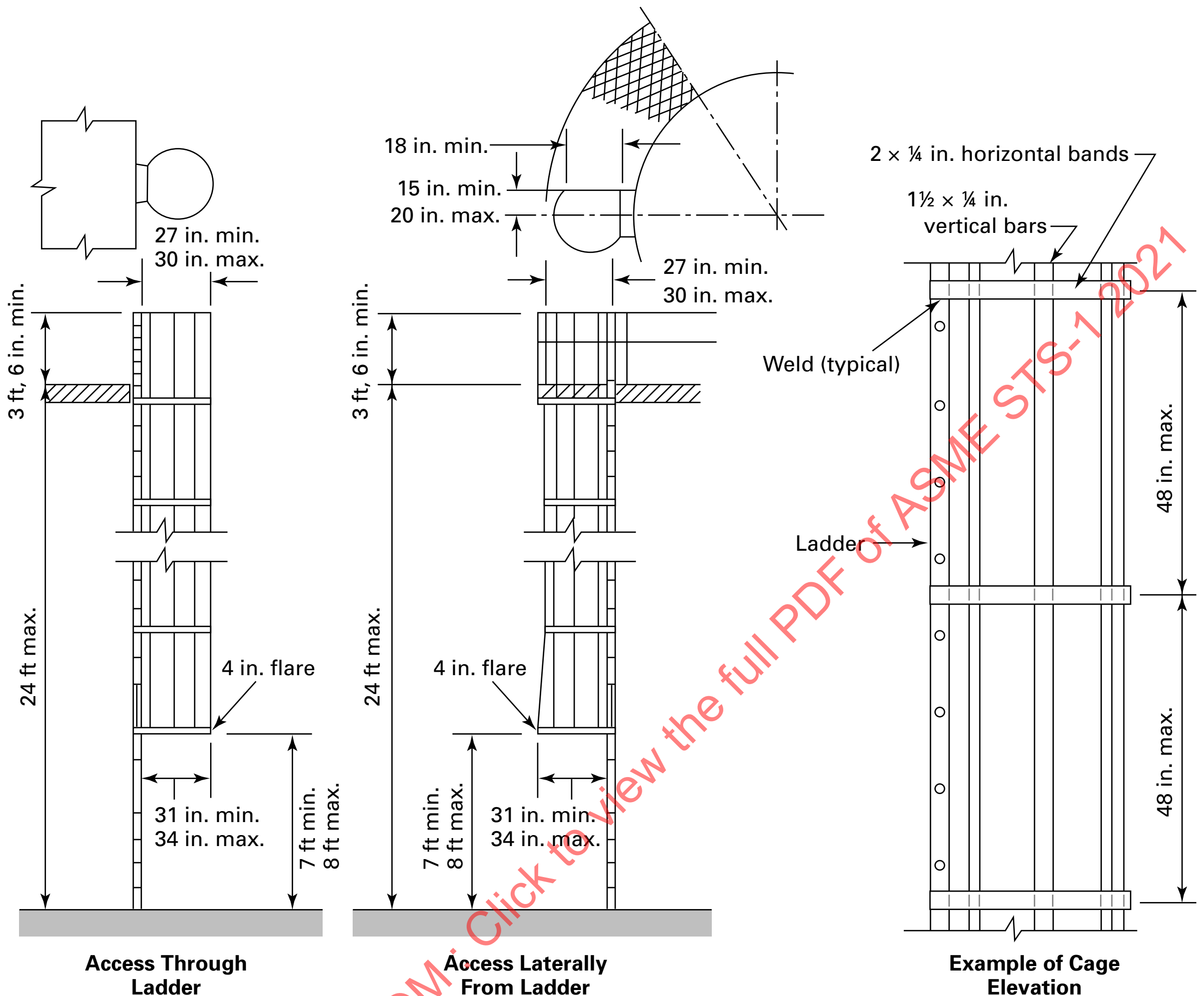
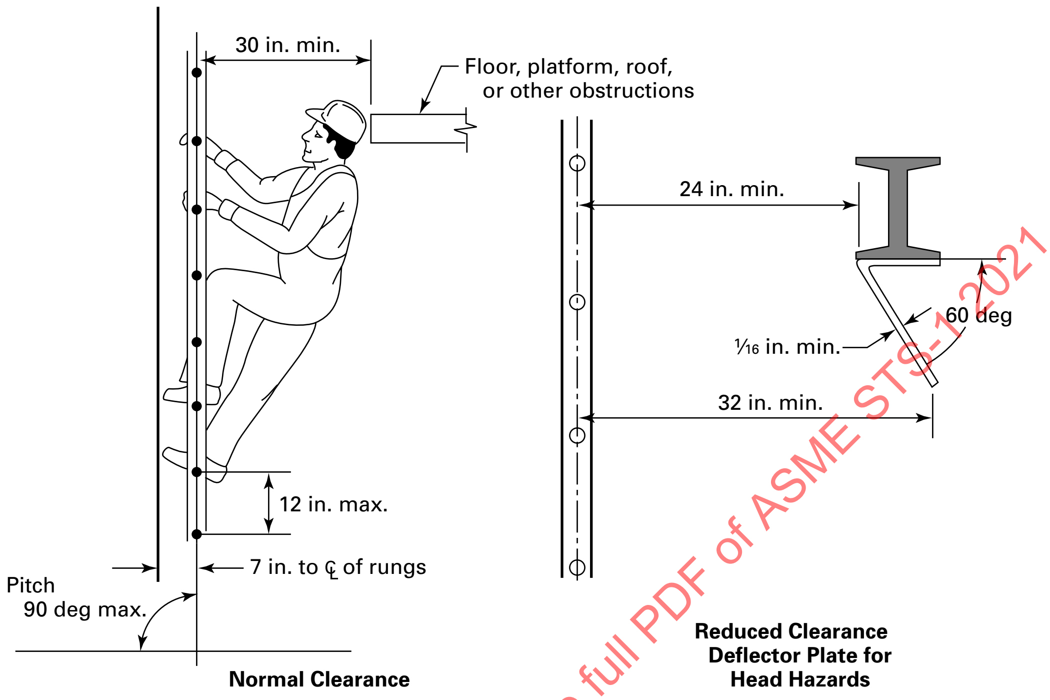


Figure 6.2.6-2
Minimum Ladder Clearances



(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 be not such that a person's position is below the ladder when climbing. (See definition of pitch in para. 6.2.6 and Figure 6.2.6-2.)

6.3.6 Clearances. The distance from the centerline of the rungs to the nearest permanent object on the climbing side of the ladder shall be not less than 36 in. for a pitch of 75 deg and 30 in. (see Figure 6.2.6-2).

(a) The distance from the centerline of the rungs to the nearest permanent object on the opposite (back) side shall be not less than 7 in. (see Figure 6.2.6-2).

(b) A clear side-to-side width of at least 15 in. shall be provided each way from the centerline of the ladder in the climbing space, except when cages are used (see Figure 6.3.6-1).

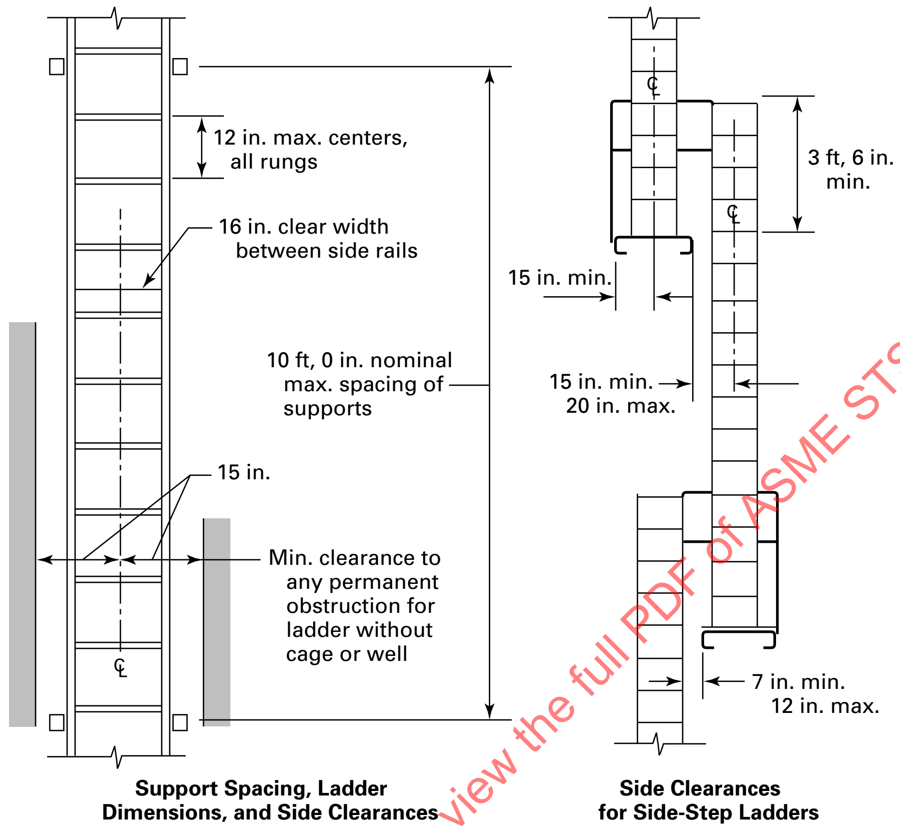
(c) The distance from the centerline of a grab bar to the nearest permanent object in the back of the grab bar shall be not less than 4 in. The grab bars shall not protrude on the climbing side beyond the rungs of the ladder that they serve.

6.3.7 Caged Ladders and Ladder Safety System Length of Climb. A description of the permissible length of climb is provided below for the different ladder configurations presented in Figure 6.3.7-1.

(a) A cage or ladder safety system is not required where the length of climb is 24 ft or less above a ground level, floor, or roof. See Figure 6.3.7-1, illustration (a).

(b) A cage or ladder safety system shall be provided where the length of climb is less than 24 ft, but the top of the ladder is at a distance greater than 24 ft above a ground level, floor, or roof. See Figure 6.3.7-1, illustration (b).

Figure 6.3.6-1
Ladder Dimensions, Support Spacing, and Side Clearances



(c) A ladder safety system shall be provided where a single length of climb is greater than 24 ft. See Figure 6.3.7-1, illustration (c).

(d) Multiple sections of ladders having all single length of climbs not exceeding 24 ft shall be provided with a cage or ladder safety system. See Figure 6.3.7-1, illustration (d). Refer to paras. 6.3.8(c) and 6.3.11(h) for landing requirements when caged ladders are used.

(e) Multiple sections of ladders having at least one single length of climb exceeding 24 ft shall be provided with a ladder safety system in place of a cage. The ladder safety system shall be provided throughout the length of climb. See Figure 6.3.7-1, illustration (d).

(f) Ladders equipped with a ladder safety system shall have rest platforms at maximum intervals of 150 ft. See Figure 6.3.7-1, illustration (e).

(g) When a ladder safety system is combined with a cage, the maximum single length of climb shall not exceed 50 ft.

6.3.8 Landing (Rest) Platforms. The requirements for landing (rest) platforms are provided below.

(a) Landing platforms shall be provided at intervals such that the maximum single length of climb provided in para. 6.3.7 is not exceeded.

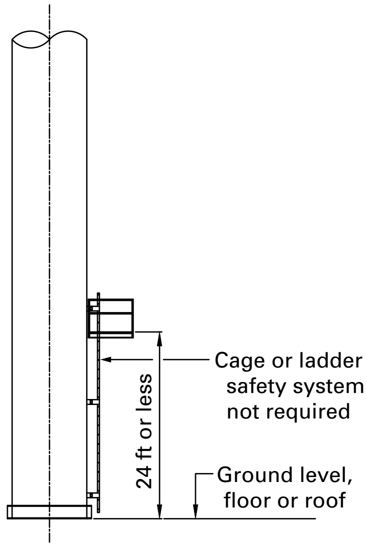
(b) The total depth of platform shall provide a minimum space of 30 in. from the ladder on the climbing side. The width of the platform shall be not less than 30 in.

(c) To prevent falls, landing platforms for caged ladders shall use additional guarding on railings adjacent to the side of the ladder and within 4 ft from the center line of the rung, unless otherwise protected. The descending ladder and swing gate placed at the ladder opening shall be offset in such a manner that it is not reasonably possible for a person to fall past the platform.

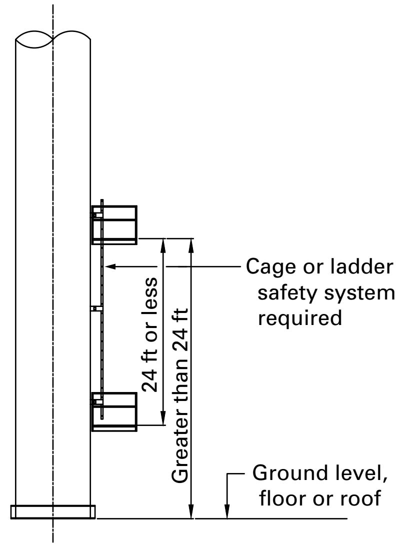
(d) The grating and structural requirements for landing platforms shall be the same as work platforms (see para. 6.4).

6.3.9 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 handholds (grab bars) are fixed at such places.

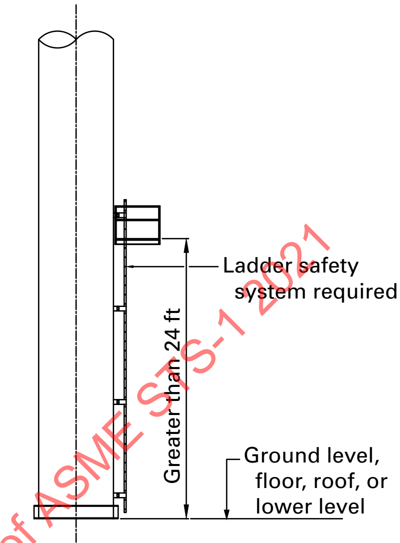
Figure 6.3.7-1
Length of Climb



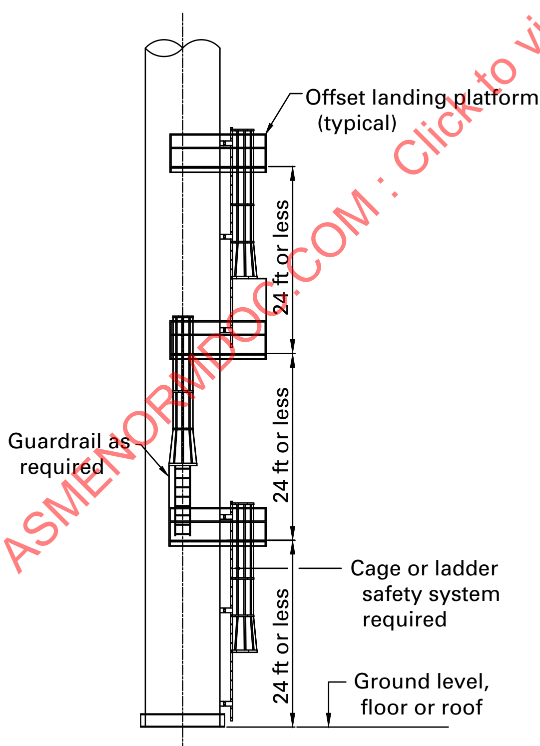
(a) Single Length of Climb 24 ft or Less



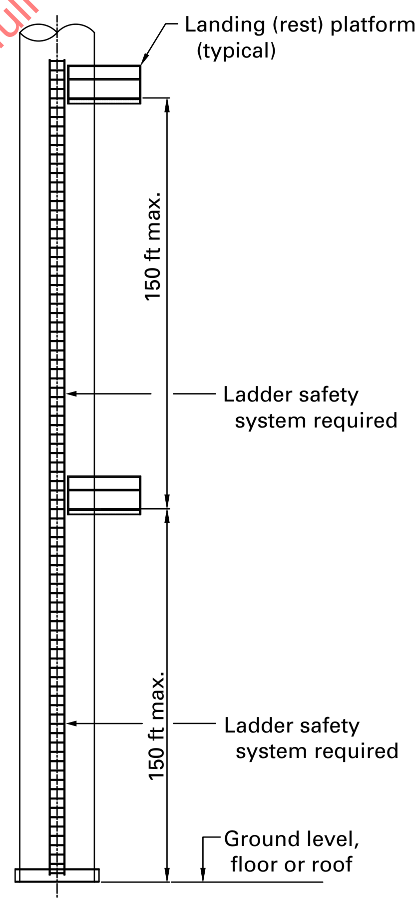
(b) Length of Climb 24 ft or Less With Elevated Access



(c) Single Length of Climb Greater Than 24 ft



(d) Multi-section Ladder 24 ft Max. Single Length of Climb [Note (1)]



(e) Total Length of Climb Greater Than 24 ft

NOTE: (1) Should any single length of climb exceed 24 ft, a ladder safety system is required for the full height in place of cage.

(a) For step-through ladders, the rungs shall be omitted from this extension. For step-through ladders, the step-across distance from the centerline of the rung to the nearest edge of the structure, building, or equipment shall be not 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 Figure 6.3.9-1).

(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 centerline of the ladder. For side-step landings, the platform shall be located at the same level as one of the rungs.

6.3.10 Ladder Safety System. The design requirements and other considerations when using a ladder safety system are provided below.

(a) A ladder safety system can be used as a fall protection on ladders without the use of a cage barrier. All components of the ladder safety system shall meet the requirements of ANSI ACS A14.3. Any system used on a steel stack shall meet the design and testing requirements of this Standard.

(b) The installation of a ladder safety system shall be per the manufacturer's installation guidelines.

(c) Individuals using ladder safety systems shall be protected from fall hazards during the process of connecting and disconnecting (transitioning) from the ladder safety system. A suitable anchor point accessible from the ladder shall be used to connect the fall protection system when transitioning.

(d) Special consideration shall be given to increased possibility of corrosion at the top of stacks resulting from exposure to stack exhaust gases.

6.3.11 Caged Ladders. The requirements for a caged ladder are provided below.

(a) The top of the cage shall be a minimum of 3 ft 6 in. above the top of the landing unless other acceptable protection is provided.

(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.

(c) Cages shall not extend less than 27 in. or more than 30 in. from the centerline of the rungs of the ladder. Cages shall be not less than 27 in. wide. 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 2 in. × $\frac{1}{4}$ in. minimum with a maximum spacing of 4 ft on centers.

(e) Vertical bars shall be $1\frac{1}{2}$ in. × $\frac{3}{16}$ 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 located in such a way 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) When a caged ladder system is combined with a ladder safety device, the cage cannot interfere with the person or the operation of the ladder safety system. A larger cage system may be required.

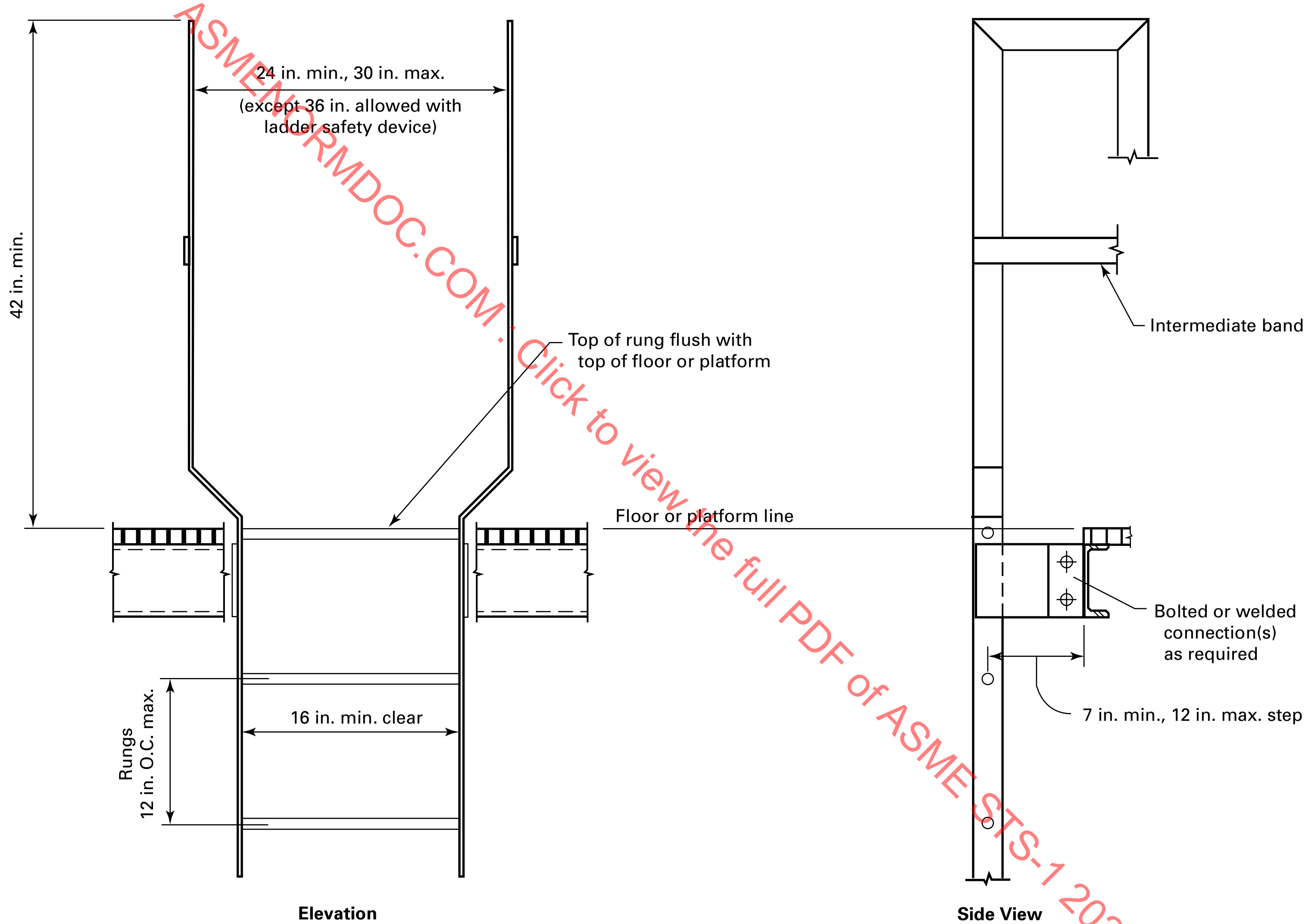
(h) When a cage is used, each section of ladder shall be horizontally offset from the adjacent sections with sufficient clearances. A landing platform shall be provided for safe access/egress with appropriate clearances to protect the user.

6.3.12 Siderails. The siderails shall be of flat bar stock and not be less than $2\frac{1}{2}$ in. × $\frac{3}{8}$ in. If siderails of other cross sections are desired, they shall be at least equal in strength to the above-sized steel bar. For additional load concentrations, attachment of ladder safety systems, or for spacing of supports that exceeds the maximum spacing recommended, the maximum size of siderails shall be increased in accordance with recognized design practices.

6.3.13 Rungs. Rungs shall be not less than ¾ in. in diameter. For ladders exposed to unusually corrosive atmospheres, rungs shall be of at least 1 in. diameter solid bars. Spacing of rungs shall not exceed 12 in. center-to-center and shall be spaced uniformly throughout the length of the ladder. For additional load concentrations or attachment of ladder safety systems, and for clear widths exceeding 16 in., the minimum size (cross section) of steps and rungs shall be increased in accordance with recognized design practices. 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 Supports. Ladder supports shall be of steel at least equivalent to the siderails in strength. Ladder supports may be bolted or welded. Ladder supports shall be not more than 10 ft apart based on the size of the siderail recommended. For additional load concentrations, attachment of ladder safety systems, or for variations in size (cross section) of siderails, the spacing of supports shall be adjusted in accordance with recognized design practices. Anchorage of ladders must account for the thermal growth of the stack.

Figure 6.3.9-1
Landing Platform Dimensions



GENERAL NOTES:
(a) All weld connections are to be ground smooth.
(b) Thermal expansion and lateral movement should be considered for all connections.

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-ft^2 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 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 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.

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.

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.

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 — 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. × 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 section 7 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 establish a standard as it relates to such items.

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 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 FAA AC 70/7460-1K. 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 used on short stacks with FAA approval.

(b) Aviation Red Obstruction Lights. Aviation red obstruction lights mounted on the stack at required elevations and specific positions around the circumference should be as required by FAA AC 70/7460-1K. 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. FAA AC 70/7460-1 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 specific positions around the circumference as required by FAA AC 70/7460-1K. This type of system is used with a light sensitive control device, which faces the north sky to control intensity.

(e) Dual Lighting With Red/Medium Intensity White Obstruction Lights. This lighting system is a combination of the red-and-white lighting systems defined in (b) and (c). A dual lighting system is most commonly used in populated areas where the use of less conspicuous red lights at night is preferred. Using white lights during daylight hours negates the need to paint the stack with obstruction markings.

7.3.3 System Access Location. Access to lights for maintenance may be by ladders and platform or by a lowering device that 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 requirements for metal stacks, as covered in NFPA 780, 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: 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.

8 FABRICATION AND ERECTION

8.1 Purpose

Section 8 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 multiflue steel stacks and applies to stacks that are free standing, self supported, guy or cable supported, or supported by structural steel braces or framework. These guidelines also pertain to shop or field fabrication and to field erection.

8.3 Welding

AWS D1.1/D1.1M or ASME BPVC, 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) Visual inspections shall be made for all welds during the welding operation and again after the work is completed to determine that thorough fusion exists between adjacent layers of weld metal and between the weld and base metals. After the welding is completed, slag shall be removed from all welds. The weld and adjacent weld metal shall be cleaned by brushing or other suitable means. The inspector shall pay particular attention to surface cracking, surface porosity, surface slag inclusion, undercut, overlap, gas pockets, and size of welds. Defective welding shall be corrected according to ASME or AWS Code requirements.

(b) A minimum of one radiograph per each three shop circumferential seams on the stack structural shell shall be made, preferably at the vertical weld intersection. The inner or outer shell shall be considered structural when it is designed to resist the controlling wind or seismic load.

(c) All structural full penetration field welds should be visually inspected. Radiographs of shell or flue field splice welds 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) Visual Inspection. This procedure is to be performed on all shop and field welds.

(c) Magnetic Particle Inspection. This procedure can be used on all ferromagnetic material welds.

(d) Ultrasonic Inspection. This procedure can be used on all shop butt welds ≥5/16 in.

(e) Dye Penetrant Inspection. This procedure shall be used as required to supplement the visual inspection. The standard methods set forth in AWS D1.1/D1.1M 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 3/4	1/4 (*t*) [Note (1)]
3/4 to 1 1/2	3/16 in.

NOTE: (1) t = normal thickness of the thinner plate at the joint, in.

(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 1/4 in. (6 mm) maximum as measured from an 18-in.-long (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) At the time of erection, the difference between the maximum and minimum inside diameters at any cylindrical shell cross section along the height shall not exceed 1% of the diameter.

(e) Local dents in plates shall be no deeper than one-half the plate thickness.

8.6 Shop Fabrication and Field Erection

8.6.1 During the assembly of bolted connections (21)

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

(b) A-325 and A-490 bolts used for flanged shell connections shall be brought to a snug-tight condition as defined in AISC. When pretensioning is specified by the engineer, bolts shall be tightened using one of the following:

(1) turn-of-the-nut method
(2) calibrated wrenches
(3) twist-off-type tension control
(4) direct-tension-indicator washers

Preinstallation testing shall be appropriate for the method used. Refer to Research Council on Structural Connections (RCSC).

(c) Bolts used for connecting appurtenances, including platforms and ladders, shall be snug-tight unless the joint design requires one of the following:

(1) slip-type connection to allow for thermal expansion or differential movement

(2) pretension or slip-critical connections to avoid significant load reversal

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 or panel butt weld seams are to be staggered a minimum of 20 deg. All welded cylindrical sections joined to other cylindrical 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 the latest applicable and/or specified codes.

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 top of the foundation shall be grouted. The grout shall be a nonshrink 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 positioned so 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.

For a database systematic inspection procedure and technique, the reader is referred to ASCE Chimney and Stack Inspection Guidelines.

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

(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

(k) loosening of splice/flanged bolts

(l) formation of "hot spots" on the shell of stacks with internal lining

(m) separation of ladder supports from the stack shell

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 (e.g., 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 3 yr. The results of these inspections should then determine the frequency of future inspections.

(21) **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, and platforms shall be inspected to ensure 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) Bolts. All bolts including 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) Linings and Coatings. These components of the stack are the most critical in terms of wear, cracks, spalls, and other deficiencies. Such deficiencies are often hidden by overlaying particulate deposits, and, therefore, proper care shall be exercised to detect deficiencies. It is suggested that pH readings be taken in areas where there is evidence of chemical corrosion. pH readings may be taken by chemical analysis of representative samples of scrapings from lining surfaces or by any other conventional method.

(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 (21)

(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) Since the main purpose of the refractory-concrete lining is to protect the steel shell from extreme heat, it is important to ensure that the integrity of the lining is not compromised. Spot discoloration of the outside of the stack, or local deformed shell plate are signs of potential lining damages. 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 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, bolted field splice connections, cleanout door, ladder, caps, lightning protection system, and any other hardware items.

(21) **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 conditions 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 (if recorded), 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.

(21) **9.5.3 Anchor Bolts.** Areas around the anchor bolts shall be kept clean and free of particle deposits and moisture. Anchor bolts should be periodically inspected and retightened if necessary.

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.

(21) # 10 REFERENCES

The following is a list of publications referenced in this Standard. Unless otherwise specified, the latest edition shall apply.

29 CFR, Part 1910 Occupational Safety and Health Standards
Code of Federal Regulations
Publisher: Occupational Safety and Health Administration (OSHA), U.S. Department of Labor, 200 Constitution Avenue, Washington, DC 20210 (www.osha.gov)

AC 70/7460-1M, Obstruction Marking and Lighting
Publisher: U.S. Department of Transportation, 1200 New Jersey Avenue, S.E., Washington, DC 20590 (www.transportation.gov)

ACI 307-08, Code Requirements for Reinforced Concrete Chimneys
Publisher: American Concrete Institute (ACI), 38800 Country Club Drive, Farmington Hills, MI 48331 (www.concrete.org)

AISC Manual of Steel Construction
Publisher: American Institute of Steel Construction (AISC), 130 East Randolph Street, Suite 2000, Chicago, IL 60601 (www.aisc.org)

ANSI ASC A14.3, Ladders — Fixed — Safety Requirements
Publisher: American National Standards Institute (ANSI), 25 West 43rd Street, New York, NY 10036 (www.ansi.org)

NFPA 780, Lightning Protection Code
NFPA 70, National Electrical Code
Publisher: National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471 (www.nfpa.org)

ASCE 7-10 and ASCE 7-16, Minimum Design Loads for Buildings and Other Structures

NOTE: Use adopted edition in jurisdiction of the facility.

ASCE Chimney and Stack Inspection Guidelines: Design and Construction of Steel Chimney Liners, 1975
Chimney and Stack Inspection Guidelines
The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications, 1995
Publisher: American Society of Civil Engineers (ASCE), 1801 Alexander Bell Drive, Reston, VA 20191 (www.asce.org)

ASHRAE Handbook
Publisher: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329 (www.ashrae.org)

ASME Technical Paper, 65WA/FU5
ASME Boiler and Pressure Vessel Code (BPVC), Section I
ASME Boiler and Pressure Vessel Code (BPVC), Section II
Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

ASTM A20/A20M, Standard Specification for General Requirements for Steel Plates for Pressure Vessels
ASTM A36/A36M, Standard Specification for Carbon Structural Steel
ASTM A193/A193M, Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications
ASTM A203/A203M, Standard Specification for Pressure Vessel Plates, Alloy Steel, Nickel
ASTM A240/A240M, Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications

ASTM A242/A242M, Standard Specification for High-Strength Low-Alloy Structural Steel
ASTM A247, Standard Test Method for Evaluating the Microstructure of Graphite in Iron Castings
ASTM A264, Standard Specification for Stainless Chromium-Nickel Steel-Clad Plate
ASTM A265, Standard Specification for Nickel and Nickel-Base Alloy-Clad Steel Plate
ASTM A283/A283M, Standard Specification for Low and Intermediate Tensile Strength Carbon Steel Plates
ASTM A285/A285M, Standard Specification for Pressure Vessel Plates, Carbon Steel, Low- and Intermediate-Tensile Strength
ASTM A307, Standard Specification for Carbon Steel Bolts, Studs, and Threaded Rod 60 000 PSI Tensile Strength
ASTM A325, Standard Specification for Structural Bolts, Steel, Heat Treated, 120/105 ksi Minimum Tensile Strength
ASTM A354, Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners
ASTM A368, Standard Specification for Stainless Steel Wire Strand
ASTM A378, Standard Specification for Flat-Rolled Electrical Steel (Withdrawn 1955)
ASTM A387/A387M, Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum
ASTM A449, Standard Specification for Hex Cap Screws, Bolts and Studs, Steel, Heat Treated, 120/105/90 ksi Minimum Tensile Strength, General Use
ASTM A463/A463M, Standard Specification for Steel Sheet, Aluminum-Coated, by the Hot-Dip Process
ASTM A474, Standard Specification for Aluminum-Coated Steel Wire Strand
ASTM A475, Standard Specification for Zinc-Coated Steels Wire Strand
ASTM A490, Standard Specification for Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints
ASTM A515/A515M, Standard Specification for Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service
ASTM A516/A516M, Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service
ASTM A517/A517M, Standard Specification for Pressure Vessel Plates, Alloy Steel, High-Strength, Quenched and Tempered
ASTM A527/A527M, Specification for Steel Sheet, Zinc-Coated (Galvanized) by the Hot-Dip Process, Lock-Forming Quality
ASTM A529/A529M, Standard Specification for High-Strength Carbon-Manganese Steel of Structural Quality
ASTM A537/A537M, Standard Specification for Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon Steel
ASTM A554, Standard Specification for Welded Stainless Steel Mechanical Tubing
ASTM A563, Standard Specification for Carbon and Alloy Steel Nuts
ASTM A569/A569M, Standard Specification for Steel, Carbon (0.15 Maximum, Percent), Hot-Rolled Sheet and Strip Commercial Quality
ASTM A570, Standard Specification for Hot-Rolled Carbon Steel Sheet and Strip, Structural Quality
ASTM A572, Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel
ASTM A586, Standard Specification for Zinc-Coated Parallel and Helical Steel Wire Structural Strand
ASTM A588, Standard Specification for High-Strength Low-Alloy Structural Steel, up to 50 ksi [345 MPa] Minimum Yield Point, With Atmospheric Corrosion Resistance
ASTM A603, Standard Specification for Zinc-Coated Steel Structural Wire Rope
ASTM A606/A606M, Standard Specification for Steel, Sheet and Strip, High-Strength, Low-Alloy, Hot-Rolled and Cold-Rolled, With Improved Atmospheric Corrosion Resistance
ASTM A607, Standard Specification for Steel Sheet and Strip, Hot-Rolled and Cold-Rolled, High-Strength, Low-Alloy Columbium and/or Vanadium
A618/A618M, Standard Specification for Hot-Formed Welded and Seamless High-Strength Low-Alloy Structural Tubing
ASTM A666, Standard Specification for Annealed or Cold-Worked Austenitic Stainless Steel Sheet, Strip, Plate, and Flat Bar
ASTM A687, Standard Specification for High-Strength Nonheaded Steel Bolts and Studs
ASTM B209, Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate
ASTM B221 Standard Specification for Aluminum and Aluminum-Alloy Extruded Bars, Rods, Wire, Profiles, and Tubes
ASTM C279, Standard Specification for Chemical-Resistant Masonry Units
ASTM C980, Standard Specification for Industrial Chimney Lining Brick
ASTM F436/F436M, Standard Specification for Hardened Steel Washers Inch and Metric Dimensions
ASTM F593, Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs
ASTM F1554, Standard Specification for Anchor Bolts, Steel 36, 55, and 105-ksi Yield Strength
ASTM F3125/F3125M, Standard Specification for High Strength Structural Bolts and Assemblies, Steel and Alloy Steel, Heat Treated, Inch Dimensions 120 ksi and 150 ksi Minimum Tensile Strength, and Metric Dimensions 830 MPa and 1040 MPa Minimum Tensile Strength

Permanence of Organic Coatings (STP-1)
Publisher: American Society for Testing and Materials (ASTM International), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959 (www.astm.org)

AWS A5.1/A5.1M, Specification for Covered Carbon Steel Arc Welding Electrodes
AWS A5.4/A5.4M, Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding
AWS A5.9/A5.9M, Specification for Bare Stainless Steel Welding Electrodes and Rods
AWS A5.11/A5.11M, Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding
AWS A5.14/A5.14M, Specification of Nickel and Nickel Alloy Bare Welding Electrodes and Rods
AWS A5.18/A5.18M, Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding
AWS A5.20/A5.20M, Specification for Carbon Steel Electrodes for Flux Cored Arc Welding
AWS D1.1/D1.1M, Structural Welding Code — Steel
AWS D1.6/D1.6M, Structural Welding Code — Stainless Steel
AWS D10.8, Recommended Practice for Welding of Chromium-Molybdenum Steel Piping and Tubing
Publisher: American Welding Society (AWS), 8669 NW 36 Street, No. 130, Miami, FL 33166 (www.aws.org)

Chimney Coatings Manual, 1996
Model Code For Steel Chimneys, 1999, Revision 1, Amendment A
Publisher: International Committee on Industrial Chimneys (CICIND), Preussenstrasse 11, D-40883 Ratingen, Germany (www.cicind.org)

Coatings and Linings Handbook
Publisher: National Association of Corrosion Engineers (NACE International), 15835 Park Ten Place, Houston, TX 77084-4906 (www.nace.org)

Design and Evaluation Guidelines For Department of Energy Facilities Subjected to Natural Phenomena Hazards, UCRL-15910, 1990
Publisher: U.S. Department of Energy, Office of Safety Appraisals, 1000 Independence Avenue, S.W., Washington, DC 20585 (www.energy.gov)

Entrainment in Wet Stacks, CS-2520, 1982
Publisher: Electric Power Research Institute (EPRI), 3420 Hillview Avenue, Palo Alto, CA 94304 (www.epri.com)

Formulas for Stress and Strain, 1965, 5th ed.
Mechanical Vibrations, 1948, 3rd ed.
Structural Engineering Handbook
Roark's Formulas for Stress and Strain, 2001, 8th ed.
Wind Effects on Structures, 1978
Publisher: McGraw-Hill Co., P.O. Box 182605, Columbus, OH 43218 (www.mhprofessional.com)

Good Painting Practice, Steel Structures Painting Manual, Vol. 1
Systems and Specifications, Steel Structures Painting Manual, Vol. 2
Publisher: SSPC: The Society for Protective Coatings, 800 Trumbull Drive, Pittsburgh, PA 15205 (www.sspc.org)

Guide for Steel Stack and Duct Design Construction
Publisher: Sheet Metal and Air Conditioning Contractors' National Association (SMACNA), 4201 Lafayette Center Drive, Chantilly, VA 20151 (www.smacna.org)

National Building Code
Publisher: Building Officials and Code Administrators (BOCA), 4051 W. Flossmoor Road, Country Club Hills, IL 60478 (www.iccsafe.org)

National Building Code Of Canada
Publisher: National Research Council of Canada (NRCC), 1200 Montreal Road, Building M-58, Ottawa, ON, K1A 0R6 Canada (nrc.canada.ca/en)

Stack Height Regulation, 40 CRF Part 51, 2015
Publisher: Environmental Protection Agency (EPA), Ariel Rios Building, 1200 Pennsylvania Avenue, N.W., Washington, DC 20460 (www.epa.gov)

Steam
Publisher: The Babcock & Wilcox Co., 20 S. Van Buren Avenue, Barberton, OH 44203-0351 (www.babcock.com)

UL 96A, UL Standard for Safety Installation Requirements for Lightning Protection Systems
Publisher: Underwriters Laboratories, Inc. (UL), 333 Pfingsten Road, Northbrook, IL 60062-2096, Order Address: Comm 2000, 151 Eastern Avenue, Bensenville, IL 60106 (www.ul.com)

MANDATORY APPENDIX I
(21) STRUCTURAL DESIGN — GUST EFFECT FACTOR CALCULATION

The gust effect factor is given by

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

where R, the resonant response factor, is given by

$$R = \sqrt{\frac{1}{\beta}R_nR_hR_B(0.53 + 0.47R_d)}$$

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

$$N_1 = \frac{n_lL_{\bar{z}}}{\bar{V}_{\bar{z}}}$$

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

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

($l = h, B, d$)

R_l = R_h setting, $\eta = 4.6n_1h/\bar{V}_{\bar{z}}$
R_B setting, $\eta = 4.6n_1B/\bar{V}_{\bar{z}}$
R_d setting, $\eta = 15.4n_1d/\bar{V}_{\bar{z}}$

β = damping ratio

$$\bar{V}_{\bar{z}} = \bar{b}\left(\frac{\bar{z}}{33}\right)^{\bar{\alpha}}V\left(\frac{22}{15}\right)$$

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

$$g_R = \sqrt{2\log_e(3{,}600n_1)} + \frac{0.577}{\sqrt{2\log_e(3{,}600n_1)}}$$

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

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

where

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

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
$L_{\bar{z}}$ = the integral length scale of turbulence at the equivalent height

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

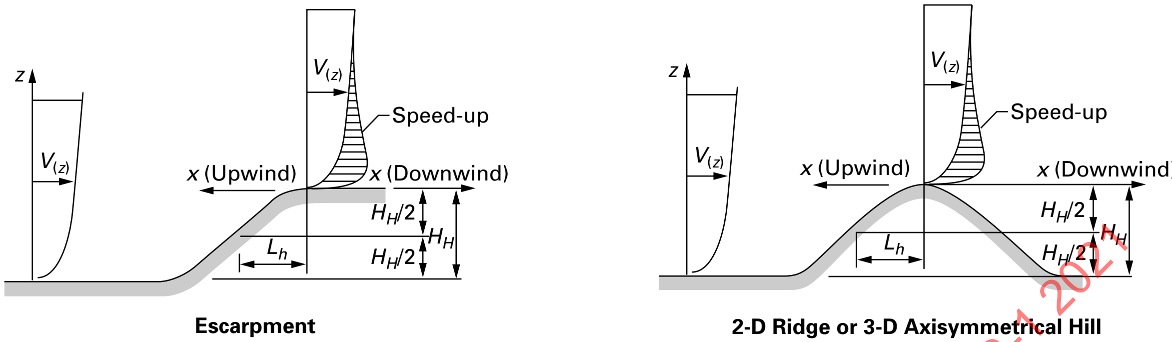
in which l and $\bar{\varepsilon}$ are as listed in Table I-1. See Figure I-1 and Tables I-2 through I-4.

Table I-1
Terrain Exposure Constants

Exposure	α	Z_g, ft	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	l, ft	$\bar{\varepsilon}$	Z_{min}, ft [Note (1)]
A	5.0	1,500	1/5	0.64	1/3.0	0.30	0.45	180	1/2.0	60
B	7.0	1,200	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}.

Figure I-1
Topographic Factor, K_{zt}



Topographic Multipliers for Exposure C [Note (1)]

	K_1 Multiplier [Note (2)]				K_2 Multiplier [Note (2)]			K_3 Multiplier [Note (2)]		
H_H/L_h [Note (3)]	2-D Ridge	2-D Escarp.	3-D Axisym. Hill	x/L_h [Note (3)]	2-D Escarp.	All Other Cases	z/L_h [Note (3)]	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

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(b) Nomenclature:

H_H = height of hill or escarpment relative to the upwind terrain, 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
L_h = distance upwind of crest to where the difference in ground elevation is half the height of hill or escarpment, ft (m)
x = distance (upwind or downwind) from the crest to the building site, ft (m)
z = height above local ground level, ft (m)
μ = horizontal attenuation factor
γ = height attenuation factor

NOTES:

(1) Multipliers are based on the assumption that wind approaches the hill or escarpment along the direction of maximum slope.
(2) For $H_H/L_h > 0.5$, assume $H_H/L_h = 0.5$ for evaluating K_1, and substitute $2H_H$ for L_h for evaluating K_2 and K_3.
(3) For values of H_H/L_h, x/L_h, and z/L_h, other than those shown, linear interpolation is permitted.

Figure I-1
Topographic Factor, K_{zt} (Cont'd)

NOTES (Cont'd)
Equations:

$$K_{zt} = (1 + K_1K_2K_3)^2$$

K_1 determined from table below

$$K_2 = 1 - \frac{|x|}{\mu L_h}$$

$$K_3 = e^{-\gamma z/L_h}$$

Parameters for Speed-Up Over Hills and Escarpments

Hill Shape	$K_1/(H_H/L_h)$ Exposure B	$K_1/(H_H/L_h)$ Exposure C	$K_1/(H_H/L_h)$ Exposure D	γ	μ Upwind of Crest	μ Downwind of Crest
Two-dimensional ridges [or valleys with negative H_H in $K_1/(H_H/L_h)$]	1.30	1.45	1.55	3	1.5	1.5
Two-dimensional escarpments	0.75	0.85	0.95	2.5	1.5	4
Three-dimensional axisymmetrical hill	0.95	1.05	1.15	4	1.5	1.5

Table I-2
Risk Category of Buildings and Other Structures for Flood, Wind, Snow, and Earthquake Loads

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life	III
Buildings and other structures, not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure	
Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released	
Buildings and other structures designated as essential facilities	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community	
Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures	

GENERAL NOTE: Data from ASCE 7-16, Table 1.5-1, with permission from the American Society of Civil Engineers (ASCE), Reston, VA.

Table I-3
Velocity Pressure Exposure Coefficients, K_z

Height Above Ground Level, z, ft (m) [Note (1)]	Exposure		
	B	C	D
0–15 (0–4.6)	0.57	0.85	1.03
20 (6.1)	0.62	0.90	1.08
25 (7.6)	0.66	0.94	1.12
30 (9.1)	0.70	0.98	1.16
40 (12.2)	0.76	1.04	1.22
50 (15.2)	0.81	1.09	1.27
60 (18.0)	0.85	1.13	1.31
70 (21.3)	0.89	1.17	1.34
80 (24.4)	0.93	1.21	1.38
90 (27.4)	0.96	1.24	1.40
100 (30.5)	0.99	1.26	1.43
120 (36.6)	1.04	1.31	1.48
140 (42.7)	1.09	1.36	1.52
160 (48.8)	1.13	1.39	1.55
180 (54.9)	1.17	1.43	1.58
200 (61.0)	1.20	1.46	1.61
250 (76.2)	1.28	1.53	1.68
300 (91.4)	1.35	1.59	1.73
350 (106.7)	1.41	1.64	1.78
400 (121.9)	1.47	1.69	1.82
450 (137.2)	1.52	1.73	1.86
500 (152.4)	1.56	1.77	1.89

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(b) Exposure categories are defined in para. 4.3.3.4.

NOTE: (1) Linear interpolation for intermediate values of height, z, is acceptable.

Table I-4
Force Coefficients, C_f

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 ($D\sqrt{q_z} > 2.5$)	Moderately smooth	0.5	0.6	0.7
($D\sqrt{q_z} > 5.3$, D in m, q_z in N/m^2)	Rough ($D'/D = 0.02$)	0.7	0.8	0.9
	Very rough ($D'/D = 0.08$)	0.8	1.0	1.2
Round ($D\sqrt{q_z} \leq 2.5$) ($D\sqrt{q_z} \leq 5.3$, D in m, q_z in Nn/m^2)	All	0.7	0.8	1.2

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(b) 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.
(c) Linear interpolation is permitted for h/D values other than shown.
(d) Nomenclature:
D = diameter of circular cross section and least horizontal dimension of square, hexagonal, or octagonal cross sections at elevation under consideration, ft (m)
D' = depth of protruding elements such as ribs, corrugated jackets, or other surface irregularities that affect the roughness of the stack, ft (m)
h = height of structure, ft (m)
q_z = velocity pressure evaluated at height z above ground, psf (N/m^2)

NONMANDATORY APPENDIX A
MECHANICAL DESIGN

(21)

See Figures A-1 through A-13 and Table A-1.

Figure A-1
Friction Factor, *f*, as Related to Reynolds Number and Stack Diameter

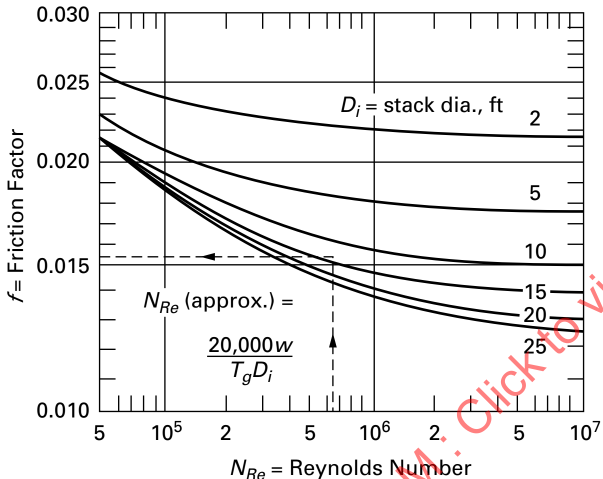


Figure A-2
External Heat Transfer Coefficient for Forced and Natural Convection

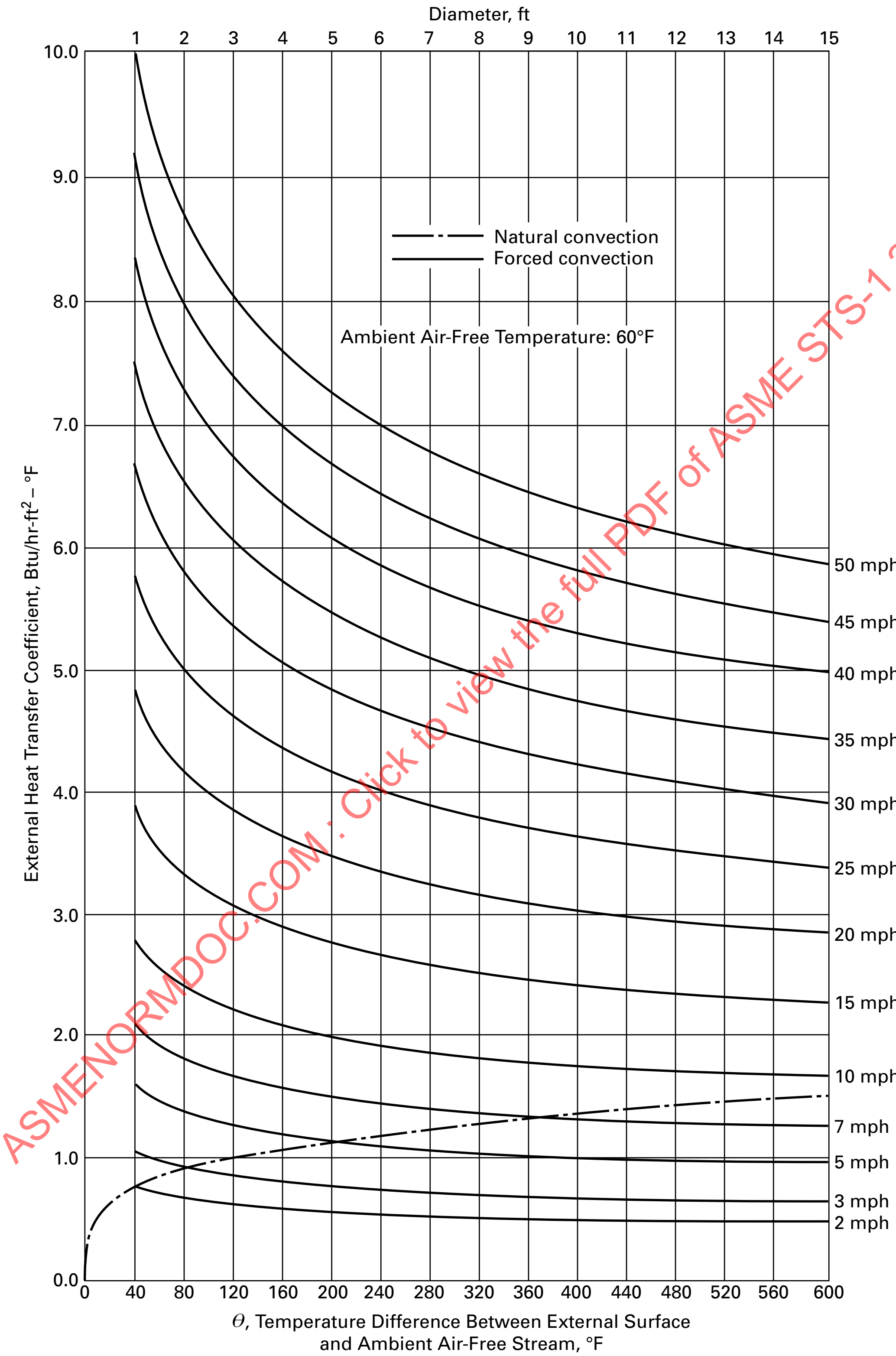
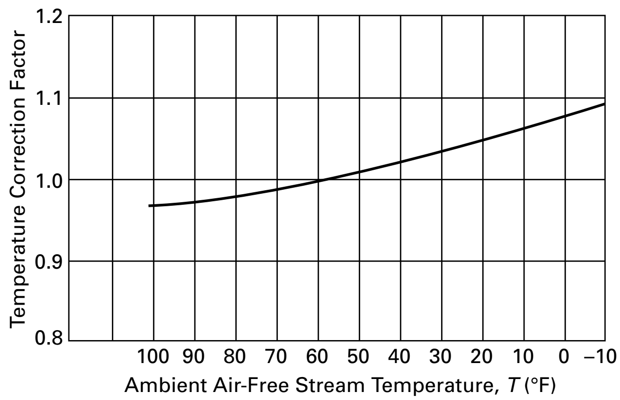


Figure A-3
Effect of a Change in the Ambient Air-Free Stream Temperature on the External Heat Transfer Coefficient for Forced Convection



GENERAL NOTE:

h_T = ($h_{60°F}$) (Temperature Correction Factor)$_T$, where

h_T = the external heat transfer coefficient for forced convection when the ambient air-free stream temperature is T (°F)

$h_{60°F}$ = the external heat transfer coefficient for forced convection for a T (°F) of 60°F (see Figure A-2)

Figure A-4
Heat Transfer Coefficient for the Air Gap Between Two Walls of a Double-Walled Metal Chimney (Mean Temperature 200°F Through 400°F)

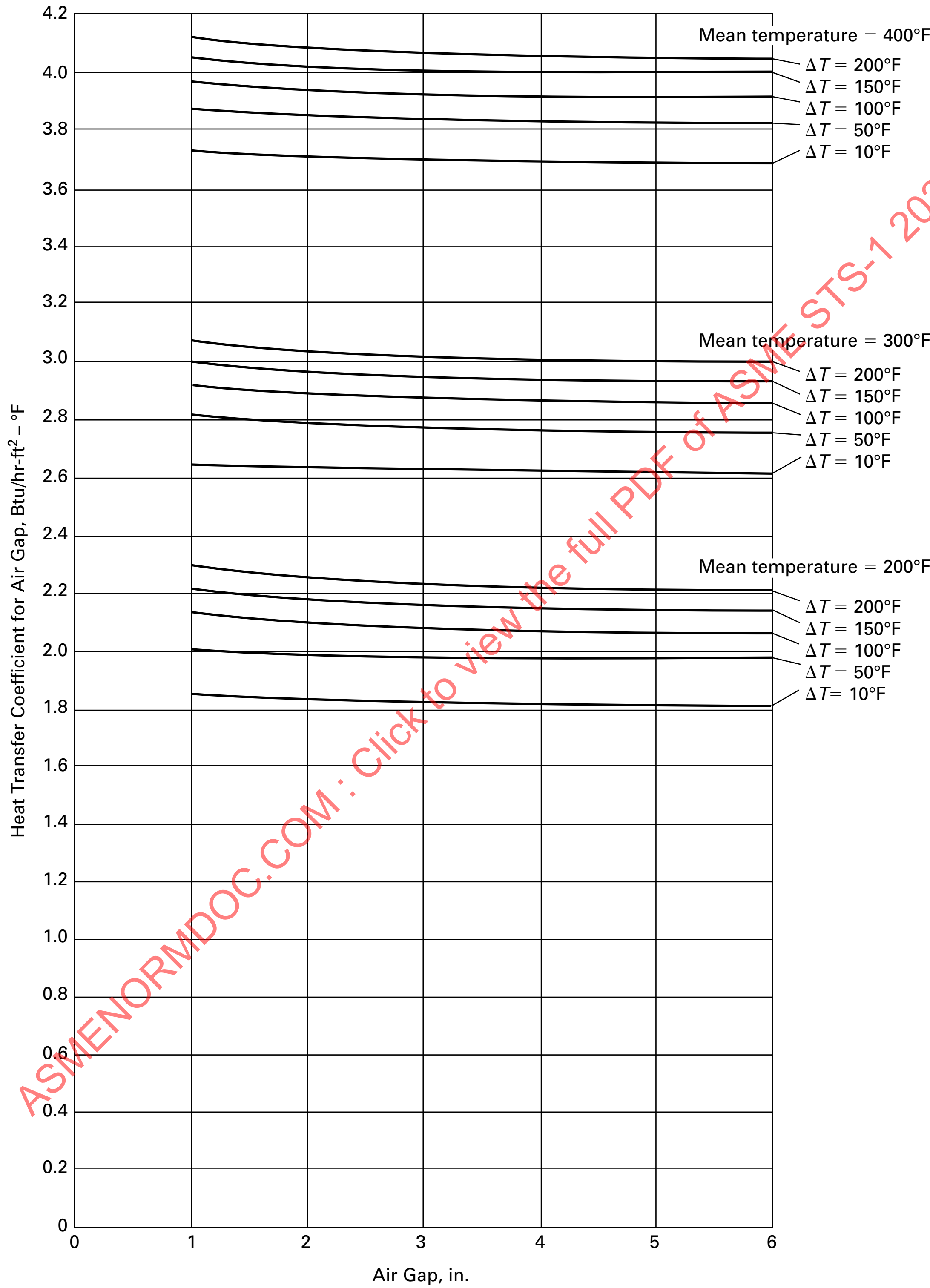


Figure A-5
Heat Transfer Coefficient for the Air Gap Between Two Walls of a Double-Walled Metal Chimney (Mean Temperature 500°F and 600°F)

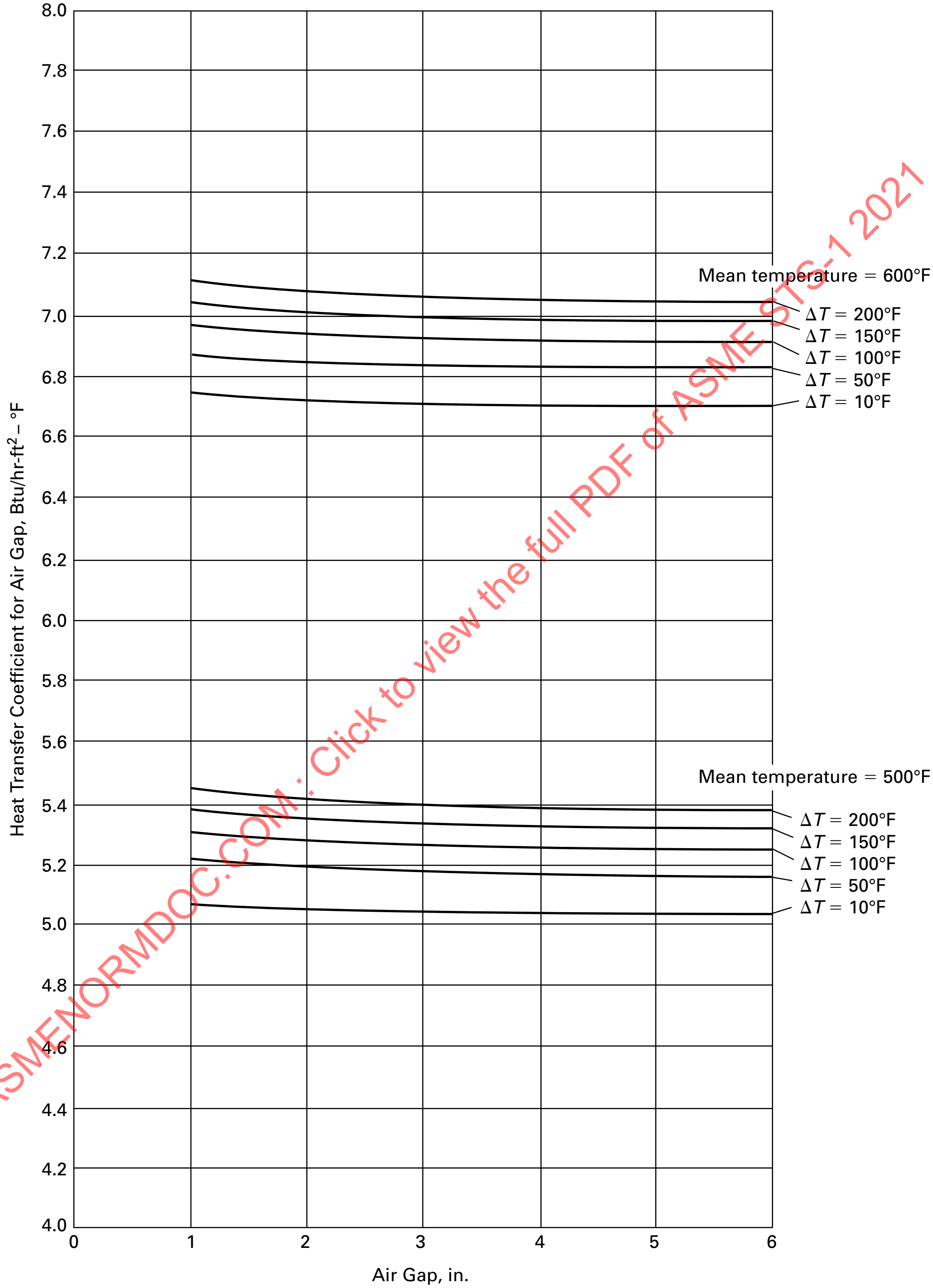


Figure A-6
Internal Heat Transfer Coefficient vs. Velocity at Film Temperature: 200°F

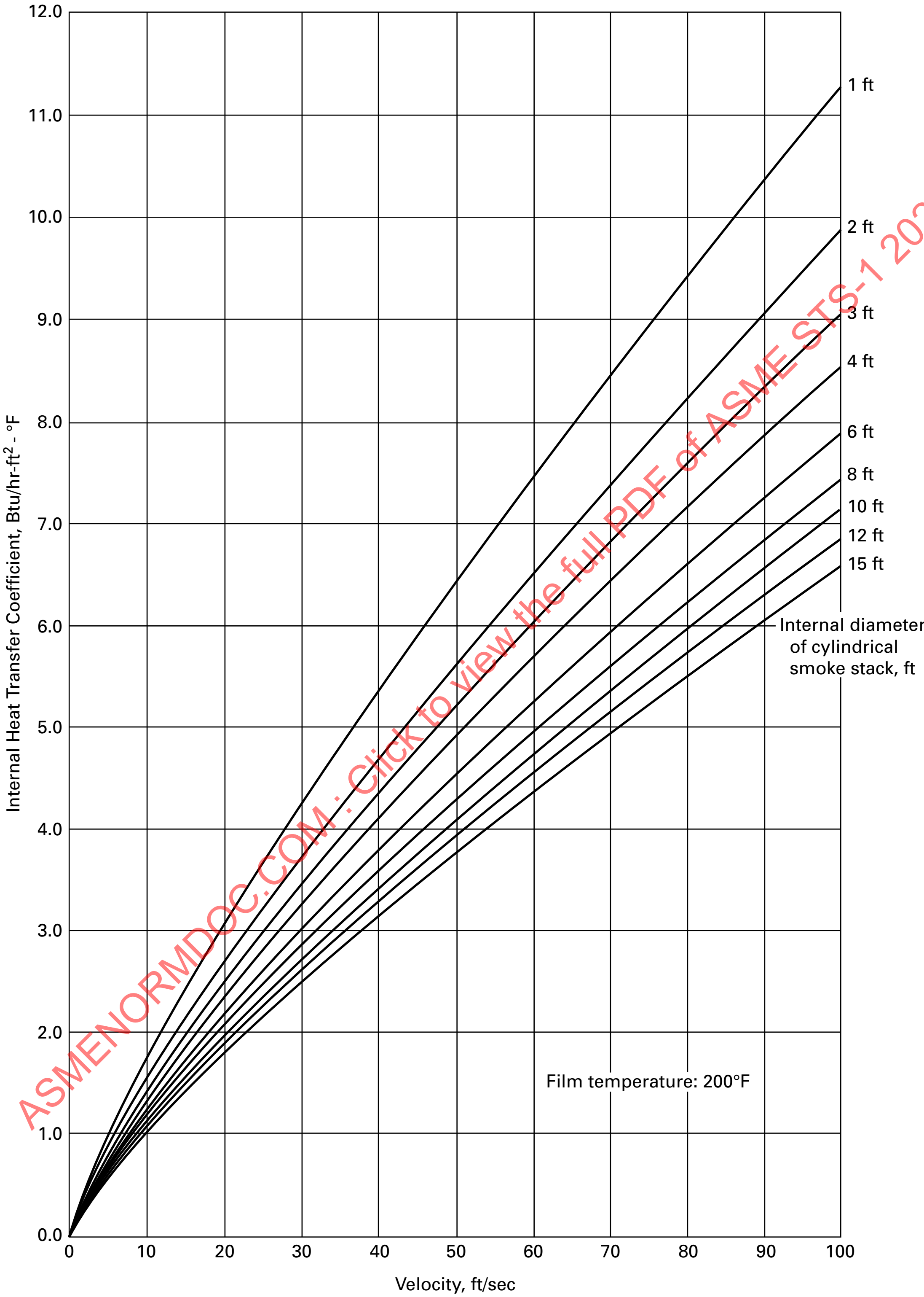


Figure A-7
Internal Heat Transfer Coefficient vs. Velocity at Film Temperature: 300°F

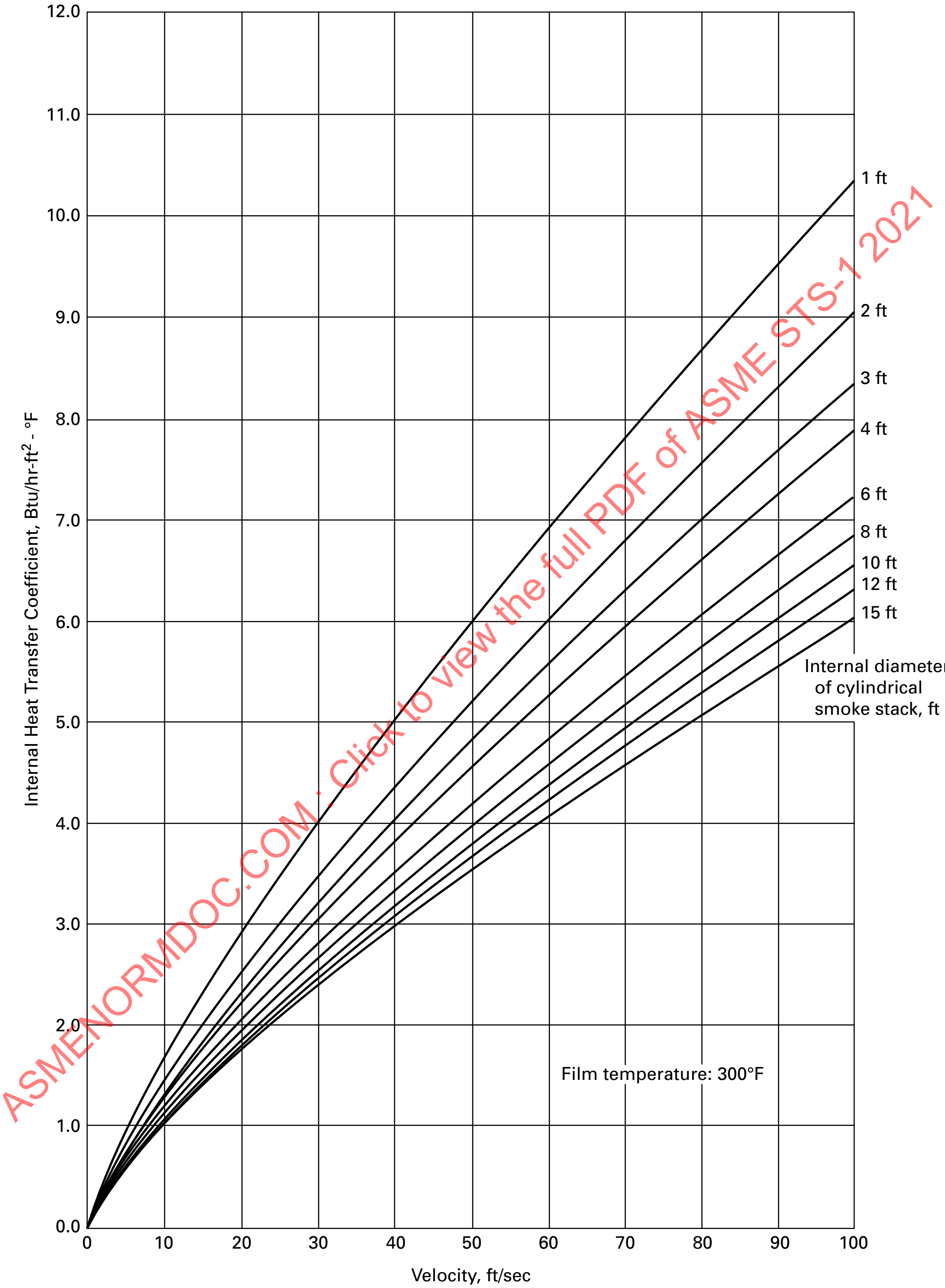


Figure A-8
Internal Heat Transfer Coefficient vs. Velocity at Film Temperature: 500°F

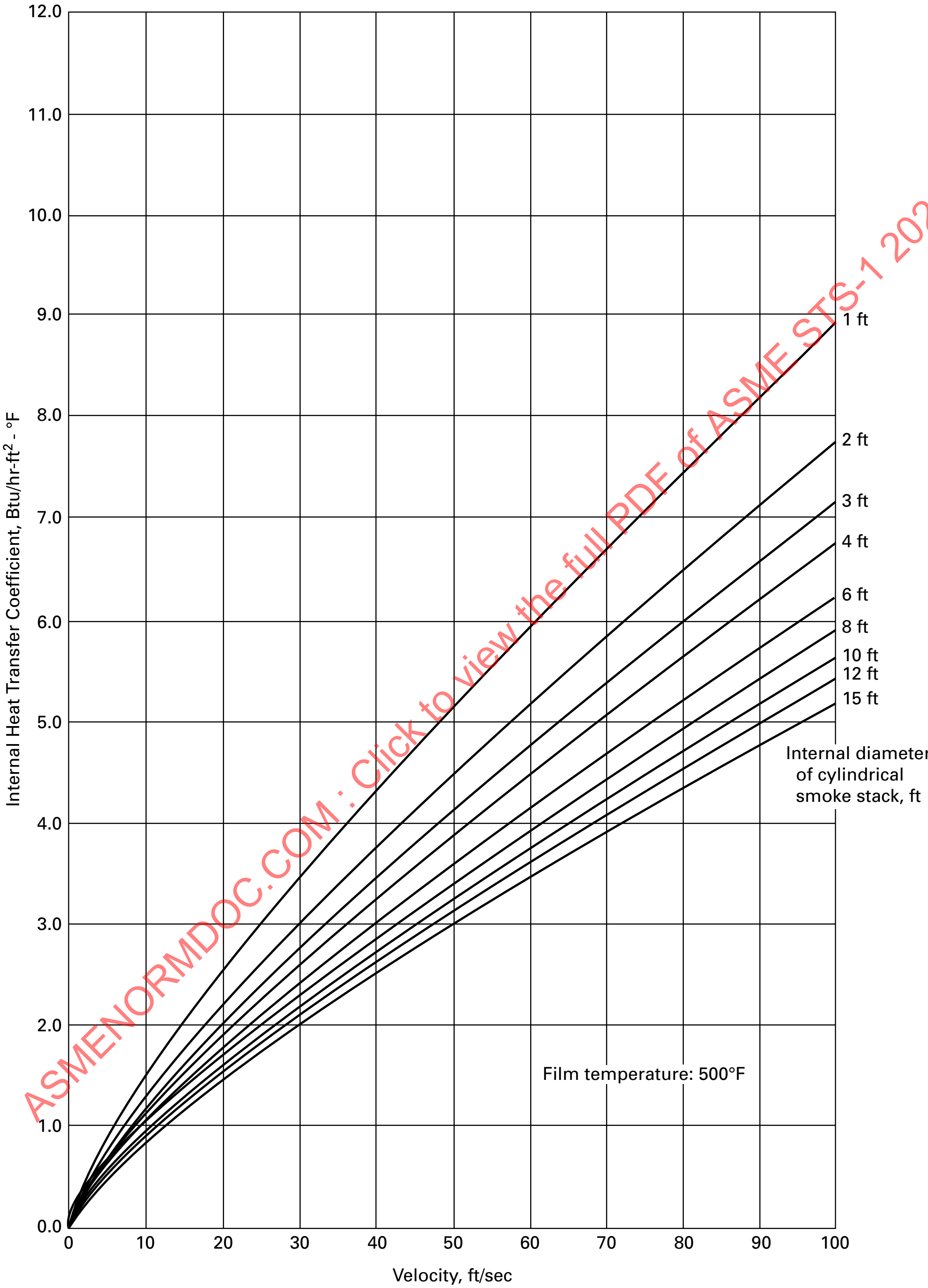


Figure A-9
Internal Heat Transfer Coefficient vs. Velocity at Film Temperature: 1,000°F

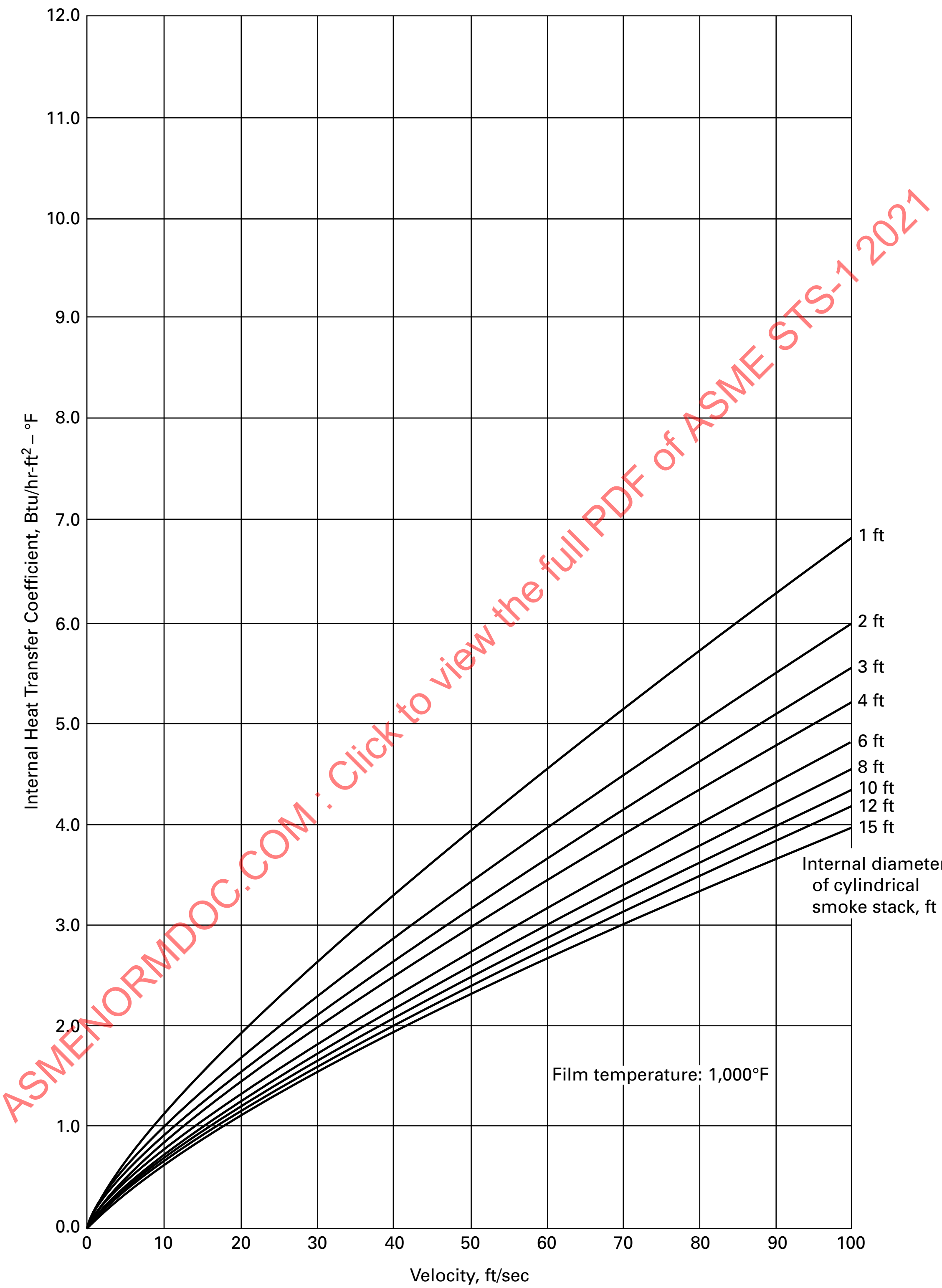
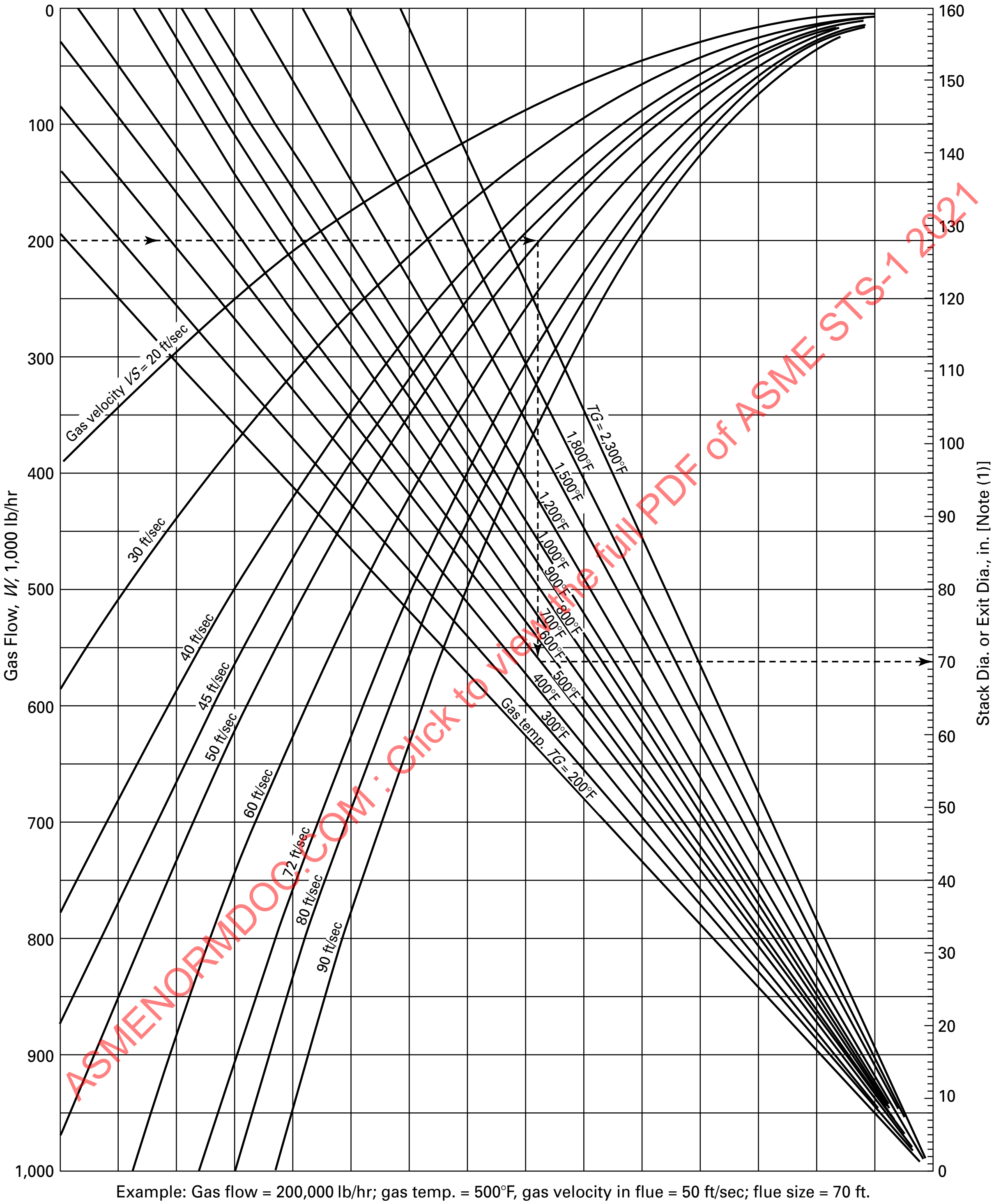
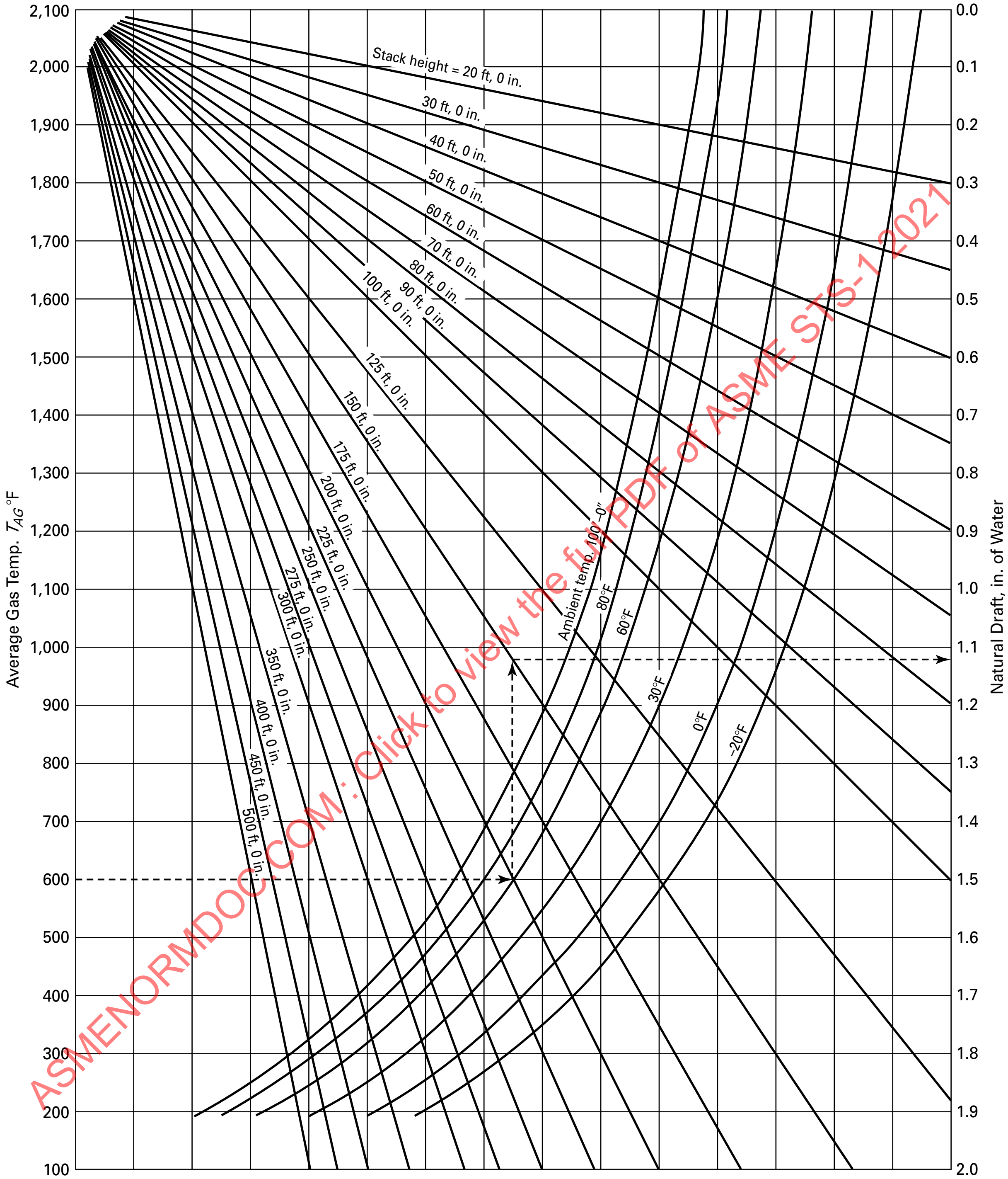


Figure A-10
Flue Size



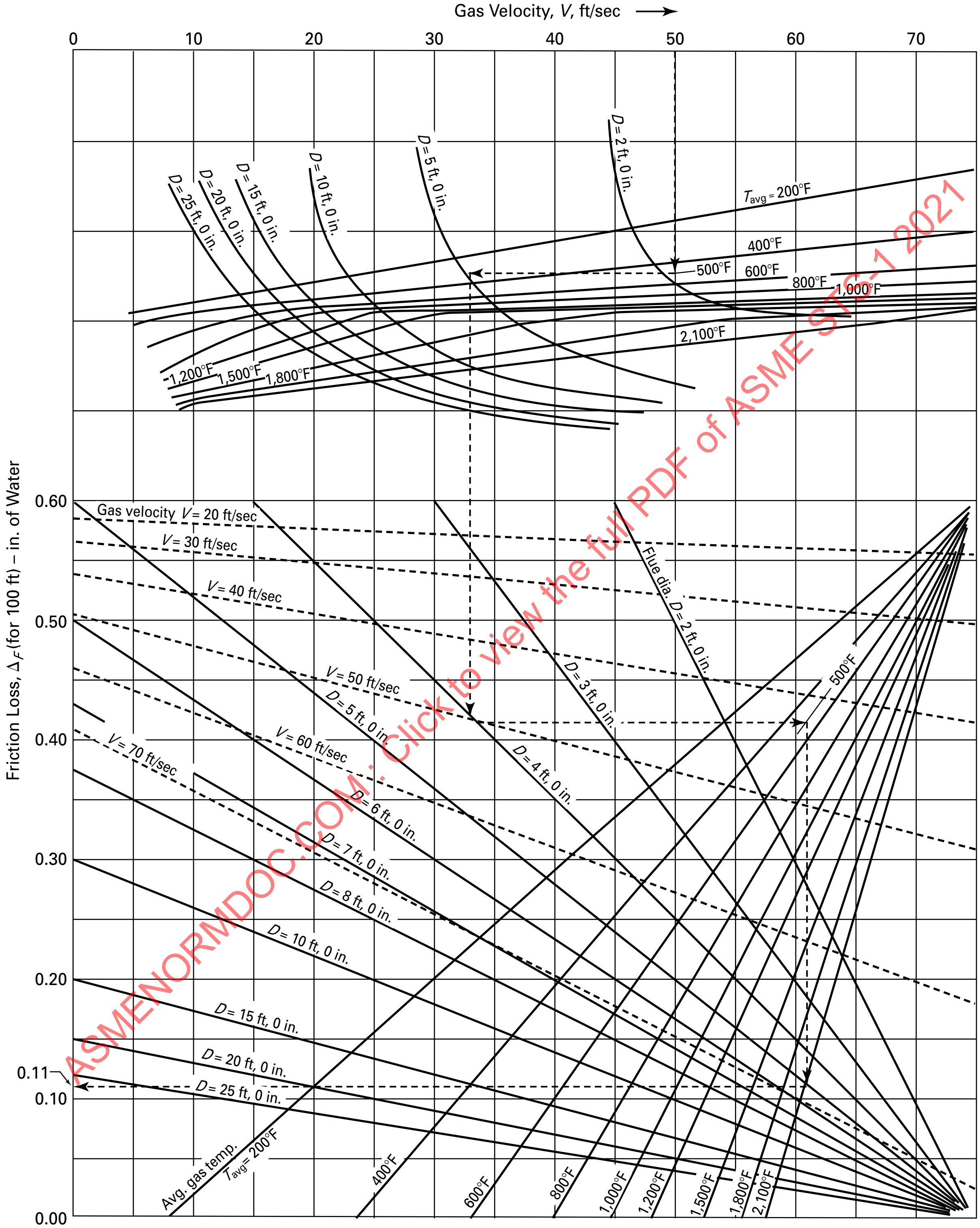
NOTE: (1) For square or rectangular flues, use equal cross-sectional areas.

Figure A-11
Natural Draft



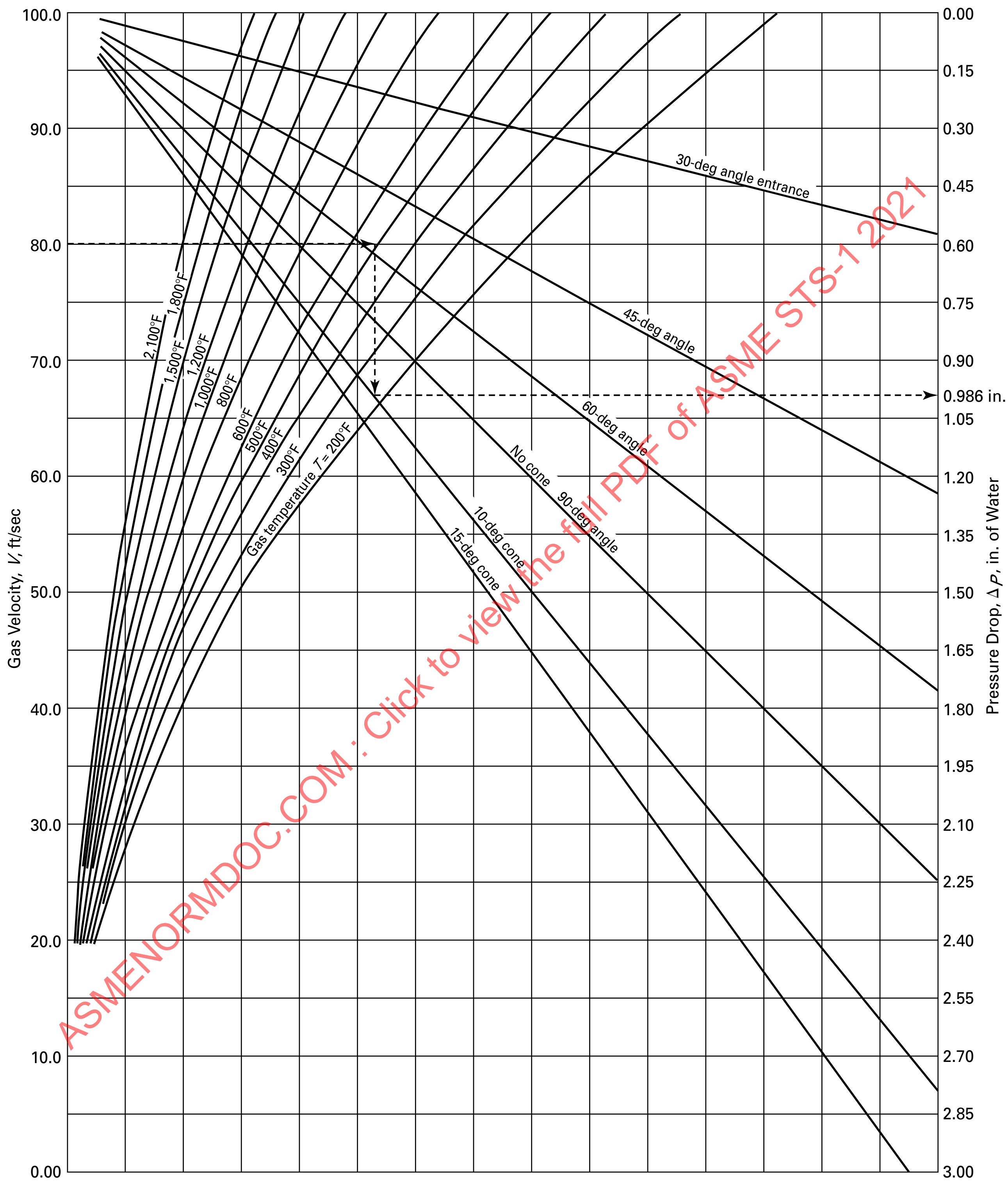
Example: T_{AG} = 600°F; H = 150 ft, 0 in.; T_{amb} = 60°F; natural draft = 1.124 in.

Figure A-12
Friction Loss



Example: D = 5 ft, 0 in.; T_{avg} = 500°F; V = 50 ft/sec. Friction loss for 100 ft, Δ_F = 0.11 (in. of water).

Figure A-13
Exit Loss and Entrance



Example: V = 80 ft/sec; T = 500°F; 10-ft exit cone; pressure drop, Δ_P ⟶ 0.986 in.

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

NONMANDATORY APPENDIX B
MATERIALS FOR AMBIENT AND ELEVATED TEMPERATURE SERVICE

See Tables B-1 through B-17.

Table B-1
ASTM A36 Carbon Steel

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.35 max.
Manganese	0.29/1.06
Phosphorus	0.048 max.
Sulfur	0.058 max.
Silicon	0.10 min.

B — Typical Annealed Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	36.0 (248.0)	58.0 (399.6)	29,676 (204 471)
100 (38)	36.0 (248.0)	58.0 (399.6)	29,062 (200 234)
150 (66)	33.8 (232.9)	58.0 (399.6)	28,831 (198 644)
200 (93)	33.0 (227.4)	58.0 (399.6)	28,600 (197 054)
250 (121)	32.4 (223.2)	58.0 (399.6)	28,350 (195 332)
300 (149)	31.8 (219.1)	58.0 (399.6)	28,100 (193 609)
400 (204)	30.8 (212.2)	58.0 (399.6)	27,700 (190 853)
500 (260)	29.3 (201.9)	58.0 (399.6)	27,100 (186 719)
600 (316)	27.6 (190.2)	58.0 (399.6)	26,400 (181 896)
650 (343)	26.7 (184.0)	58.0 (399.6)	25,850 (178 106)
700 (371)	25.8 (177.8)	58.0 (399.6)	25,300 (174 317)
750 (399)	24.9 (171.6)	57.3 (394.8)	24,650 (169 838)
800 (427)	24.1 (166.0)	53.3 (367.2)	24,000 (165 360)
850 (454)	23.4 (161.2)	48.5 (334.2)	23,150 (159 503)
900 (482)	22.8 (157.1)	43.3 (298.3)	22,300 (153 647)
950 (510)	22.1 (152.3)	38.0 (261.8)	21,250 (146 413)
1,000 (538)	21.4 (147.4)	33.4 (230.1)	20,200 (139 178)

GENERAL NOTES:
(a) Properties taken from ASME Boiler and Pressure Vessel Code (BPVC), Section II.
(b) Properties are “typical,” unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-2
ASTM A387 Grade 11 Alloy Steel

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.15 max.
Manganese	0.30/0.61
Phosphorus	0.045 max.
Sulfur	0.045 max.
Silicon	0.50 max.
Chromium	0.80/1.25
Molybdenum	0.44/0.65

B — Typical Annealed Properties (Class/Cond./Temper = 1)

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	35.0 (241.2)	60.0 (413.4)	30,076 (207 227)
100 (38)	35.0 (241.2)	60.0 (413.4)	29,462 (202 990)
150 (66)	33.3 (229.4)	60.0 (413.4)	29,231 (201 400)
200 (93)	32.3 (222.5)	60.0 (413.4)	29,000 (199 810)
250 (121)	31.5 (217.0)	60.0 (413.4)	28,750 (198 088)
300 (149)	30.7 (211.5)	60.0 (413.4)	28,500 (196 365)
400 (204)	29.5 (203.3)	60.0 (413.4)	28,000 (192 920)
500 (260)	28.4 (195.7)	60.0 (413.4)	27,400 (188 786)
600 (316)	27.4 (188.8)	60.0 (413.4)	26,900 (185 341)
650 (343)	26.9 (185.3)	60.0 (413.4)	26,550 (182 929)
700 (371)	26.4 (181.9)	60.0 (413.4)	26,200 (180 518)
750 (399)	25.9 (178.5)	60.0 (413.4)	25,900 (178 451)
800 (427)	25.2 (173.6)	60.0 (413.4)	25,600 (176 384)
850 (454)	24.5 (168.8)	58.3 (401.7)	25,200 (173 628)
900 (482)	23.8 (164.0)	55.8 (384.5)	24,800 (170 872)
950 (510)	22.9 (157.8)	52.6 (362.4)	24,350 (167 771)
1,000 (538)	21.9 (150.9)	48.8 (336.2)	23,900 (164 671)

C — Typical Normalized and Tempered Properties (Class/Cond./Temper = 2)

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	45.0 (310.1)	75.0 (516.8)	30,076 (207 227)
100 (38)	45.0 (310.1)	75.0 (516.8)	29,462 (202 990)
150 (66)	42.8 (294.9)	75.0 (516.8)	29,231 (201 400)
200 (93)	41.5 (285.9)	75.0 (516.8)	29,000 (199 810)
250 (121)	40.5 (279.0)	75.0 (516.8)	28,750 (198 088)
300 (149)	39.5 (272.2)	75.0 (516.8)	28,500 (196 365)
400 (204)	37.9 (261.1)	75.0 (516.8)	28,000 (192 920)
500 (260)	36.5 (251.5)	75.0 (516.8)	27,400 (188 786)
600 (316)	35.3 (243.2)	75.0 (516.8)	26,900 (185 341)
650 (343)	34.6 (238.4)	75.0 (516.8)	26,550 (182 929)
700 (371)	34.0 (234.3)	75.0 (516.8)	26,200 (180 518)
750 (399)	33.2 (228.7)	75.0 (516.8)	25,900 (178 451)
800 (427)	32.5 (223.9)	75.0 (516.8)	25,600 (176 384)
850 (454)	31.6 (217.7)	72.8 (501.6)	25,200 (173 628)
900 (482)	30.6 (210.8)	69.7 (480.2)	24,800 (170 872)
950 (510)	29.4 (202.6)	65.7 (452.7)	24,350 (167 771)
1,000 (538)	28.4 (195.7)	61.0 (420.3)	23,900 (164 671)

Table B-2
ASTM A387 Grade 11 Alloy Steel (Cont'd)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-3
ASTM A387 Grade 12 Alloy Steel

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.15 max.
Manganese	0.30/0.61
Phosphorus	0.045
Sulfur	0.045 max.
Silicon	0.50/1.00
Chromium	1.00/1.50
Molybdenum	0.44/0.65

B — Typical Annealed Properties (Class/Cond./Temper = 1)

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	33.0 (227.4)	55.0 (379.0)	30,076 (207 227)
100 (38)	33.0 (227.4)	55.0 (379.0)	29,462 (202 990)
150 (66)	31.0 (213.6)	55.0 (379.0)	29,231 (201 400)
200 (93)	29.8 (205.3)	54.0 (372.1)	29,000 (199 810)
250 (121)	28.9 (199.1)	53.5 (368.3)	28,750 (198 088)
300 (149)	28.1 (193.6)	52.9 (364.5)	28,500 (196 365)
400 (204)	26.8 (184.7)	52.9 (364.5)	28,000 (192 920)
500 (260)	25.9 (178.5)	52.9 (364.5)	27,400 (188 786)
600 (316)	25.1 (172.9)	52.9 (364.5)	26,900 (185 341)
650 (343)	24.8 (170.9)	52.9 (364.5)	26,550 (182 929)
700 (371)	24.4 (168.1)	52.9 (364.5)	26,200 (180 518)
750 (399)	24.0 (165.4)	52.9 (364.5)	25,900 (178 451)
800 (427)	23.6 (162.6)	52.9 (364.5)	25,600 (176 384)
850 (454)	23.1 (159.2)	52.9 (364.5)	25,200 (173 628)
900 (482)	22.5 (155.0)	51.4 (354.1)	24,800 (170 872)
950 (510)	21.7 (149.5)	48.9 (336.9)	24,350 (167 771)
1,000 (538)	20.9 (144.0)	45.8 (315.6)	23,900 (164 671)

C — Typical Normalized and Tempered Properties (Class/Cond./Temper = 2)

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	40.0 (275.6)	65.0 (447.9)	30,076 (207 227)
100 (38)	40.0 (275.6)	63.8 (439.6)	29,462 (202 990)
150 (66)	37.5 (258.4)	62.5 (430.6)	29,231 (201 400)
200 (93)	36.2 (249.4)	62.5 (430.6)	29,000 (199 810)
250 (121)	35.0 (241.2)	62.5 (430.6)	28,750 (198 088)
300 (149)	34.0 (234.3)	62.5 (430.6)	28,500 (196 365)
400 (204)	32.5 (223.9)	62.5 (430.6)	28,000 (192 920)
500 (260)	31.4 (216.3)	62.5 (430.6)	27,400 (188 786)
600 (316)	30.5 (210.1)	62.5 (430.6)	26,900 (185 341)
650 (343)	30.1 (207.4)	62.5 (430.6)	26,550 (182 929)
700 (371)	29.6 (203.9)	62.5 (430.6)	26,200 (180 518)
750 (399)	29.1 (200.5)	62.5 (430.6)	25,900 (178 451)
800 (427)	28.6 (197.1)	62.5 (430.6)	25,600 (176 384)
850 (454)	28.0 (192.9)	62.5 (430.6)	25,200 (173 628)
900 (482)	27.2 (187.4)	60.8 (418.9)	24,800 (170 872)
950 (510)	26.3 (181.2)	57.8 (398.2)	24,350 (167 771)
1,000 (538)	25.3 (174.3)	54.2 (373.4)	23,900 (164 671)

Table B-3
ASTM A387 Grade 12 Alloy Steel (Cont'd)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-4
ASTM A242 Type 1, A606 Type 4 (Corten A)

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.12 max.
Manganese	0.20/0.50
Phosphorus	0.07/0.15
Sulfur	0.05 max.
Silicon	0.25/0.75
Copper	0.25/0.55
Chromium	0.50/1.25
Vanadium	0.65 max.

GENERAL NOTE: Reprinted with permission from USS Steels for Elevated Temperature Service, 1976 revision.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	54.1 (372.7)	81.3 (560.2)	30,000 (206 700)
80 (27)	54.1 (372.7)	81.3 (560.2)	30,000 (206 700)
200 (93)	50.8 (350.0)	76.2 (525.0)	29,000 (199 810)
400 (204)	47.6 (328.0)	76.4 (526.4)	28,000 (192 920)
600 (316)	41.1 (283.2)	81.3 (560.2)	26,900 (185 341)
800 (427)	39.9 (274.9)	76.4 (526.4)	25,600 (176 384)
1,000 (538)	35.2 (242.5)	52.8 (363.8)	23,900 (164 671)
1,200 (649)	20.5 (141.2)	27.6 (190.2)	21,800 (150 202)
1,400 (760)	20.5 (141.2)	10.6 (73.0)	18,900 (130 221)

GENERAL NOTES:
(a) Considerable deviation from the listed properties may occur as a result of the relatively broad chemical composition range shown.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.
(c) Values taken from USS Steels for Elevated Temperature Service, 1976 revision.
(d) Reprinted with permission from USS Steels for Elevated Temperature Service, 1976 revision.

Table B-5
ASTM A588 Grade A, A709 (Corten B)

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.10/0.19
Manganese	0.90/1.25
Phosphorus	0.04 max.
Sulfur	0.05 max.
Silicon	0.15/0.30
Copper	0.25/0.40
Chromium	0.40/0.65
Vanadium	0.02/0.10

GENERAL NOTE: Reprinted with permission from USS Steels for Elevated Temperature Service, 1976 revision.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	55.0 (379.0)	86.7 (597.4)	30,000 (206 700)
80 (27)	55.0 (379.0)	86.7 (597.4)	30,000 (206 700)
200 (93)	51.7 (356.2)	81.4 (560.8)	29,000 (199 810)
400 (204)	48.4 (333.5)	79.8 (549.8)	28,000 (192 920)
600 (316)	46.7 (321.8)	75.5 (520.2)	26,900 (185 341)
800 (427)	45.1 (310.7)	71.1 (489.9)	25,600 (176 384)
1,000 (538)	35.8 (246.7)	52.0 (358.3)	23,900 (164 671)
1,200 (649)	20.0 (137.8)	30.3 (208.8)	21,800 (150 202)
1,400 (760)	9.4 (64.8)	11.3 (77.9)	18,900 (130 221)

GENERAL NOTES:
(a) Considerable deviation from the listed properties may occur as a result of the relatively broad chemical composition range shown.
(b) This material should not be used above 800°F for load-bearing structures because of possible loss of ductility.
(c) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.
(d) Values taken from USS Steels for Elevated Temperature Service, 1976 revision.
(e) Reprinted with permission from USS Steels for Elevated Temperature Service, 1976 revision.

Table B-6
ASTM A240 Stainless Steel Type 410

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.15
Manganese	1.00
Phosphorus	0.04
Sulfur	0.03
Silicon	1.00
Chromium	11.50/13.50
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	30.0 (206.7)	65.0 (447.9)	29,729 (204 836)
100 (38)	30.0 (206.7)	65.0 (447.9)	29,015 (199 916)
150 (66)	28.4 (195.7)	65.0 (447.9)	28,708 (197 796)
200 (93)	27.6 (190.2)	65.0 (447.9)	28,400 (195 676)
250 (121)	27.0 (186.0)	64.4 (443.4)	28,150 (193 953)
300 (149)	26.6 (183.3)	63.7 (438.9)	27,900 (192 231)
400 (204)	26.2 (180.5)	62.6 (431.3)	27,300 (188 097)
500 (260)	25.8 (177.8)	61.6 (424.4)	26,800 (184 652)
600 (316)	25.3 (174.3)	60.1 (414.1)	26,200 (180 518)
650 (343)	24.8 (170.9)	59.0 (406.5)	25,850 (178 107)
700 (371)	24.3 (167.4)	57.5 (396.2)	25,500 (175 695)
750 (399)	23.6 (162.6)	55.6 (383.1)	25,000 (172 250)
800 (427)	22.7 (156.4)	53.4 (367.9)	24,500 (168 805)
850 (454)	21.6 (148.8)	50.7 (349.3)	23,850 (164 327)
900 (482)	20.3 (139.9)	47.7 (328.7)	23,200 (159 848)
950 (510)	18.9 (130.2)	44.2 (304.5)	22,350 (153 992)
1,000 (538)	17.2 (118.5)	40.3 (277.7)	21,500 (148 135)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are “typical,” unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-7
ASTM A240 Stainless Steel Type 304

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.06
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	18.0/12.00
Nickel	8.0/10.5
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	30.0 (206.7)	75.0 (516.8)	28,776 (198 270)
100 (38)	30.0 (206.7)	75.0 (516.8)	28,115 (193 715)
150 (66)	26.7 (184.0)	73.0 (503.0)	27,808 (191 595)
200 (93)	25.0 (172.3)	71.0 (489.2)	27,500 (189 475)
250 (121)	23.6 (162.6)	68.6 (472.7)	27,250 (187 753)
300 (149)	22.4 (154.3)	66.2 (456.1)	27,000 (186 030)
400 (204)	20.7 (142.6)	64.0 (441.0)	26,400 (181 896)
500 (260)	19.4 (133.7)	63.4 (436.8)	25,900 (178 451)
600 (316)	18.4 (126.8)	63.4 (436.8)	25,300 (174 317)
650 (343)	18.0 (124.0)	63.4 (436.8)	25,050 (172 594)
700 (371)	17.6 (121.3)	63.4 (436.8)	24,800 (170 872)
750 (399)	17.2 (118.5)	63.4 (436.8)	24,450 (168 461)
800 (427)	16.9 (116.4)	62.8 (432.7)	24,100 (166 049)
850 (454)	16.5 (113.7)	62.0 (427.2)	23,800 (163 982)
900 (482)	16.2 (111.6)	60.8 (418.9)	23,500 (161 915)
950 (510)	15.9 (109.6)	59.3 (408.6)	23,150 (159 503)
1,000 (538)	15.5 (106.8)	57.4 (395.5)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-8
ASTM A240 Stainless Steel Type 316

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.08
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	16.0/18.00
Nickel	10.0/14.0
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	30.0 (206.7)	75.0 (516.8)	28,776 (198 270)
100 (38)	30.0 (206.7)	75.0 (516.8)	28,115 (193 715)
150 (66)	27.4 (188.8)	75.0 (516.8)	27,808 (191 595)
200 (93)	25.9 (178.5)	75.0 (516.8)	27,500 (189 475)
250 (121)	24.6 (169.5)	72.9 (502.3)	27,250 (187 753)
300 (149)	23.4 (161.2)	71.9 (495.4)	27,000 (186 030)
400 (204)	21.4 (147.4)	71.8 (494.7)	26,400 (181 896)
500 (260)	20.0 (137.8)	71.8 (494.7)	25,900 (178 451)
600 (316)	18.9 (130.2)	71.8 (494.7)	25,300 (174 317)
650 (343)	18.5 (127.5)	71.8 (494.7)	25,050 (172 594)
700 (371)	18.2 (125.4)	71.8 (494.7)	24,800 (170 872)
750 (399)	17.9 (123.3)	71.5 (492.6)	24,450 (168 461)
800 (427)	17.7 (122.0)	70.8 (487.8)	24,100 (166 049)
850 (454)	17.5 (120.6)	69.7 (480.2)	23,800 (163 982)
900 (482)	17.3 (119.2)	68.3 (470.6)	23,500 (161 915)
950 (510)	17.1 (117.8)	66.5 (458.2)	23,150 (159 503)
1,000 (538)	17.0 (117.1)	64.3 (443.0)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are “typical,” unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-9
ASTM A240 Stainless Steel Type 304L

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.03
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	18.0/20.00
Nickel	8.0/12
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	25.0 (172.3)	70.0 (482.3)	28,776 (198 270)
100 (38)	25.0 (172.3)	70.0 (482.3)	28,115 (193 715)
150 (66)	22.7 (156.4)	68.1 (468.9)	27,808 (191 595)
200 (93)	21.4 (147.4)	66.1 (455.4)	27,500 (189 475)
250 (121)	20.26 (139.2)	63.7 (438.5)	27,250 (187 753)
300 (149)	19.2 (132.3)	61.2 (421.7)	27,000 (186 030)
400 (204)	17.5 (120.6)	58.7 (404.4)	26,400 (181 896)
500 (260)	16.4 (113.0)	57.5 (396.2)	25,900 (178 451)
600 (316)	15.5 (106.8)	56.9 (392.0)	25,300 (174 317)
650 (343)	15.2 (104.7)	56.7 (390.7)	25,050 (172 594)
700 (371)	15.0 (103.4)	56.4 (388.6)	24,800 (170 872)
750 (399)	14.7 (101.3)	56.0 (385.8)	24,450 (168 461)
800 (427)	14.5 (99.9)	55.4 (381.7)	24,100 (166 049)
850 (454)	14.3 (98.5)	54.6 (376.2)	23,800 (163 982)
900 (482)	14.0 (96.5)	53.6 (369.3)	23,500 (161 915)
950 (510)	13.7 (94.4)	52.3 (360.3)	23,150 (159 503)
1,000 (538)	13.3 (91.6)	50.7 (349.3)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are “typical,” unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-10
ASTM A240 Stainless Steel Type 316L

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.03
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	16.0/18.00
Nickel	10.0/14.0
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	25.0 (172.3)	70.0 (482.3)	28,776 (198 270)
100 (38)	25.0 (172.3)	70.0 (482.3)	28,115 (193 715)
150 (66)	22.7 (156.4)	69.1 (475.8)	27,808 (191 595)
200 (93)	21.3 (146.8)	68.1 (469.2)	27,500 (189 475)
250 (121)	20.1 (138.5)	66.1 (455.1)	27,250 (187 753)
300 (149)	19.0 (130.9)	64.0 (441.0)	27,000 (186 030)
400 (204)	17.5 (120.6)	62.2 (428.6)	26,400 (181 896)
500 (260)	16.4 (113.0)	61.8 (425.8)	25,900 (178 451)
600 (316)	15.6 (107.5)	61.7 (425.1)	25,300 (174 317)
650 (343)	15.3 (105.4)	61.6 (424.4)	25,050 (172 594)
700 (371)	15.0 (103.4)	61.5 (423.7)	24,800 (170 872)
750 (399)	14.7 (101.3)	61.1 (421.0)	24,450 (168 461)
800 (427)	14.4 (99.2)	60.5 (416.8)	24,100 (166 049)
850 (454)	14.1 (97.1)	59.7 (411.3)	23,800 (163 982)
900 (482)	13.8 (95.1)	58.6 (403.8)	23,500 (161 915)
950 (510)	13.5 (93.0)	57.1 (393.4)	23,150 (159 503)
1,000 (538)	13.2 (90.9)	55.4 (381.7)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-11
ASTM A240 Stainless Steel Type 317

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.08
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	18.0/20.0
Nickel	11.0/15.0
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	30.0 (206.7)	75.0 (516.8)	28,776 (198 270)
100 (38)	30.0 (206.7)	75.0 (516.8)	28,115 (193 715)
150 (66)	27.4 (188.8)	75.0 (516.8)	27,808 (191 595)
200 (93)	25.9 (178.5)	75.0 (516.8)	27,500 (189 475)
250 (121)	24.6 (169.5)	72.9 (502.3)	27,250 (187 753)
300 (149)	23.4 (161.2)	71.9 (495.4)	27,000 (186 030)
400 (204)	21.4 (147.4)	71.8 (494.7)	26,400 (181 896)
500 (260)	20.0 (137.8)	71.8 (494.7)	25,900 (178 451)
600 (316)	18.9 (130.2)	71.8 (494.7)	25,300 (174 317)
650 (343)	18.5 (127.5)	71.8 (494.7)	25,050 (172 594)
700 (371)	18.2 (125.4)	71.8 (494.7)	24,800 (170 872)
750 (399)	17.9 (123.3)	71.5 (492.6)	24,450 (168 461)
800 (427)	17.7 (122.0)	70.8 (487.8)	24,100 (166 049)
850 (454)	17.5 (120.6)	69.7 (480.2)	23,800 (163 982)
900 (482)	17.3 (119.2)	68.3 (470.6)	23,500 (161 915)
950 (510)	17.1 (117.8)	66.5 (458.2)	23,150 (159 503)
1,000 (538)	17.0 (117.1)	64.3 (443.0)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-12
ASTM A516 Grade 70

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.28
Manganese	0.85/1.20
Phosphorus	0.035
Sulfur	0.035
Silicon	0.15/0.40

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	38.0 (261.8)	70.0 (482.3)	29,876 (205 849)
100 (38)	38.0 (261.8)	70.0 (482.3)	29,262 (201 612)
150 (66)	35.7 (246.0)	70.0 (482.3)	29,031 (200 022)
200 (93)	34.8 (239.8)	70.0 (482.3)	28,800 (198 432)
250 (121)	34.2 (235.6)	70.0 (482.3)	28,550 (196 709)
300 (149)	33.6 (231.5)	70.0 (482.3)	28,300 (194 987)
400 (204)	32.5 (223.9)	70.0 (482.3)	27,900 (192 231)
500 (260)	31.0 (213.6)	70.0 (482.3)	27,300 (188 097)
600 (316)	29.1 (200.5)	70.0 (482.3)	26,500 (182 585)
650 (343)	28.2 (194.3)	70.0 (482.3)	26,000 (179 140)
700 (371)	27.2 (187.4)	70.0 (482.3)	25,500 (175 695)
750 (399)	26.3 (181.2)	69.1 (476.1)	24,850 (171 217)
800 (427)	25.5 (175.7)	64.3 (443.0)	24,200 (166 738)
850 (454)	24.7 (170.2)	58.6 (403.8)	23,350 (160 882)
900 (482)	24.0 (165.4)	52.3 (360.3)	22,500 (155 025)
950 (510)	23.3 (160.5)	45.9 (316.3)	21,450 (147 791)
1,000 (538)	22.6 (155.7)	40.4 (278.4)	20,400 (140 556)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are “typical,” unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-13
ASTM A240 Stainless Steel Type 309

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.08
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	22/24
Nickel	12/15
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	30.0 (206.7)	75.0 (516.8)	28,776 (198 270)
100 (38)	30.0 (206.7)	75.0 (516.8)	28,115 (193 715)
150 (66)	27.6 (190.2)	75.0 (516.8)	27,808 (191 595)
200 (93)	26.3 (181.2)	75.0 (516.8)	27,500 (189 475)
250 (121)	25.1 (172.9)	74.9 (515.7)	27,250 (187 753)
300 (149)	24.2 (166.7)	74.7 (514.7)	27,000 (186 030)
400 (204)	22.7 (156.4)	73.2 (504.0)	26,400 (181 896)
500 (260)	21.6 (148.8)	71.6 (493.3)	25,900 (178 451)
600 (316)	20.8 (143.3)	70.2 (483.7)	25,300 (174 317)
650 (343)	20.5 (141.2)	69.3 (477.5)	25,050 (172 594)
700 (371)	20.2 (139.2)	68.3 (470.6)	24,800 (170 872)
750 (399)	20.0 (137.8)	67.2 (463.0)	24,450 (168 461)
800 (427)	19.7 (135.7)	65.8 (453.4)	24,100 (166 049)
850 (454)	19.4 (133.7)	64.2 (442.3)	23,800 (163 982)
900 (482)	19.1 (131.6)	62.5 (430.6)	23,500 (161 915)
950 (510)	18.8 (129.5)	60.4 (416.2)	23,150 (159 503)
1,000 (538)	18.4 (126.8)	58.2 (401.0)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are "typical," unless otherwise indicated, and should not be taken as guaranteed properties.

Table B-14
ASTM A240 Stainless Steel Type 310

A — Chemical Composition of Elements

Elements	Chemical Composition, %
Carbon	0.08
Manganese	2.00
Phosphorus	0.045
Sulfur	0.030
Silicon	0.75
Chromium	24/26
Nickel	19/22
Iron	Bal.

B — Typical Tensile Properties

Temperature, °F (°C)	Minimum Yield, ksi (MPa)	Minimum Tensile, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
−20 (−29)	30.0 (206.7)	75.0 (516.8)	28,776 (198 270)
100 (38)	30.0 (206.7)	75.0 (516.8)	28,115 (193 715)
150 (66)	27.9 (192.2)	74.6 (514.0)	27,808 (191 595)
200 (93)	26.5 (182.6)	74.2 (511.2)	27,500 (189 475)
250 (121)	25.3 (174.3)	72.5 (499.5)	27,250 (187 753)
300 (149)	24.2 (166.7)	70.8 (487.8)	27,000 (186 030)
400 (204)	22.6 (155.7)	69.6 (479.5)	26,400 (181 896)
500 (260)	21.4 (147.4)	69.5 (478.9)	25,900 (178 451)
600 (316)	20.6 (141.9)	69.5 (478.9)	25,300 (174 317)
650 (343)	20.2 (139.2)	69.5 (478.9)	25,050 (172 594)
700 (371)	19.9 (137.1)	69.3 (477.5)	24,800 (170 872)
750 (399)	19.6 (135.0)	68.8 (474.0)	24,450 (168 461)
800 (427)	19.4 (133.7)	68.0 (468.5)	24,100 (166 049)
850 (454)	19.1 (131.6)	66.9 (460.9)	23,800 (163 982)
900 (482)	18.8 (129.5)	65.5 (451.3)	23,500 (161 915)
950 (510)	18.5 (127.5)	63.8 (439.6)	23,150 (159 503)
1,000 (538)	18.2 (125.4)	61.6 (424.4)	22,800 (157 092)

GENERAL NOTES:
(a) Properties taken from ASME BPVC, Section II.
(b) Properties are “typical,” unless otherwise indicated, and should not be taken as guaranteed properties.

(21)

Table B-15
Other Stainless Steels, Nickel Alloys, and Titanium Used for Stacks and Chimney Liners

Designations			Nominal Chemical Composition, wt %								
Alloy	UNS	ASTM	C	Cr	Ni	Mo	Cu	N	Ti	Fe	Other
409	S40900 [Note (1)]	A240	0.08	11	0.5	...	...	...	...	Bal.	0.75 max.
317L	S31703	A240	0.03	19	13.0	3.25	...	...	...	Bal.	...
317LM	S31725	A240	0.03	19	16.0	4.25	...	...	...	Bal.	...
317LMN	S31726	A240	0.03	19	16.0	4.0	...	0.15	...	Bal.	...
2205	S31803	A240	0.03	22	5.0	3.0	...	0.15	...	Bal.	...
255	S32550	A240	0.03	25	6.0	3.0	2.0	0.15	...	Bal.	...
...	6% Mo [Note (2)]	A240 B688	0.02	20/24	18/25	6/7.3	0/1	0.2/0.5	...	Bal.	...
625	N06625	B443	0.05	22	Bal.	9.0	...	...	...	...	Cb+Ta
276	N10276	B575	0.02	16	Bal.	16.0	...	...	...	...	W
22, 622	N06022	B575	0.02	22	Bal.	13.0	...	...	...	...	W
59	N06059	B575	0.02	23	59.0	16.0	...	...	...	...	...
686	N06686	B575	0.01	21	57.0	16.0	...	...	...	...	W
...	Titanium R50250	B265	0.08	...	...	...	...	...	Bal.	0.12	Residuals

NOTES:
(1) Per A240, an order specifying S40900 or Type 409 shall be specified by any one of S40910, S40920, or S40930.
(2) Because the 6% molybdenum super-austenitic stainless steels are proprietary, it is necessary to show a range of compositions.

Table B-16
Thermal Coefficients of Expansion

	Average Coefficient of Linear Thermal Expansion (in./in./°F × 10^{-6}) From 32°F				
ASTM Alloy Designation	400°F (204°C)	600°F (316°C)	800°F (427°C)	1,000°F (538°C)	1,200°F (649°C)
ASTM A36	6.8	7.2	7.7	8.0	8.2
ASTM A242	6.9	7.0	7.2	7.5	7.6
ASTM A588	6.9	7.0	7.2	7.5	7.6
ASTM A387, Grade 11, 12	6.8	7.2	7.5	7.8	8.1
ASTM A176, Type 409	5.8	6.1	6.4	6.6	6.8
ASTM A176, Type 410	5.8	6.1	6.4	6.6	6.8
ASTM A240, Type 304	9.6	9.8	10.1	10.3	10.5
ASTM A240, Type 316	9.6	9.8	10.1	10.3	10.5
ASTM A240, Type 309	8.8	9.3	9.5	9.7	9.9
ASTM A240, Type 310	8.1	8.3	6.7	9.0	9.0
ASTM B686, 6% Mo	8.9	9.3	9.8	10.0	...
ASTM B443, Alloy 625	7.3	7.4	7.6	7.8	8.2
ASTM B575, Alloy C-276	6.2	6.7	7.3	7.4	7.8

Table B-17
Maximum Nonscaling Temperature

ASTM Type or Grade [Note (1)]	Maximum Temperature, °F (°C)
A36	800°F (427°C)
A242, Type 1	950°F (510°C)
A387, Grade 11, 12	1,050°F (566°C)
A176, Type 409	1,300°F (704°C)
A176, Type 410	1,300°F (704°C)
A240, Type 304	1,650°F (899°C)
A240, Type 316	1,650°F (899°C)
A240, Type 317	1,650°F (899°C)
A240, Type 309	1,900°F (1 038°C)
A240, Type 310	2,000°F (1 038°C)

NOTE: (1) Manufacturers of types or grades not listed should be consulted for recommendations.

NONMANDATORY APPENDIX C
LININGS AND COATINGS

See Figures C-1 and C-2 and Tables C-1 and C-2.