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Revision Memo

- 12/03** Technical Update to include the latest design provisions from ASCE STS-1.
Highlights of this revision are:
1. The fastest mile wind speed previously used with ASME STS-1 (1992) has been changed to a 3-second gust.
 2. Long and cross wind calculations have been updated to match ASME STS-1 (2000).
 3. Additional damping information added.
 4. Updated provisions for long and cross wind interference affects.
 5. Provided information regarding crosswind fatigue calculations.



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SCOPE

This section covers the specification, structural design and analysis of steel stacks of circular cross section and their foundations. This DP is intended as a supplementary guide to GP 04-05-01 (Steel Stacks), but it is not intended to supersede the GP and referenced codes and standards in the GP and this DP. It also covers the design of any linings installed inside the stack and / or insulation applied outside the stack. The section does not cover the thermal design of the stack, aimed at deriving its height, diameter and draught conditions.

While the section is aimed primarily at the specification and design of new stacks, it can also be used to assist in inspecting existing stacks and in developing solutions to problems discovered in existing stacks.

REFERENCES

GLOBAL PRACTICES

GP 04-01-03,	Design Loads for Structures
GP 04-05-01,	Steel Stacks
GP 04-06-01,	Reinforced Concrete Foundations, Anchor Bolts and Grout
GP 19-01-01	Paint and Protective Coatings
GP 19-03-03,	Castable Linings for Fired Heaters

DESIGN PRACTICES

[XXIX-A](#) Civil Design Data

OTHER REFERENCES

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- API 560, *Fired Heaters For General Refinery Service*, American Petroleum Institute, 2003.
- ASCE 7, *Minimum Design Loads for Buildings and other Structures*, 2002
- AISC, Supplement No. 1 to the Specification for Structural Steel Buildings, 2001



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OBJECTIVE

The intent of this section is to provide a relatively simple explanation of the various hazards faced by steel stacks and to amplify and explain the design requirements of **GP 04-05-01**.

It is hoped that, by using this guide:

- The purchaser will be able to write a specification that will truly reflect the needs and aspirations of the owner.
- ExxonMobil's supervising engineer will understand the work of the specialist designer.
- Inspectors will efficiently inspect existing stacks and develop solutions to problems found.

BACKGROUND

The design of steel stacks is normally carried out by a specialist stack builder, following the requirements of a specification, written by the purchaser. ExxonMobil's involvement with new stacks will normally be in helping to develop the specification and supervising the work of the designer.

Provided he/she follows the requirements of **GP 04-05-01**, an experienced stack designer should be able to design a stack that is safe, fully operable and which should provide trouble-free service throughout its design life. However, this expectation can only be realized if the designer is fully aware of the Owner's needs, which includes by implication, all relevant information about the plant served by the stack.

Unfortunately, in the past, purchasers have often not been aware of the necessity to convey this information in full to the stack builder at the time of inviting bids. Also, while preparing their bids, stack builders have been reluctant to risk jeopardizing their competitive position by inquiring more closely into the purchaser's needs. As a result, many stacks have been built which perform badly purely because the designer was not fully aware of the owner's needs and the full extent of the operating conditions.

The means by which the purchaser makes his needs known is the specification and a major aim of this section is to help ensure that stack specifications provide all of the information that a specialist designer needs to design a safe, economic and trouble-free stack.

Besides the problems discussed above, which are common to many plant equipment items, steel stacks are subject to certain specific hazards. One major such hazard is its potential for dynamic response to the wind. While this phenomenon has been known and studied for a century or more, it is only recently that researchers have developed sufficient knowledge to propose design methods (**Reference 1**) capable of approximating the self induced cross-wind response of a single stack or its response to aerodynamic interference by a nearby stack or tower. Even so, currently there is no reliable parameter which takes account of aerodynamic interference by a nearby stack or tower. In the past, designers used a number of parameters, some more reliable than others (**Reference 2**), to design both single and grouped stacks. As a result, some older stacks have histories of troublesome movement in the wind, for which various remedies have been used. These remedies will be discussed and analyzed later in this section.

Another major hazard which must be considered in the design of a steel stack is chemical attack. In a refinery or chemical plant, this will normally take the form of attack by condensing sulfur oxides ("acid corrosion").

These factors are fully taken into account in **GP 04-05-01**, which is based upon the **ASME STS-1** Code entitled *Steel Stacks*. This, in turn, is heavily influenced by the **CICIND Model Code for Steel Chimneys (Reference 3)**, first published in May 1988. (**CICIND** is the "Comite International des Cheminees Industrielles," an organization established in 1973 by chimney builders, designers and owners, to study chimney problems and harmonize the rather disparate national codes for their design and construction that existed at that time. The mechanism by which this was done was the development of "Model Codes.")

SPECIFYING STACKS

CHOICE OF STACK

Stacks can be of reinforced concrete, steel or plastic. They can be unlined or lined. They are normally self-supported and designed as cantilevers, fixed at the base. Sometimes, however, they are supported within a steelwork structure or by guy ropes or are stayed against an adjacent building. The choice of chimney type will be determined by cost and construction schedule and by its suitability for the required duty.

Steel or Concrete?

Steel stacks are usually more economic than concrete when the top diameter is less than 13 ft (4 m) and the height is 230 ft (70 m) or less. Stacks greater than 330 ft (100 m) tall are usually more economic in concrete than steel. Between heights of 230 ft and 330 ft (70 m and 100 m), the cost differential is very small and will be influenced by local conditions. Steel stacks can normally be designed, fabricated and erected faster than concrete chimneys of equivalent height. They also have a better record with regard to maintenance. If the cost differential is small, therefore, a steel stack should normally be chosen.

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preference to the concrete alternative. If the top diameter exceeds 13 ft (4 m), delivery of prefabricated stack sections becomes difficult, with consequent increases in cost.

Free-standing, Guyed or Tower Supported?

Guyed stacks can be more slender, lighter and, consequently, are often more economic than free-standing stacks. The guy ropes, however, may pose awkward restrictions on operations around the stack and are, in consequence, usually avoided in the confined spaces available in process plants.

The wind loading on the structure encompassing a tower-supported stack normally exceeds the wind load on a self-supporting cylindrical stack. In consequence, the combined cost of the support structure and relatively lightweight stack will normally exceed that of a self-supported stack of similar height and top diameter. If, however, the stack is required to support external vertical pipes and many platforms, this relationship could change and a structure supported stack could become economic.

Where possible, it is desirable to position a stack on top of the heater being served. This eliminates the costs of horizontal ducting, the lower part of the stack and its foundation. This saving is, however, partially counterbalanced by the additional cost of steelwork in the furnace structure. If a stack is positioned close to a substantial tall building or structure, consideration should be given to designing it as a "Stayed" stack. See [Figure 1](#) for examples of stacks.

DATA REQUIRED BY THE DESIGNER

The design of a stack is a complex business, requiring a great deal of skill and experience from the designer. For a given set of operating conditions, specification is simple and a satisfactory design can usually be found. Unfortunately, constant operating conditions are rarely found and, in practice, they tend to vary over quite a wide range. In these circumstances, the designer has to make compromises, balanced between the requirements of the different conditions within the range of operations. In order to do this, he requires information about the full range of anticipated operating conditions. This information includes:

Environmental Data

- Limitations on the ground level concentrations of sulphur oxides, nitrogen oxides and particulates.
 - Minimum and maximum permitted stack heights.
 - Minimum and maximum permitted flue gas exit velocities.
- Note:** These considerations may have already been taken into account by ExxonMobil's designers in preparing a Design Specification which specifies height and top diameter only.
- Existence of aggressive gases from other nearby sources.
 - Requirements for testing flue gas condition, such as constituent analysis, particulate content, temperature, velocity, acid dew point temperature. Responsibilities for provision of this equipment should be defined.
 - Requirement for aircraft warning lights.
 - Maximum and minimum ambient air temperature.
 - Altitude and any special nearby topographic features (Cliffs, hills, etc).

Description of Plant

- Type of heater served (e.g., Boiler, furnace, incinerator, etc).
- Existence of nearby stacks or other tall structures, with details.
- Presence of **FGD** (Flue Gas Desulfurization) or other pollution control equipment.
- Presence of air preheater or other energy conservation equipment.
- Definitions of anticipated abnormal operations, if any (e.g., overload operation, steam/air decoking, by-pass of air preheater, turn-down, etc.).
- Presence of water quenching or tube washing equipment.
- Location(s) of flue gas entry point(s) into stack.

Operating Conditions

- Nature of chimney operation, whether continuous, intermittent, or occasional.
- Maximum and minimum mass flows of each flue gas stream entering the stack, during normal and abnormal operations.
- Maximum and minimum temperatures of each flue gas stream entering the stack under normal operating conditions.

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- Maximum and minimum temperatures of each flue gas stream entering the stack, during each anticipated type of abnormal operation, together with an estimate of the probable duration and frequency.
- Desired drafts at entry of flue gas ducts into stack, during normal and abnormal operations.
- Type of fuel being burned and anticipated composition of the flue gases.
- Anticipated concentrations of deleterious chemicals in the flue gas streams. In particular, the concentrations of SO₃, NO_x, HF, HCl, Chlorine, and alkalis.
- If known, the range of maximum acid dew point temperatures of the flue gas streams during the various operating conditions.
- Concentration of abrasive dust in the flue gases.
- Planned frequency of shut-downs, allowing access for inspection and maintenance.

Possible Future Change of Operating Conditions

An assessment should be made of the possibility that operating conditions may change in the future. If such a change is considered possible, the specialist designer should be able to provide advice about its impact on the stack's performance. He may also be able to suggest a minor change to the stack's initial design that would minimize the necessity for future expensive modifications, required to accommodate the change of operation. Typical changes of operation are:

- Installation of a new (or removal of an existing) FGD or other pollution control system.
- Installation or removal of an air preheater or other energy conservation system.
- Change in operating mode, from continuous to intermittent or vice-versa.
- Change of fuel.
- Turn down or upturn of the unit served.

Unplanned Hazards

The most serious unplanned hazard for a steel stack is an internal fire. The specifier should consider the likelihood that internal fire could occur and also should assess the effect that a consequent shut-down for repairs would have on plant operation. If the risk is high and a prolonged stack shut-down would be unacceptable, the designer should be required to provide a chimney capable of withstanding an internal fire without the requirement for a shut-down for repairs.

DESIGN CONSIDERATIONS

ALONG-WIND LOADS

Down-wind loads are based on **ASME STS-1**, assuming exposure Category "C" and using the appropriate value for the locality of the "Design Wind speed." This is the basic wind speed corresponding to a 3-second gust speed at 33 ft. above ground associated with an annual probability of 0.02 of being equaled or exceeded (50-year mean recurrence interval). This corresponds directly with the requirements set forth in Par. 3.3 in **GP 04-01-03** and **ASCE 7** (2002).

The previous version of **ASME STS-1 (1992)** used "Fastest Mile" (FM) wind speeds (approximating the wind speed, average over about 30-50 seconds) for the design of stacks. This method is now outdated. The site specific data needed to determine environmental loads are usually provided in the Job Specifications (GII). [Section XXIX-A](#), Civil Design Data describes the methodology for determining/obtaining these data. The subsection also lists values for the seismic zone factors and design wind speeds for a number of ExxonMobil plant sites worldwide and provides procedures that can be used to determine design values for locations not listed. [Section XXIX-A](#) of this DP also describes how to convert between wind speeds averaged over different durations.

Because all equations, charts and figures within **ASME STS-1** are applicable only when using U.S. Customary Units, this Section of the DPs provides stack design information in U.S. Customary units only.

The design load distribution is given by:

$$w(Z) = \bar{w}(Z) + w_D(Z) \quad \text{Eq. (1)}$$



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where:

$$\bar{w}(Z) = \frac{C_f q_z K_{zt} K_z D}{12(1 + 6.8I_{\bar{z}})} \quad \text{Eq. (2)}$$

and:

$$w_D(Z) = \frac{3ZM_0}{h^3} [G_f (1 + 6.8I_{\bar{z}}) - 1] \quad \text{Eq. (3)}$$

and:

- $w(\bar{Z})$ = Along wind load, lb/ft
- $w_D(Z)$ = Along wind fluctuating load, lb/ft
- C_f = Force coefficient
- K_{zt} = Topographic factor
- K_z = Velocity pressure exposure coefficient evaluated at height z
- D = Stack diameter, in
- $I_{\bar{z}}$ = Intensity of turbulence at height z
- M_0 = Moment at the base of the stack due to $w(\bar{Z})$, lbf-ft
- h = Height of stack, ft

The velocity pressure, q_z (psf), shall be calculated by:

$$q_z = 0.00256V^2 I \quad \text{Eq. (4)}$$

Where: V = 3-second gust wind speed, mph
 I = Importance factor

Notes:

- (1) **ASCE 7 (Reference 18)** calculates the velocity pressure similarly; however, [equation \(4\)](#) is multiplied by K_z and K_{zt} . In **ASME STS-1** these factors are accounted for in equation (2) resulting in equivalent $w(Z)$ results. The problem arises in the calculation of the shape factor (C_f). **ASME STS-1** uses the exact shape factor coefficient table from **ASCE 7**. Within this table, shape factor values for round cross-sections are based on the equation $D^*(q_z)^{(1/2)}$. Thus, **ASME STS-1** and **ASCE 7** will result in varying shape factor results. This appears to be an error. In order to calculate $w(Z)$ correctly [Eq. \(4\)](#) should be multiplied by K_{zt} and K_z before choosing shape factor values from **ASCE 7**. The K_{zt} and K_z factors should then be omitted from [Eq. \(2\)](#) to calculate $w(z)$ properly.
- (2) Section 4 of **AMSE STS-1** uses the diameter of the stack (D) in inches. Section 5 of **ASME STS-1** uses the diameter of the stack (D) in feet.

The effect of the stack's dynamic response to gusts is taken into account in **ASME STS-1, Paragraph 4.3.3.6**. This is the same approach taken from **ASCE 7** for a flexible or dynamically sensitive structure (See [DP XXIX-D](#) Appendix B for the procedure and Appendix C for an example).

In establishing the area affected by the wind pressure, allowance should be made for the stack, any support structure, ladders, platforms, attached pipes, etc., per the procedure in [DP XXIX-D](#). No allowance should be made for shielding. Structural Force Coefficients are also obtained from [DP XXIX-D](#).

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DYNAMIC RESPONSE TO THE WIND

Cross-Wind Flexural Response

When wind blows past a stack, vortices are shed at regular intervals, alternately from one side and the other. These are called "Von Karman vortices." As they are shed, they create pulses of differential pressure, causing an alternating force in the direction normal to the wind. The frequency with which these vortices are shed depends upon the wind speed, stack diameter, and a parameter known as the "Strouhal Number." When the frequency of vortex shedding is close to a natural frequency of the stack, resonance effects can magnify the response of the stack and, if its mass and structural damping are low, very large oscillations can result. At worst these oscillations have led to stack collapses and, at best, the large movements have caused considerable alarm. In addition to this "Resonant response", which occurs over a fairly narrow range of wind speed, the response of the stack also increases slowly as the wind speed increases, due to random or "Stochastic" response.

Cross-wind response effects are defined in **ASME STS-1**, which is based on the **CICIND** Model Code for Steel Chimneys. The "Critical wind speed," V_c in ft/s (i.e., the wind speed at which resonance occurs between vortex shedding and the stack's first mode natural frequency) is calculated using the following formula:

$$V_c = \frac{n_1 \bar{D}}{S} \quad \text{Eq. (5)}$$

where: n_1 = Stack's frequency for mode shape being considered, usually the first mode
 (Note that the value of n_1 for a stack mounted on a furnace or other structure will be significantly affected by the support steelwork's stiffness), Hz.
 $\bar{D}$ = Mean external diameter of upper third of stack, ft
 $\bar{S}$ = Strouhal Number (usually used as 0.2 for single stacks and may vary due to Reynolds Number and multiple stacks)

Across wind loads for plumb or nearly plumb (less than +/-10% diameter variation over the top 1/3) stacks, the mean hourly speed at 5/6 height above ground, $V_{Z_{cr}}$ (ft/sec), shall be used for evaluating the critical vortex shedding velocity. The value of $V_{Z_{cr}}$, in ft/s, shall be calculated as follows:

$$V_{Z_{cr}} = \bar{b} \left(\frac{Z_{cr}}{33} \right)^{\bar{\alpha}} \left(\frac{22}{15} \right) V_R \quad \text{Eq. (6)}$$

where: Z_{cr} = 5/6 of the stack height, ft
 V_R = Reference wind speed corresponding to a 3-second gust speed at 33 ft above ground in exposure C, mph
 $\bar{b}, \bar{\alpha}$ = tabulated below

Notes:

- (1) In [equation 6](#) above, the $\bar{b}$ value converts the 3 second wind speed into a mean hourly wind speed.
- (2) In [equation 6](#) above, the $\bar{\alpha}$ value is used as a height correction factor depending on the terrain exposure constant
- (3) In [equation 6](#) above, the (22/15) converts the reference wind speed into ft/s



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a. Terrain Exposure Constants

Exposure	$\bar{\alpha}$	$\bar{b}$
A	1/3.0	0.30
B	1/4.0	0.45
C	1/6.5	0.65
D	1/9.0	0.80

Notes:

- (1) **GP 04-01-03** (Design Loads) requires that Exposure Category C shall be used unless the terrain condition of the site justifies a different exposure category subject to the approval of the Owner.
- (2) Exposure Category A has been removed from **ASCE 7-02**

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

Vortex shedding loads shall be calculated for all modes of vibration where $V_{z_{cr}} < V_c < 1.2 V_{z_{cr}}$. The procedure in **ASME STS-1** Non-mandatory Appendix E may be used. The resulting loads may be reduced by the factor $(V_{z_{cr}}/V_c)^2$. Fatigue analysis need not be considered.

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

Notes:

- (1) **API 560** (Section 9.5) allows vortex shedding loads to be ignored if the critical wind speed of the stack is greater than 60 mph or 88 ft/s (mean hourly). **ASME STS-1** does not have such a limit. EMRE recommends this limit not be used for newly constructed steel stacks. However, the design of existing stacks may have used this limit. Therefore, when analyzing an existing stack, it may be practical to consider the **API 560** 60 mph limit. When modifying an existing stack, the **API 560** 60 mph limit should only be used when modifications are minor.
- (2) It is very common for stacks to be supported on fired heaters. In this case, accurately calculating the natural frequency (See [Eq. 5](#)) of the total structure (heater and stack combination) can be complicated. **EMRE** recommends that the natural frequency of the stack be determined as if the stack were supported on grade. This method will produce fairly accurate results because typically fired heaters are very stiff. If the entire structure is modeled, the heater's walls must be included when calculating the structures natural frequency. In either case, **EMRE** recommends that a range of natural frequencies be evaluated (+/- 5%).

Due to the liberalizing effect of the modern codes, very tall, slender steel stacks have become economically viable. As their aspect ratio increases, the effects of second mode oscillations are becoming significant. If the critical velocity for the second mode ($V_c = n_1 D / S$) is less than $1.2 V_{z_{cr}}$, advice should be sought from EMRE (where n_1 is the natural frequency for the second mode).

Damping

The response of a stack varies inversely with its structural damping (See [Figure 3](#)). Steel stacks have relatively low inherent structural damping. Additional damping may be gained from the inclusion of a brick or refractory lining, foundation system, or aerodynamic methods which disrupt vortex formation, although the last, in fact, reduces the damping (See the Controlling Flexural Dynamic Response Section). For the wind loads, the structural damping values (β_s) shall be as shown in the table below.

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a. Steel Stack Structural Damping Values

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

Notes:

- (1) A Rigid Support condition should be used for foundations on bedrock, end-bearing piles or other rigid base support conditions.
- (2) An Elastic Support conditions should be used 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 in this table.

It is very common for stacks to be supported on fired heaters. Because a heater is some what flexibility and will absorb energy, it is EMRE's recommendation that the support be considered elastic for determining damping values (even if the heater is supported on a rigid foundation). However, because a vortex shedding analysis can be very sensitive to damping values, it is also recommended that a range of damping values be evaluated (+/- 0.001).

The total damping value used for the dynamic response of stack should be the addition of both the structural (β_s) and aerodynamic damping (β_a) values.

$$\beta = \beta_s + \beta_a \quad \text{Eq. (7)}$$

and:

$$\beta_a = \frac{C_f \rho \bar{D} \bar{V}_z}{4\pi m_a n_1} \quad \text{Eq. (8)}$$

where: C_f = Force Coefficient
 ρ = Density of Air, 0.078 lb/ft³
 $\bar{D}$ = Mean diameter of the top 1/3 of the stack, ft
 $\bar{V}_z$ = Mean hourly wind speed, ft/s
 m_a = Mass per unit length of the top 1/3 of the stack, lb/ft
 n_1 = Natural frequency of the stack for the mode being considered (usually first mode shape), Hz

Aerodynamic Interference

The relationships given in the ALONG-WIND LOADS section and the *Cross-Wind Flexural Response* section apply only to isolated stacks having no stack or tower of similar or greater height in the immediate vicinity. If such a stack or tower is within a distance of about 15d (where "d" is the external diameter of either structure, whichever is the greater), significant increases can be expected in the response of both, if their mass-damping is near or below the limits given in the *Cross-Wind Flexural Response* section.

The effect is very sensitive to the wind direction, being at a maximum when the wind is blowing approximately along the line tangentially joining the two (see [Figure 4](#)).

This increase is due to aerodynamic interference effects of various types, depending upon the spacing and diameter ([References 1, 4, and 5](#)).

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Effect on Wind Load in the Along Wind Direction When interference effects are expected from a nearby structure, **CICIND (Reference 6)** recommends that the design wind speed used to determine the wind load should be increased by a factor k_i as defined below:

1. Where the height of the interfering structure is less than half the stack height, $k_i = 1.0$.
2. Where the height of the interfering structure is $>$ half stack height and it is approximately cylindrical in shape, k_i is determined from the following expression for values of A/D between 1 and 30:

$$k_i = 1.2 - 0.0067 \frac{A}{D} \quad \text{Eq. (9)}$$

Where:

A = Distance of stack down-wind from the interfering structure (center to center), ft

D = Diameter of the interfering structure, ft

ASME STS-1 provides less information, but suggests that for grouped or clustered stacks having a center-to-center distance of 3.0 diameters or less, an increase in the force coefficient value of 20% is suggested in the absence of model wind tunnel testing or existing full scale data.

Effect on Cross-Wind Response

When an approximately cylindrical structure (e.g., another stack or process tower) is upwind and within 15 diameters (center-to-center) of a stack of similar or smaller height (but greater than 1/2 the upwind stack height), aerodynamic "Wake Interference" effects can considerably increase the stack's cross-wind response (the diameter concerned being that of the interfering structure). The associated critical wind speed increases with decreasing values of A/D due to a reduction in the value of the Strouhal Number. [Figure 5](#) shows the relationship between Strouhal Number and A/D . The equation below (**ASME STS-1**) estimates the reduction of the Strouhal Number for closely spaced stacks:

$$S = 0.16 + \frac{1}{300} \left(\frac{A}{D} - 3 \right) \quad \text{for } A/D \leq 15 \quad \text{Eq. (10)}$$

$$S = 0.20 \quad \text{for } A/D > 15 \quad \text{Eq. (11)}$$

where:

A = Horizontal center-to-center distance between two stacks, ft

D = Diameter of the stack in consideration, ft

This increase may result in decreasing the critical velocity beyond the design consideration value of $1.2 V_{Z_{cr}}$ for wind directions near the line of the stacks. If oscillation induced stresses exceed allowable stresses, the stack's structural damping should be increased (e.g., by the use of a tuned mass damper) to reduce across wind response. Note that aerodynamic stabilizers (e.g., helical spoilers) are ineffective in controlling response in cases of wake interference.

When the interfering tower or stack is less than 2 diameters away, "Interference Galloping" can cause even greater increases in the stack's response, due to the vortices shed by the upstream stack or tower impacting different parts of the downwind stack as it moves in response to shedding its own vortices. In this case, the **CICIND Model Code** recommends either to fit tuned mass dampers, or connect structurally, the stack to the interfering structure, using an energy absorbing connection system (See [Figure 18](#)).

When a new stack is built near an existing stack, the interference effect of the new stack on the existing stack should also be investigated when the wind direction is reversed.

Ovalling Effects

In addition to causing flexural response of a stack, vortex shedding can also set up vibrations in the horizontal plane (Ovalling, first about one axis and then about an axis normal to the first - see [Figure 6](#)). A stack lined with 3 in. cast refractory will



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normally have sufficient structural damping and a high natural frequency to prevent excessive motion. For unlined steel stacks, the ovaling natural frequency (Hz) is calculated as follows:

$$f_o = \frac{680t}{D^2} \quad \text{Eq. (12)}$$

and the critical wind velocity for ovaling (ft/s) is:

$$v_{co} = \frac{f_o D}{2S} \quad \text{Eq. (13)}$$

where: t = Average steel thickness over upper third of stack, in
 D = Stack diameter, ft
 S = Strouhal Number

If the V_{co} is less than the mean hourly wind speed, the unlined stack should be reinforced with ring stiffeners meeting the requirements of **Section 5.2.2 of ASME STS-1**.

Fatigue

ASME STS-1 requires that a fatigue analysis must be considered if $V_c < V_{zcr}$. For normally proportioned steel stacks over the height range considered in this Design Practice that will not experience large tip amplitude motion due to vortex shedding, fatigue loads need not be considered. For stacks which experience large tip motion, fatigue loads shall be analyzed. The procedure for a fatigue analysis is provided in **Appendix E of ASME STS-1**. **ASME STS-1** also allows the fatigue loads to be analyzed using the method in **CICIND**, Model Code for Steel Chimneys (**Reference 3**). Either method is complicated and if fatigue loads must be considered advice should be sought from EMRE.

EARTHQUAKE LOADS

While **ASME STS-1** provides guidance on the derivation of earthquake loads, generally wind loads will govern for all but the most severe earthquakes (exceeding Mercalli Scale 10). If a heavy mass (a water tank or similar) is fitted near the top of the stack, earthquake loading could become more critical than wind, but such a configuration is rare in refineries and chemical plants. **DP XXIX-D** provides procedures for calculating seismic loads.

INTERNAL PRESSURE CHANGES

When a damper is suddenly closed, a transient wave of suction may be induced in the stack. Its maximum value (P), in psf, is given by:

$$P = \frac{\alpha c v}{32.2} \quad \text{Eq. (14)}$$

where: α = Gas density, lb/ft³
 c = Sonic velocity in the flue gas, ft/s
 v = Velocity of flue gas prior to damper closure, ft/s

These suctions will rarely be a problem in stacks having the thickness / diameter ratios common in refinery or chemical plants. Due to the strength and ductility of the shell, a steel stack is well able to cope with overpressures caused for instance by an internal explosion.

THERMAL EFFECTS

When a stack is restrained from adopting a deformed shape in response to differential expansion, bending stresses will be introduced into the shell. These deformations can be large when a single unlined stack carries flue gases from two or more sources at significantly different temperatures or if a single side entry introduces gases at high temperatures. In addition, the resulting differential metal temperatures will introduce secondary thermal stresses. Typical cases of such restraint are to be

