2.2.1 General Considerations
(a) Materials shall conform to the applicable requirements in the sections hereinafter detailed.
(b) The contractor shall submit one copy of the chemical-composition and mechanical-property mill test reports for all steels used to the owner for approval prior to construction unless otherwise indicated.
(c) When required for testing purposes, the contractor will furnish the owner with identified scrap samples of the shell plates.
(d) This section does not apply to linings and coatings of stacks. See section 3.
(e) Corrosion allowances shall be considered (typically 1/16 in. to 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.

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

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 1/16 in. to 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.

2.2.2 Shell and Base Plates. For more information on this subject, see Tables B-1 through B-11 in Nonmandatory Appendix B. Additional materials or material grades may be applicable.
2.2.3 Stiffeners and Structural Braces and/or Framework
   (a) Stiffeners and structural braces and/or framework typically may be of one or more of the following materials:
      (1) carbon steels conforming to the ASTM A36, A283, or A529 Specifications
      (2) high-strength, low-alloy steels conforming to the ASTM A242, A572, or A588 Specifications
      (3) stainless steels conforming to the ASTM A240 or A666 Specifications or nickel-containing alloys having compositions similar to those of the shell plate
   (b) Protection may be required against corrosion for components exterior to the shell and against corrosion and/or oxidation for components on the shell interior. Section 3 should be consulted and utilized as appropriate.

2.2.6 Bolts, Washers, and Nuts
   (a) Unless otherwise specified, carbon and high-strength steel bolts conforming to the ASTM A307, A325, or A449 Specification will be utilized.
   (b) High-strength alloy steel bolts may be required, and these should conform to the ASTM A354 or A490 Specification.
   (c) For high-temperature applications, bolt material should conform to the ASTM A193, Grade B7 Specification covering alloy and stainless steels. Stainless steel bolts are also covered under the ASTM F593 Specification.
   (d) Unless otherwise specified, nuts should conform to the ASTM A563 Specification. Stainless/heat-resisting nuts shall be of a material corresponding to that of the bolt unless galling/seizing considerations dictate otherwise.
   (e) Washers shall conform to the ASTM F436 Specification. Stainless/heat-resisting washers shall be of a material corresponding to that of the bolt.
   (f) Protection from corrosion may be required. Section 3 should be consulted and utilized as appropriate.
2.2.7 Appurtenances

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

(2) Because of potential corrosion problems, stainless steel conforming to the ASTM A240 Specification or higher alloyed, corrosion-resistant materials should be considered.

(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. Drain pipe shall be of corrosion-resistant material such as Type 304 or Type 316 stainless steel conforming to the ASTM A240 or A666 Specification, nickel alloy, or plastic.

2.2.8 Welding Electrodes

(a) AWS D1.1, Structural Welding Code Steel is usually specified for structural welding of steel stacks. As an alternative, ASME BPVC, Section IX, Welding, Brazing, and Fusing Qualifications 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.
(b) Welding electrodes with a minimum tensile strength of 70 ksi are to be used for carbon steel applications in steel stack construction. The type of electrode specified is a function of the welding process to be used.

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

(d) For steel stack construction using alloy steels, such as ASTM A335 and A387, E8018-B2L electrode with welding procedures conforming to AWS D10.8, Recommended Practice for Welding of Chromium-Molybdenum Steel Piping and Tubing should be used.

(e) When stainless steels and nickel alloys are used as plate, sheet, or as clad plate, the following specifications apply:
   (1) AWS A5.4, Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding
   (2) AWS A5.9, Specification for Bare Stainless Steel Welding Electrodes and Rods
   (3) AWS A5.11, Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding
   (4) AWS A5.14, Specification of Nickel and Nickel Alloy Bare Welding Electrodes and Rods
   (5) AWS A5.1, Specification for Covered Carbon Steel Arc Welding Electrodes
   (6) AWS A5.18, Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding
   (7) AWS A5.20, Specification for Carbon Steel Electrodes for Flux Cored Arc Welding

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

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

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

3.2.1 Temperature/Corrosion.

(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).

3.2.2 Other Critical Temperatures

(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 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.

(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.

(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 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 1100°F (593°C).
3.2.4.1 Organic Linings
Most acid-resistant organic linings fail or lose their flexibility and ability to resist liquid or vapor penetration at temperatures over 300°F (149°C). Some manufacturers claim that their products can perform up to 500°F (260°C). 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.

3.2.4.2 Inorganic Linings
(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 utilize chemically inert fillers. They are particularly suited for severe chemical environments and mild/moderate temperature environments.
3.3.1 Classification of Coatings.

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

(j) 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.

(k) 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 2100o F (1100oC). The high strength and density of geopolymers also provide excellent abrasion resistance.

3.3.1 Classification of Coatings.

(h) Epoxy Coating Systems. These coatings provide good resistance to industrial fumes and marine atmosphere exposures. These coatings exhibit good flexibility, hardness, and excellent toughness and are of 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.

(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, but 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.

FOR INFORMATION ONLY: existing 3.3.1(j) through (n) will be redesignated (k) through (o).
### 3.3.2 Important Coating Considerations

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<tr>
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<tr>
<td>(a) environment (rural, industrial, and marine)</td>
<td>(a) environment (rural, industrial, and marine)</td>
</tr>
<tr>
<td>(b) exposure to temperature</td>
<td>(b) exposure to temperature</td>
</tr>
<tr>
<td>(c) weathering</td>
<td>(c) chemical exposure</td>
</tr>
<tr>
<td>(d) aesthetic color retention</td>
<td>(d) weathering</td>
</tr>
<tr>
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<td>(d) aesthetic color retention</td>
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<tr>
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<td>(e) durability</td>
</tr>
<tr>
<td>(g) cost</td>
<td>(f) surface preparation</td>
</tr>
<tr>
<td>(h) coating manufacturer’s recommendation</td>
<td>(g) cost</td>
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<tr>
<td></td>
<td>(h) coating manufacturer’s recommendation</td>
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</table>
Record #19-2949 – Revision STS-1-2016 – Concrete Refractory

The below are proposed additions. Existing para. 4.13 will be redesignated as para 4.14:

4.13 Stacks with Refractory-Concrete Lining

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 un-lined 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.
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<th>Proposed Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>9.4.3 Inspection Procedure</strong></td>
<td><strong>9.4.3 Inspection Procedure</strong></td>
</tr>
<tr>
<td>(c) The Integrity of the lining shall be judged on a visual basis, supplemented by routine probing to determine hardness, soundness, and/or general conditions.</td>
<td>(c) Since the main purpose of the refractory-concrete lining is to protect the steel shell from extreme heat, it is important to ensure 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.</td>
</tr>
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Table B-15  Other Stainless Steels, Nickel Alloys, and Titanium Used for Stacks and Chimney Liners

<table>
<thead>
<tr>
<th>Designations</th>
<th>Nominal Chemical Composition (% Weight)</th>
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<td>Alloy</td>
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<td>409</td>
<td>S40900</td>
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<tr>
<td>317L</td>
<td>S31703</td>
</tr>
<tr>
<td>317LM</td>
<td>S31725</td>
</tr>
<tr>
<td>317LMN</td>
<td>S31726</td>
</tr>
<tr>
<td>2205</td>
<td>S31803</td>
</tr>
<tr>
<td>255</td>
<td>S32550</td>
</tr>
<tr>
<td>. . . 6% Mo</td>
<td>S31726</td>
</tr>
<tr>
<td>625</td>
<td>N06625</td>
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<tr>
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<td>22, 622</td>
<td>N06022</td>
</tr>
<tr>
<td>59</td>
<td>N06059</td>
</tr>
<tr>
<td>686</td>
<td>N06686</td>
</tr>
<tr>
<td>. . Titanium</td>
<td>R50250</td>
</tr>
</tbody>
</table>

**NOTES:**

(1) Because the 6% molybdenum super-austenitic stainless steels are proprietary, it is necessary to show a range of compositions.

(2) Per A240, an order specifying S40900 or Type 409 shall be satisfied by any one of S40910, S40920, or S40930.

ADD TO SECTION 10 REFERENCES:

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
NONMANDATORY APPENDIX E
EXAMPLE CALCULATIONS

E-1 EXAMPLE CALCULATIONS

E-1.1 Example 1: VELOCITY PRESSURE CALCULATIONS

See Table E-1.1-1.

E-1.2 Example 2

See Table E-1.2-1.

E-1.3 Example 3: Calculation Along Wind Loads

See Table E-1.3-1. Wind design based upon ASCE 7, as applicable for steel stack design used as an Example of the design method for STS-1.

Stack Height (H) = 140

Stack Diameter — Top 5/8 (D) K = 8

Importance Factor (unitsless) T = 1.00 (Tables E-3.1 and E-3.2)

Exposure Category C

PARAGRAPH 4.3.35

Table E-1.1-1 Example 1: Velocity Pressure, $q_a$, Calculations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Stack 1</th>
<th>Stack 2</th>
<th>Stack 3</th>
<th>Stack 4</th>
<th>Units of Measure/References</th>
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<tbody>
<tr>
<td>$V$</td>
<td>Basic wind speed</td>
<td>125.000</td>
<td>125.000</td>
<td>125.000</td>
<td>125.000</td>
<td>mph</td>
</tr>
<tr>
<td>$h$</td>
<td>Stack height</td>
<td>140.000</td>
<td>140.000</td>
<td>140.000</td>
<td>140.000</td>
<td>ft</td>
</tr>
<tr>
<td>$d$</td>
<td>Top outside diameter</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
<td>ft</td>
</tr>
<tr>
<td>$K_a$</td>
<td>Topographical factor</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>Eq. (4-6)</td>
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<tr>
<td>$K_e$</td>
<td>Exposure coefficient</td>
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<td>1.350</td>
<td>1.350</td>
<td>1.350</td>
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<td>Velocity pressure</td>
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<td>54.400</td>
<td>54.400</td>
<td>54.400</td>
<td>psf</td>
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Table E-1.1-1: Velocity Pressure, $q_a$, Calculations

<table>
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<th>Variable</th>
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<th>Stack 1</th>
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<th>Stack 3</th>
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<tr>
<td>$V$</td>
<td>Basic wind speed</td>
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<td>125.000</td>
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<td>mph</td>
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<td>$K_e$</td>
<td>Exposure coefficient</td>
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<td>1.350</td>
<td>Table E-4</td>
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<td>$q_a$</td>
<td>Velocity pressure</td>
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<td>54.400</td>
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For specific information, please refer to the ASME Standards and Certification.
Table E-1.3-1 Stack Along Wind Loading

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<thead>
<tr>
<th>Location, ( i )</th>
<th>Elevation, ( z_i ), ft</th>
<th>Velocity Pressure Coefficient, ( C_{o,i} )</th>
<th>Velocity Pressure, ( q_{i,V} ), psf</th>
<th>Force Coefficient, ( C_z )</th>
<th>Mean Load, ( M_i ), kip</th>
<th>Base Moment, ( M_i ), kip-ft</th>
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<tbody>
<tr>
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<td>140</td>
<td>1.360</td>
<td>36.836</td>
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<td>120</td>
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<tr>
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<tr>
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<td>80</td>
<td>1.310</td>
<td>30.975</td>
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<td>76.0000</td>
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<td>13</td>
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<td>23.660</td>
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<td>66.6400</td>
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<td>21.260</td>
<td>0.583</td>
<td>62.9598</td>
<td>58.0640</td>
</tr>
</tbody>
</table>

**General Notes:**

1. Total Base Moment: \( M_b = M_i + M_b^* = 1,549.15 \) kip-ft
2. A linear variation in load between the calculation points is assumed in calculation of the moments.

**Reduced Frequency**

Coefficient \( R_a \) (continued)

\[
R_a = n_a \left( \frac{h}{L} \right)^{2} = 7.3500 \times 0.5^{2} = 1.9525 \times 0.5^{2} = 0.4884 \]

Coefficient \( g_v \) (unitless)

\[
g = 4.68 q_i / V_i^2 = 9.907 \times \frac{4.68}{9.907} = 0.4603 \times 9.907 = 4.5459 \times 9.907 = 0.4949 \]

Coefficient \( g_{z_{31}} \) (unitless)

\[
g_{z_{31}} = 0.8 \times \left( \frac{z_{i}}{L} - \frac{1}{2} \right)^{2} = 0.8 \times 1^{2} = 0.8 \times 0.25 = 0.2 \]

Coefficient \( R_b \) (unitless)

\[
R_b = \frac{C_{o_i} / C_{o_i} - 0.0007}{1 + 0.0007} = 0.0494 \times \frac{1}{1 + 0.0007} = 0.0494 \times 0.9993 = 0.0492 \]

Coefficient \( R_c \) (unitless)

\[
R_c = \frac{C_{o_i} / C_{o_i} - 0.0007}{1 + 0.0007} = 0.0492 \times \frac{1}{1 + 0.0007} = 0.0492 \times 0.9993 = 0.0491 \]

Coefficient \( R_d \) (unitless)

\[
R_d = \frac{C_{o_i} / C_{o_i} - 0.0007}{1 + 0.0007} = 0.0491 \times \frac{1}{1 + 0.0007} = 0.0491 \times 0.9993 = 0.0490 \]

Coefficient \( R_e \) (unitless)

\[
R_e = \frac{C_{o_i} / C_{o_i} - 0.0007}{1 + 0.0007} = 0.0490 \times \frac{1}{1 + 0.0007} = 0.0490 \times 0.9993 = 0.0489 \]

\[
R_f = \frac{C_{o_i} / C_{o_i} - 0.0007}{1 + 0.0007} = 0.0489 \times \frac{1}{1 + 0.0007} = 0.0489 \times 0.9993 = 0.0488 \]

**Mass per unit length of top one-third of stack** \( m_i \) (lbm-ft)

\[
m_i = \frac{4.68 q_i}{V_i} = 4.68 \times 0.4603 \times 9.907 = 2.200 \times 9.907 = 2.180 \times 9.907 = 2.150 \]

**Air Density** \( \rho \) (lbm/ft³)

\[
\rho = 0.076474 \]

**Avg. Stack Diameter** \( D_i \) (ft)

\[
D_i = 0.0000 \]

**Aerodynamic Diameter** \( D_i \) (ft)

\[
D_i = 0.0000 \]

**Aerodynamic Diameter** \( D_i \) (ft)

\[
D_i = 0.0000 \]

**Structural Diameter** \( B_{i} \) (unitless)

\[
B_{i} = \frac{C_{o_i} \sigma_{y} \rho D_i V_i}{4 m_i n_i \sqrt{1.6}} = 0.009 \]

**Total Diameter** \( B \) (unitless)

\[
B = B_{i} = 0.0012284 = 0.013 \]
### Table E-1.3-1 Stack Along Wind Loading

<table>
<thead>
<tr>
<th>Location, Location,</th>
<th>Elevation, ft</th>
<th>Velocity Pressure Coefficient, $C_v$</th>
<th>Velocity Pressure, $P_v$, lb/ft$^2$</th>
<th>Force Coefficient, $C_f$</th>
<th>Force Load, $P_f$, kip</th>
<th>Base Moment, $M_o$, ft-kip</th>
<th>Base Moment, $M^*$, kip-ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140</td>
<td>1.360</td>
<td>38.856</td>
<td>0.0103</td>
<td>84.2740</td>
<td>122.4351</td>
<td>111.7013</td>
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<tr>
<td>2</td>
<td>130</td>
<td>1.355</td>
<td>38.717</td>
<td>0.0103</td>
<td>83.3746</td>
<td>113.4475</td>
<td>113.7013</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>1.350</td>
<td>38.576</td>
<td>0.0103</td>
<td>82.4878</td>
<td>114.1000</td>
<td>114.7013</td>
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<td>4</td>
<td>110</td>
<td>1.285</td>
<td>32.886</td>
<td>0.0103</td>
<td>80.0884</td>
<td>120.6897</td>
<td>115.7013</td>
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<td>5</td>
<td>100</td>
<td>1.260</td>
<td>32.256</td>
<td>0.0103</td>
<td>78.5856</td>
<td>117.3525</td>
<td>117.7013</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
<td>1.210</td>
<td>31.744</td>
<td>0.0103</td>
<td>77.2757</td>
<td>118.9967</td>
<td>119.7013</td>
</tr>
<tr>
<td>7</td>
<td>80</td>
<td>1.210</td>
<td>30.920</td>
<td>0.0103</td>
<td>75.5890</td>
<td>119.6403</td>
<td>120.7013</td>
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<td>8</td>
<td>70</td>
<td>1.170</td>
<td>29.951</td>
<td>0.0103</td>
<td>73.0822</td>
<td>120.2757</td>
<td>121.7013</td>
</tr>
<tr>
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<td>60</td>
<td>1.130</td>
<td>28.928</td>
<td>0.0103</td>
<td>70.6504</td>
<td>120.8714</td>
<td>122.7013</td>
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<tr>
<td>10</td>
<td>50</td>
<td>1.000</td>
<td>27.904</td>
<td>0.0103</td>
<td>68.2186</td>
<td>121.4291</td>
<td>123.7013</td>
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<tr>
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<td>40</td>
<td>1.000</td>
<td>26.624</td>
<td>0.0103</td>
<td>65.7956</td>
<td>121.9148</td>
<td>124.7013</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>0.980</td>
<td>25.488</td>
<td>0.0103</td>
<td>63.4083</td>
<td>122.3414</td>
<td>125.7013</td>
</tr>
<tr>
<td>13</td>
<td>20</td>
<td>0.990</td>
<td>24.040</td>
<td>0.0103</td>
<td>59.0204</td>
<td>122.7181</td>
<td>126.7013</td>
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<td>0.950</td>
<td>22.700</td>
<td>0.0103</td>
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<td>123.0666</td>
<td>127.7013</td>
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<tr>
<td>15</td>
<td>0</td>
<td>0.950</td>
<td>21.700</td>
<td>0.0103</td>
<td>52.0588</td>
<td>123.4042</td>
<td>128.7013</td>
</tr>
</tbody>
</table>

**GENERAL NOTES:**
(a) Total Base Moment: $M = M_o + M^* = 5,669.45$ kip-ft
(b) A linear variation in load between the calculation points is assumed in calculation of the moments.

\[
M_o = 749.2419 \\
M^* = 799.9092
\]

\[
M_o = 1170.897 \\
M^* = 1390.197
\]
For a group of two or more identical steel stacks, the amplification factor $a$ and Strouhal Number $S$ are given as,

$$a = 1.58 - \frac{A_i}{D} - 3$$

$$S = 0.16 + \frac{1}{300} \left[ \frac{A_i}{D} \right]$$

For $\frac{A_i}{D} < 3$ or for groups of identical steel stacks or nonidentical steel stack groups, interference effects shall be established by reference to model test or other studies of similar arrangements.

E-3 COMPUTATION OF VORTEX-INDUCED RESPONSE

E-3.1 Evaluation of Loads Due to Vortex Shedding

The equation defining $a_i/D$ can be written as,

$$\frac{a_i}{D} = \left[ \frac{A_i}{D} \left( 1 - \frac{A_i}{D} \right) \right]^{\frac{1}{2}}$$

$$A_i = C_1 C_{m_i} m_{0} \sqrt{\beta_i} \lambda_i$$

For $m_{0} \beta_i > 0.8$

$$a_i = \left[ \frac{A_i}{D} \left( 1 - \frac{A_i}{D} \right) \right]^{\frac{1}{2}}$$

For $m_{0} \beta_i < 0.4$

$$a_i = 0.5 \left( \frac{m_{0} \beta_i}{C_1} \right)^{\frac{1}{2}}$$

E-3.2 Practical Application

The general solution may be reduced to the following formulas of vortex shedding and then used to determine equivalent static loads. For any values of $m_{0} \beta_i$,

$$C_M = \left( \frac{1}{H} \right) \int_{0}^{\gamma_f} \left( \phi^{(0)}(\gamma) d\gamma \right)$$

$$R = \left( \frac{1}{H} \right) \int_{0}^{\gamma_f} \phi^{(1)}(\gamma) d\gamma$$

where $\phi^{(0)}$ and $\phi^{(1)}$ are the peak values for vortex shedding response at:

$$\gamma = \xi, \eta_0$$

and $\xi = \bar{a}, \eta_0$

where $\bar{a}$ is the maximum value and used to calculate peak loads and stresses, while $\eta_0$ defines equivalent constant amplitude for fatigue calculations. The values of $\xi$ and $\eta_0$ are determined from the following:

For $m_{0} \beta_i > 0.8$

$$\xi = 4.0$$

$$\eta = 2.0$$

For $m_{0} \beta_i < 0.4$

$$\xi = 1.6$$

$$\eta = 1.5$$

Linear interpolation is used for $0.4 < m_{0} \beta_i < 0.8$.

E-3.3 Equivalent Static Loads

The equivalent static loads corresponding to the displacement $u_{eq}$ are given by

$$\delta_{eq} = \delta_{eq}(\text{strain}) \phi^{(0)}(\gamma) d\gamma$$

$$w_{eq} = w_{eq}(\text{strain}) \phi^{(1)}(\gamma) d\gamma$$

The number of cycles in $T$ years at the equivalent constant amplitude $u_{eq}$ is given by

$$N_{eq} = \left( \frac{1}{2} \right) \int_{0}^{\gamma_f} \left( \phi^{(0)}(\gamma) \right) \left( \phi^{(1)}(\gamma) \right) d\gamma$$

$V_{eq}$ and $V_{eq}$ are evaluated at the same height.

A fatigue analysis can be performed using the methods in the CIC/NMD Model Code for Steel Chimneys or the American Institute of Steel Construction (AISC).

E-3.4 Variable Diameter Stacks

For variable diameter stacks, the preceding method may be used with the following modifications to account for the range of possible critical diameters. The previous method is used with the following changes in formulas. The peak response is determined by varying the range of height being considered for any mean diameter, $D_M$, for a portion of the stack where the diameter varies 15% from this mean diameter. The peak response is determined by iterations over the full height of the stack.

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\[ R = 1.0 \text{ for nearly parallel} \]
\[ C_0 = 0.6 \times R \]

The limits change to
\[ w, f < 0.88 \]
\[ w, f > 0.48 \]

### E.3.5 Symbols and Definitions

- \( A_1, A_2 \) = constant
- \( F \) = maximum value amplitude for static equivalent design loads, ft
- \( f \) = maximum value amplitude for static equivalent fatigue loads, ft
- \( \Delta f_{D} \) = rms dynamic displacement at \( z = z_0 \), ft
- \( C_2 \) = constant for grouped/isolated stacks
- \( C_3 \) = mode shape constant
- \( D \) = mean diameter for the segment \( z_0 \) to \( z_1 \) or for stacks with less than ±10\% variation over the top one-third of the value of \( D \) is the average over the top one-third, ft
- \( g \) = gravitational acceleration (32.2 ft/sec^2)
- \( g_0 \) = constant for maximum static equivalent loads
- \( g_1 \) = constant for fatigue static equivalent loads
- \( H \) = height of steel stack, ft
- \( h_0 \) = equivalent uniform mass per unit length, lbm/ft
- \( n_0 \) = dimensionless mass
- \( n_0(z) \) = mass per unit length at height \( z \), lbm/ft
- \( n_1 \) = natural frequency of mode, Hz
- \( N_0 \) = effective number of cycles in period years
- \( N_0 \) = constant for tapered stacks
- \( S \) = Strouhal number
- \( T \) = life of stack in years
- \( V_c \) = critical speed for the segment \( z_1 \) to \( z_2 = 5n_0D, \text{ft/sec} \)
- \( V_{m} \) = mean hourly design speed (50-yr return period) at the critical height \( z_c \), used for evaluating the critical wind velocity (ft/sec)
- \( z \) = height z under consideration, ft
- \( z_0, z_1 \) = upper and lower limits of a section of the stack over which the diameter changes by 30\% (e.g., \( D \times 1.30\%), ft
- \( z_0 \) = \( \frac{1}{2}(z_1 + z_2) \) or, for stacks with less than ±10\% variation over the top third, \( z_0 = \frac{3}{4}D, \text{ft} \)
- \( z_{m0} \) = height at maximum modal shape displacement (H for mode 1), ft

### Table E-4.1 Mode Shape by Element

<table>
<thead>
<tr>
<th>( k )</th>
<th>( \Delta f_{D} )</th>
<th>( n_0(z) )</th>
<th>( m_{D} )</th>
<th>( m_{S} )</th>
<th>( m_{L} )</th>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>135</td>
<td>10</td>
<td>320</td>
<td>3.0000</td>
</tr>
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<td>130</td>
<td>125</td>
<td>10</td>
<td>320</td>
<td>0.0022</td>
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<td>120</td>
<td>115</td>
<td>10</td>
<td>320</td>
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</tr>
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<td>110</td>
<td>105</td>
<td>10</td>
<td>320</td>
<td>0.0702</td>
</tr>
<tr>
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<td>100</td>
<td>95</td>
<td>10</td>
<td>320</td>
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</tr>
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<td>85</td>
<td>10</td>
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<td>80</td>
<td>75</td>
<td>10</td>
<td>320</td>
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<td>70</td>
<td>65</td>
<td>10</td>
<td>320</td>
<td>0.3413</td>
</tr>
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<td>60</td>
<td>55</td>
<td>10</td>
<td>320</td>
<td>0.2646</td>
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<td>50</td>
<td>45</td>
<td>10</td>
<td>320</td>
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<td>35</td>
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<td>320</td>
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<td>0</td>
<td>0</td>
<td>10</td>
<td>320</td>
<td>0.0000</td>
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</tbody>
</table>

### Table E-4.2 Equivalent Fatigue and Static Loads by Element

<table>
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<tr>
<th>( k )</th>
<th>( A_h )</th>
<th>( n_0(z) )</th>
<th>( n_0(z) )</th>
<th>( n_0(z) )</th>
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</thead>
<tbody>
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<td>1.00</td>
<td>140.00</td>
<td>3.266</td>
<td>3.155</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
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</tr>
<tr>
<td>3.00</td>
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<td>0.00</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \phi(z) \) = normalized mode shape at height \( z \) (unitless)
\( \Delta(z) \) = max normalized modal displacement \( \phi(z) \) for mode at \( z = z_{m0} \) for the first mode
\( \Delta(z) \) = equivalent static load, ft
\( \Delta(z) \) = equivalent fatigue load, lbm/ft

### E.4 VORTEX SHEDDING EXAMPLE

**EXAMPLE CALCULATION**

See Tables E-4.1 and E-4.2. Vortex Shedding Design Per E.2 for steel stacks with less than 10\% variation in diameter in the upper one-third of the stack. Stack is 140 ft tall and has an 8 ft diameter and 0.3125 in. constant wall thickness.

Height (H):
\( H = 140.00 \text{ ft} \)
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NOTE: Additional revisions are highlighted in yellow.

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Critical Elevation:
\[ z_c = \frac{5}{6} H \]
\[ = 116.67 \text{ ft} \]
\[ z_t = 140.00 \text{ ft} \]
\[ z_i = 0.00 \text{ ft} \]

Critical Velocity:
\[ V_c = \frac{1}{8} \sqrt{\frac{g \cdot D_m}{c_f}} \]
\[ = 53.80 \text{ fps} \]
\[ V_{cr} = 36.41 \text{ mph} \]

Mean Hourly Design Speed at SH/6 (ft):
\[ V_c = \frac{\sqrt{\frac{g \cdot D_m}{c_f} \cdot 36}}{\sqrt{12}} \]
\[ = 115.78 \text{ fps} \]

If \[ V_c > 1.2 \times V_{cr} \] and region
**Region:**
- \[ V_c > V_{cr} \] **Need not Consider**
- **Consider**

If \[ V_c > V_{cr} \] but less than 1.2 \times V_{cr}, reduction factor allowed:

Grouped Chimney effects must be considered below:

\[ A < 15 \quad \frac{A}{z} < 20 \]

For spacing between stacks:

Advice: If
- \[ \frac{A}{z} < 3 \quad \text{“Seek Advice,” “Use Code”} \]

\[ \eta_{cr} = 1.0 \]
\[ \eta_{CR} = 1.5 \left( \frac{A}{z} \right) \]
\[ \eta_{CR} = 0.85 \]

Advice: “Use Code”

\[ \eta_{CR} = 2.0 \]

\[ \eta_{CR} = 0.5 \left( \frac{A}{z} \right) \]

- \[ \sqrt{\frac{g \cdot D_m}{c_f} \cdot 36} \]

95
For Peak Loads:
\[ V_E = 80 \text{kW} \]
\[ N_L = 4.8134 \]

For Fatigue:
\[ a_n = 4.5125 \]
\[ a_r = 4.5925 \]
\[ a_i = 2.67 \]
\[ \beta = 0.264 \]

Maximum Deflection at Top for First Mode:
\[ M_n = 1.0 \]
\[ C_1 = 0.60 \]
\[ m_n = 65.34 \]
\[ m_n = C_1 C_2 \]
\[ A_1 = 0.01390 \]
\[ A_2 = 2.30 \]

\[ \alpha_n = \frac{0.5}{A_1} \]

For any value of $a_n \times \beta$:  
\[ \alpha_n = \frac{(m_n \beta < 0.4)}{0.4} \]
\[ \alpha_n = 3.81 \]

\[ V_E = \left[ \frac{1}{(50)} \right] \left( \frac{V_{CR}}{V_{CR}} \right)^{10.5} \exp \left[ -15 \frac{V_{CR}}{V_{CR}} \right] \]

Number of Stresses at Peak Moment for Fatigue Consideration:
\[ N = 1.17 \times 10^8 \text{ cycles (based on 50 yr)} \]

\[ \text{Calculate Bending Stress Due to Peak Moment for Fatigue Consideration.} \]

Section Modulus:
\[ D = 8.0 \text{ in} \]
\[ D_0 = \frac{D}{4} \]
\[ S = \frac{32 D (D^2 - D_0^2)}{3} \]
\[ m_n = \frac{2.3995}{12} \]
\[ M = 12 \]
\[ N = 93.4 \text{ kips} \]

High bending stress level indicates failure for this stack configuration. Additional damping or aerodynamic wind screens such as helical strakes are required.
4.13 Section 4 Symbols and Definitions

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

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

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

*Note: The addition of \textit{unfactored} to the definition was approved in a previous ballot and is not a part of this record.