An American National Standard

Standard Guide for
Design, Fabrication, and Erection of Fiberglass Reinforced (FRP) Plastic Chimney Liners with Coal-Fired Units[1]

This standard is issued under the fixed designation D5364; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Federal and state environmental regulations have imposed strict requirements to clean the gases leaving a chimney. These regulations have resulted in taller chimneys (600–1000 ft (183–305 m)) and lower gas temperatures (120–200°F (49–93°C)) due to the use of Air Quality Compliance Systems (ACQS). These regulations led to the development of fiber reinforced plastics (FRP) chimney liners in the 1970's.

Fiberglass-reinforced plastic liners have proven their capability to resist corrosion and carry loads over long periods of time. Successful service has been demonstrated in the utility and general-process industries for over 40 years. The taller FRP structures and larger diameters (10–30 ft (3–9 m)) imposed new design, fabrication, and erection challenges.

The design, fabrication, and erection of FRP liners involves disciplines which must address the specific characteristics of the material. Areas that have been shown to be of importance include the following:

(1) Flue-gas characteristics such as chemical composition, water and acid dew points, operating and excursion temperature, velocity, etc.

(2) Plant operation as it relates to variations in the flue-gas characteristics.

(3) Material selection and laminate design.

(4) Quality control throughout the design, fabrication, and erection process to ensure the integrity of the corrosion barrier and the structural laminate.

(5) Secondary bonding of attachments, appurtenances, and joints.

(6) Installation and handling.

(7) Inspections and Confirmation Testing.

Chimney components include an outer shell, one or more inner liners, breeching ductwork, and miscellaneous platforms, elevators, ladders, and miscellaneous components. The shell provides structural integrity to environmental forces such as wind, earthquake, ambient temperatures, and supports the liner or liners. The liner or liners inside the shell protects the shell from the thermal, chemical, and abrasive environment of the hot boiler gases (generally 120–560°F (49–293°C)). These liners have been made of FRP, acid-resistant brick, carbon steel, stainless steel, high-alloy steel, shotcrete-coated steel, and shotcrete-coated shells. The selection of the material type depends on the chemical composition and temperature of the flue gas, liner height, diameter, and seismic zone. Also, variations in flue-gas characteristics and durations of transient temperatures affect material selection and design. For FRP liners, the flue gas maximum operating temperature is generally limited to 200°F (90°C) for 2 hours and for maximum transient temperatures to 400°F (204°C) for 30 minutes.

1. Scope

1.1 This guide offers direction and guidance to the user concerning available techniques and methods for design, material selection, fabrication, erection, inspection, confirmatory testing, quality control and assurance.

1.2 These minimum guidelines, when properly used and implemented, can help ensure a safe and reliable structure for the industry.

1.3 This guide offers minimum requirements for the proper design of a FRP liner once the service conditions relative to thermal, chemical, and erosive environments are defined. Due to the variability in liner height, diameter, and the environment, each liner must be designed and detailed individually.

1.4 Selection of the necessary resins and reinforcements, composition of the laminate, and proper testing methods are offered.

1.5 Once the material is selected and the liner designed, procedures for proper fabrication of the liner are developed.

1.6 Field erection, sequence of construction, proper field-joint preparation, and alignment are reviewed.

1.7 Quality control and assurance procedures are developed for the design, fabrication, and erection phases. The quality-assurance program defines the proper authority and responsibility, control of design, material, fabrication and erection, inspection procedures, tolerances, and conformity to standards. The quality-control procedures provide the steps required to implement the quality-assurance program.

1.8 Appendix X1 includes research and development subjects to further support recommendations of this guide.

1.9 *Disclaimer*—The reader is cautioned that independent professional judgment must be exercised when data or recommendations set forth in this guide are applied. The publication of the material contained herein is not intended as a representation or warranty on the part of ASTM that this information is suitable for general or particular use, or freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability arising from such use. The design of structures is within the scope of expertise of a licensed architect, structural engineer, or other licensed professional for the application of principles to a particular structure.

NOTE 1—There is no known ISO equivalent to this standard.

1.10 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.11 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of

---

[1] This guide is under the jurisdiction of ASTM Committee D20 on Plastics and is the direct responsibility of Subcommittee D20.23 on Reinforced Plastic Piping Systems and Chemical Equipment.

Current edition approved Oct. 1, 2014. Published October 2014. Originally approved in 1993. Last previous edition approved in 2008 as D5364 – $08^{\epsilon 1}$. DOI: 10.1520/D5364-08.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

the Guarded-Hot-Plate Apparatus

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C581 Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service

C582 Specification for Contact-Molded Reinforced Thermosetting Plastic (RTP) Laminates for Corrosion-Resistant Equipment

D638 Test Method for Tensile Properties of Plastics

D648 Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position

D695 Test Method for Compressive Properties of Rigid Plastics

D790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

D883 Terminology Relating to Plastics

D2393 Test Method for Viscosity of Epoxy Resins and Related Components (Withdrawn 1992)[3]

D2471 Practice for Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins (Withdrawn 2008)[3]

D2583 Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor

D2584 Test Method for Ignition Loss of Cured Reinforced Resins

D3299 Specification for Filament-Wound Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks

D4398 Test Method for Determining the Chemical Resistance of Fiberglass-Reinforced Thermosetting Resins by One-Side Panel Exposure

E84 Test Method for Surface Burning Characteristics of Building Materials

E228 Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer

2.2 *American Concrete Institute (ACI) Standard:*

ACI Standard 307 Specification for the Design and Construction of Reinforced Concrete Chimneys[4]

2.3 *NFPA Standard:*

NFPA 77 Recommended Practice on Static Electricity[5]

2.4 *ASME Standards:*

Section X Fiberglass Reinforced Plastic Pressure Vessels[6]

RTP-1 Reinforced Thermoset Plastic Corrosion Resistant Equipment[6]

3. Terminology

3.1 *Definitions:*

3.1.1 Terms used in this guide are from Terminology D883 unless otherwise indicated in 3.2.

3.2 *The following applicable definitions in this guide are provided for reference:*

3.2.1 *accelerator*—a material added to the resin to increase the rate of polymerization (curing).

3.2.2 *axial*—in the direction of the axis (lengthwise centerline) of the equipment.

3.2.3 *Barcol hardness*—measurement of the degree of cure by means of resin hardness. The Barcol impressor is the instrument used (see Test Method D2583).

3.2.4 *binder*—chemical treatment applied to the random arrangement of glass fibers to give integrity to mats. Specific binders are utilized to promote chemical compatibility with various laminating resins used.

3.2.5 *blister*—refer to Terminology D883.

3.2.6 *bonding*—joining of two or more parts by adhesive forces.

3.2.7 *bond strength*—force per unit area (psi) necessary to rupture a bond in interlaminar shear.

3.2.8 *buckling*—a mode of failure characterized by an unstable lateral deflection due to compressive action on the structural element involved.

3.2.9 *burned areas*—areas of laminate showing evidence of decomposition (for example, discoloration and cracking) due to excessive resin exotherm.

3.2.10 *burn out (burn off)*—thermal decomposition of the organic materials (resin and binders) from a laminate specimen in order to determine the weight percent and lamination sequence of the glass reinforcement.

3.2.11 *carbon veil*—a nonwoven surface veil that is made of carbon fiber or is coated with conductive carbon for purposes of providing static dissipation. This could be carbon veil, or polyester veil impregnated with carbon.

3.2.12 *catalyst*—an organic peroxide material used to activate the polymerization of the resin.

3.2.13 *chopped-strand mat*—reinforcement made from randomly oriented glass strands that are held together in a mat form by means of a binder.

3.2.14 *chopper gun*—a machine used to cut continuous fiberglass roving to predetermined lengths [usually 0.5–2 in. (13–51 mm)] and propel the cut strands to the mold surface. In the spray-up process, a catalyzed resin is deposited simultaneously on the mold. When interspersed layers are provided in filament winding, the resin spray is not used.

3.2.15 *contact molding*—process for molding reinforced plastics in which reinforcement and resin are placed on an open mold or mandrel. Cure is without application of pressure; includes both hand-lay-up and spray-up.

3.2.16 *corrosion barrier*—the integral inner barrier of the laminate which is made from resin, veil, and chopped mat.

3.2.17 *coverage*—see *winding cycle.*

3.2.18 *crazing*—the formation of tiny hairline cracks in varying degrees throughout the resin matrix, particularly in resin-rich areas.

3.2.19 *cut edge*—end of a laminate resulting from cutting that is not protected by a corrosion barrier.

---

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from American Concrete Institute (ACI), P.O. Box 9094, Farmington Hills, MI 48333-9094, http://www.concrete.org.

[5] Available from National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471, http://www.nfpa.org.

[6] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

3.2.20 *delamination*—physical separation or loss of bond between laminate plies.

3.2.21 *dry spot*—an area where the reinforcement fibers have not been sufficiently wetted with resin.

3.2.22 *edge sealing*—application of reinforcement and resin, or resin alone, to seal cut edges and provide a corrosion-resistant barrier. The final layer should be paraffinated.

3.2.23 *entrapped-air void*—see *void*.

3.2.24 *environment*—state of the surroundings in contact with the internal and external surfaces, including the temperature, pressure, chemical exposure, relative humidity, and presence of liquids or gases.

3.2.25 *exotherm*—evolution of heat by the resin during the polymerization reaction.

3.2.26 *exotherm ply*—that ply of chopped mat at which the lamination process is stopped to allow gelation and exotherm of the existing laminate.

3.2.27 *fabricator*—the producer of the equipment who combines resin and reinforcing fibers to produce the final product.

3.2.28 *fatigue*—the change in properties of the laminate over time under cycling of loads, including mechanical, temperature, and other environmental exposures.

3.2.29 *fiber(glass)*—a fine, continuously formed thread of glass. *E*-glass is used for strength and durability, *E-CR*-glass is a modified *E*-glass with improved corrosion resistance to most acids, and *C*-glass is resistant to corrosion by most acids.

3.2.30 *fiberglass roving*—see *roving*.

3.2.31 *fiberglass woven roving*—heavy fabric woven from strands of glass fiber.

3.2.32 *fiber wetting*—coating of the fiberglass with resin by means of rollout or immersion.

3.2.33 *filament winding*—a process for forming FRP parts by winding resin-saturated continuous-roving strands onto a rotating mandrel.

3.2.34 *fillers*—inert materials that are added to the resin to increase density, increase viscosity, improve abrasion resistance, enhance resin-application properties, decrease resin shrinkage, and reduce cost.

3.2.35 *fill picks*—the rovings in a woven roving that run in the transverse direction of the fabric, that is, across the fabric roll width.

3.2.36 *flame-retardant resin*—halogenated resins that can be used with or without additives to provide a laminate having a reduced flame-spread rating as measured in accordance with Test Method E84. The resins are not flame retardant in their liquid state.

3.2.37 *flame-spread rating*—index number for any laminate of definite composition resulting from testing in accordance with Test Method E84.

3.2.38 *gap filling*—the filling of voids between joined parts, elements, or components with resin putty or resin.

3.2.39 *gel*—the initial jelly-like solid phase that develops during the polymerization of resin.

3.2.40 *gel time*—time from the initial mixing of the resin with catalyst to gelation.

3.2.41 *glass*—see *fiber(glass).*

3.2.42 *glass content*—weight percent of glass-fiber reinforcement in the laminate.

3.2.43 *gun roving*—fiberglass roving designed for use in a chopper gun.

3.2.44 *hand lay-up*—see *contact molding.*

3.2.45 *heat-deflection temperature (HDT)*—temperature at which a specified bar specimen deflects 0.010 in. (0.25 mm) when loaded as a simple beam at a constant 264 psi (1820 kPa). Test Method D648 usually refers to a cured-resin casting, not a laminate.

3.2.46 *helical winding*—filament winding where the angle at which the reinforcement is placed is other than 0 or 90°.

3.2.47 *hoop winding*—filament winding where the winding angle is essentially 90°. The winding strands are applied immediately adjacent to the strands applied on the previous mandrel revolution.

3.2.48 *intersperse*—chopped fiberglass used in a filament-wound laminate, usually in thin layers between winding coverages.

3.2.49 *isotropic*—having uniform properties in all directions. The measured properties of the material are independent of the axis of testing. The opposite is anisotropic, which is the case for FRP laminates.

3.2.50 *joint overlay*—an overlay that joins the adjoining surfaces of two contacting parts or elements.

3.2.51 *laminate*—the total of the part constructed by combining one or more layers of material (reinforcement and resin). As used in this guide, the laminate consists of the corrosion barrier on the inner surface, the interior structural layer, and the outer surface.

3.2.52 *laminate composition*—the sequence of reinforcement materials on a type, class, and category basis that make up a laminate.

3.2.53 *lamination analysis*—procedure by which, given the amount and properties of the resin and the properties and orientation of the reinforcement, it is possible to calculate the elastic physical and mechanical properties of the individual layers of a laminate and using weighted-averaging techniques to determine the elastic properties of the total laminate (see section 2.4).

3.2.54 *lamination theory*—see *lamination analysis.*

3.2.55 *mandrel*—mold around which a laminate is formed to fabricate a cylindrical section.

3.2.56 *macro*—denotes the properties of the laminate as a total structural element.

3.2.57 *matrix*—resin phase of a fiberglass-reinforced laminate.

3.2.58 *micro*—denotes the properties of the constituent elements of the laminate; that is, matrix and reinforcements and interface only, and their effect on the laminate properties.

3.2.59 *mold*—form over or into which resin and reinforcements are placed to form the laminate product shape.

3.2.60 *monomer*—the basic polymerizing element for the formation of the matrix; in FRP-liner fabrication, this is mostly styrene.

3.2.61 *overlay*—laminate applied over base FRP structures to secure a joint, seal a seam, or attach a nozzle.

3.2.62 *paraffinated resin*—resin containing a small amount of dissolved paraffin wax. This wax will come out of the solution during cure and bloom to the surface, preventing the normal air inhibition at the atmospheric exposed surface.

3.2.63 *parting agents*—compounds that assist in releasing the FRP part from its mold; also referred to as mold-release agents.

3.2.64 *pass*—in filament winding, one "round trip" of the carriage (which applies the winding strand to the mandrel) from one end of the mandrel to the other and return.

3.2.65 *pit*—crater-like area in the surface of the laminate.

3.2.66 *polyester resin*—resin produced by the condensation of dihydroxy glycols and dibasic organic acids or anhydrides. In FRP fabrications, the polyester plastic contains at least one unsaturated constituent and is dissolved in styrene and subsequently reacted to give a highly crosslinked thermoset matrix.

3.2.67 *profile*—the roughness (or smoothness) of a surface that has been prepared for bonding.

3.2.68 *promoter*—a material which activates the catalyst that cures the resin.

3.2.69 *PVA*—abbreviation for polyvinyl alcohol, a widely used parting agent.

3.2.70 *reinforcement*—glass fibers in the form of continuous strand, chopped-strand, or fabric. These fibers are added to the resin matrix to give strength and other properties to the laminate.

3.2.71 *release film*—film used to facilitate removal of the fabricated part from the mold. Oriented polyester film, 3 to 5 mils thick has been found suitable for this purpose.

3.2.72 *resin putty*—resin filled with clay, silica fume, milled fibers, or other inert materials, or both, to yield a material for filling gaps, cracks, and fillets.

3.2.73 *resin richness*—excessive amounts or uneven distribution of resin in the laminate. Such areas are the result of improper wetout or drainage and are prone to cracking.

3.2.74 *roll-out*—densification of the laminate by working reinforcement into and air out of the resin, using a serrated thermoplastic or metal roller.

3.2.75 *roving*—a number of strands or filaments gathered with little or no twist in a package called a roving ball. Also see *woven roving.*

3.2.76 *secondary bond strength*—adhesive force that holds a separately cured laminate to the basic substrate laminate.

3.2.77 *sizing*—surface treatment or coating applied to filaments to improve the filament-to-resin bond.

3.2.78 *spray-up*—method of contact molding where resin and chopped strands of continuous-filament glass fiber are deposited on the mold directly from a chopper gun.

3.2.79 *strain*—elongation per unit length.

3.2.80 *stress*—load per unit area.

3.2.81 *structural layer*—the portion of the laminate having the primary mechanical strength.

3.2.82 *surface preparation*—the act of roughening, priming, or otherwise treating the laminate surface to achieve surface conditions that are conducive to adhesion of a subsequently applied laminate.

3.2.83 *surfacing veil*—a very thin (10 to 20 mils) mat of *C*-glass or synthetic material such as non-woven polyester fabric, used to reinforce the corrosion-resistant resin on the inside or outside surface of the FRP laminate.

3.2.84 *unidirectional roving*—continuous parallel roving held together with periodic stitching.

3.2.85 *vinyl ester resin*—resin characterized by reactive unsaturation, located predominately in terminal positions that can be compounded with styrene and reacted to produce crosslinked copolymer matrices.

3.2.86 *void*—unfilled space caused by air or gas in the resin mix or entrapment of such gases during lay-up of individual plies of glass.

3.2.87 *warp ends*—the strands in a woven roving that run in the longitudinal direction of the fabric, that is, along the roll length of the fabric.

3.2.88 *winding angle*—the angle between the winding strand and the longitudinal axis of the cylindrical liner, sometimes called the helix angle. The winding angle can be determined by measuring the included angle along the longitudinal axis of the pipe at the intersection of strands and dividing this angle by two.

3.2.89 *winding cycle*—the complete covering of the mandrel surface by two bi-directional layers of filament winding. Hoop winding will use one pass; in helical winding many passes are required to complete one winding cycle.

3.2.90 *woven roving*—a plain-weave reinforcement fabric made of rovings. The standard configuration requires five rovings in the warp direction and four rovings in the weft direction and a nominal weight of 24 oz/yd^2 (814 g/m^2).

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *can*—an individual fabricated cylindrical liner section.

3.3.2 *quality assurance (QA)*—a system, employed by the owner or his designate, to monitor the manufacturer's quality control and to recognize and resolve any nonconformances. This system is administered by a quality-assurance representative who is empowered to verify the QA and the resolution of all noncompliances.

3.3.3 *quality-assurance program*—a plan that documents the procedures or instructions used to ensure the quality control of the manufacturing process.

3.3.4 *quality control (QC)*—a system of measurements and checks employed to monitor the manufacture of the FRP

TABLE 1 Stress and Modulus of Elasticity Symbols, psi

Description	Stress Type		
	Membrane Tension	Membrane Compression	Bending
Calculated longitudinal	f_z^t	f_z^c	f_z^b
Calculated circumferential	f_θ^t	f_θ^c	f_θ^b
Allowable longitudinal	F_z^t	F_z^c	F_z^b
Allowable circumferential	F_θ^t	F_θ^c	F_θ^b
Ultimate longitudinal	F_z^{tu}	. . .	F_z^{bu}
Ultimate circumferential	F_θ^{tu}	. . .	F_θ^{bu}
Critical buckling, longitudinal	. . .	F_z^{cr}	. . .
Critical buckling, circumferential	. . .	F_θ^{cr}	. . .
Modulus of elasticity, longitudinal	E_z^t	E_z^c	E_z^b
Modulus of elasticity, circumferential	E_θ^t	E_θ^c	E_θ^b

† Editorially corrected column alignment in March 2010.

chimney liner and to assess compliance of manufacture to the critical quality requirements.

3.4 *Symbols:* (*see* Table 1)

a = winding angle (with respect to the longitudinal axis of the liner), degree
A_θ = hoop membrane stiffness of the liner wall, lb/in.
AT = abnormal temperature load
CP = circumferential pressure load, psi
D = dead load
D_s = theoretical draft (without losses), inches of water
D_x, D_θ = longitudinal and hoop bending stiffness, of the liner wall, lb-in.^{2}/in.
$(EI)s$ = transformed flexural stiffness of ring stiffener, lb-in.^{2}
EQ = earthquake load
f = ovalling natural frequency, cycles per second
g = acceleration due to gravity, in/s^2
H = total height of liner above breeching, ft
h_1 = flue-gas film coefficient of thermal conductivity, BTU/ft^2/in/h/°F
h_3 = film coefficient of thermal conductivity outside of liner, BTU/ft^2/in/h/°F
I = center-line moment of inertia of liner section, in.^{4} $= \pi r^3 t$
I_s = moment of inertia of one stiffener
k = coefficient of thermal conductivity for FRP liner (in absence of data use $k = 2$), BTU/ft^2/in/h/°F
k_n = knockdown factor
k_R = ratio of thermal resistance from gas stream to the middle of the liner wall to the total radial thermal resistance of liner
L = distance between lateral supports, ft
L_1 = spacing between full circumferential stiffeners, in, determined as the sum of half the distance to adjacent stiffeners on either side of the stiffener under consideration
LF = load factor
L_L = total length of the continuous liner
MRF = material resistance factor
P = external pressure, psi
p' = atmosphere pressure at plant grade level, psi
r = average radius of the liner wall, in.
R_1 = displacement-induced seismic response (force, displacement, or stress)
R_2 = inertia-induced seismic response (force, displacement, or stress)
R_c = radius of the liner to the centroid of the stiffener
R_s = radius of the stiffener
R_t = total seismic response (force, displacement, or stress)
RF = capacity-reduction factor = MRF × TTRF
t = thickness of the liner (structural) wall, in.
T = normal temperature load,
T_a = ambient air temperature, Degrees Fahrenheit
t_c = thickness of corrosion barrier, in.
t_e = equivalent liner thickness, including stiffener contribution, on basis of equal mass
T_g = flue gas temperature, Degrees Fahrenheit
T_m = mean liner temperature, $(T_1 + T_2)/2$, Degrees Fahrenheit
T_n = annulus air temperature, Degrees Fahrenheit
T_o = temperature at inside surface of corrosion barrier, Degrees Fahrenheit
T_1 = temperature at interface between corrosion barrier and structural layer, Degrees Fahrenheit
T_2 = temperature at outside surface of structural layer, Degrees Fahrenheit
ΔT_g = flue-gas temperature difference across the diameter of the liner, at height z, °F
$(\Delta T_g)_{BASE}$ = ΔT_g at top of breeching, °F (minimum $T_{g\text{-}BASE} = 25$°F)
ΔT_m = difference of temperature, T_m, across the diameter of the liner, °F
ΔT_w = temperature differential across the structural layer, °F $(T_2 - T_1)$
$TTRF$ = time and temperature reduction factor
W = wind load
W_{cm} = compressive modulus of elasticity of the winding material (glass), psi
W_L = total weight of the continuous liner, including corrosion barrier, and stiffeners
W_{tm} = tension modulus of elasticity of the winding material (glass), psi
z = distance from top of breeching, in.
α = coefficient of thermal expansion in the direction specified by subscript, in./in./°F
μ = average Poisson's ratio

$$=(\mu_{z\theta} \times \mu_{\theta z})^{1/2}$$

$\mu_{\theta z}$ = Poisson's ratio of longitudinal strain to an imposed hoop strain
$\mu_{z\theta}$ = Poisson's ratio of hoop strain to an imposed longitudinal strain
γ = unit weight of liner, lb/in.^{3}
γ_a = specific weight of ambient air, lb/ft^3
γ_g = specific weight of gas, lb/ft^3

δ = longitudinal deflection, in.

4. Significance and Use

4.1 This guide provides information, requirements and recommendations for design professionals, fabricators, installers and end-users of FRP chimney liners. FRP is a cost-effective and appropriate material of construction for liners operating at moderate temperatures in a corrosive chemical environment.

4.2 This guide provides uniformity and consistency to the design, fabrication, and erection of fiberglass-reinforced plastic (FRP) liners for concrete chimneys with coal-fired units. Other fossil fuels will require a thorough review of the operating and service conditions and the impact on material selection.

4.3 This guide is limited specifically to FRP liners within a supporting concrete shell and is not applicable to other FRP cylindrical structures.

5. Service and Operating Environments

5.1 *Service Conditions:*

5.1.1 To properly select the optimum design for an FRP chimney liner, it is essential to define the operating and service conditions and the effect they may have on the lining. The chemical, erosion/abrasion, and temperature environments should be determined for the full height of the FRP liner.

5.1.2 Owing to the variability in details of design and system configuration, each FRP liner design must be considered individually. The information given is for coal-fired units, but the general principles are applicable to units fired with other fuels.

5.2 *Environmental Condition*—The environment for a chimney liner is classified as to its chemical, erosion, and temperature condition. Two chemical conditions, three erosion conditions, and four temperature conditions are identified, together with the circumstances in which they usually occur. The combinations of circumstances applicable to a particular chimney liner should be determined.

5.3 *Chemical Environment:*

5.3.1 *Condition 1*—Occasional exposure of certain areas to low pH from acid condensation, occurring with reheated gas or un-scrubbed gas at localized cold areas, such as the liner hood or during start-up.

5.3.2 *Condition 2*—Constant exposure to low pH, acid condensation with concentration based on equilibrium concentration of H_2SO_4, water vapor in the gas stream at temperatures above the water dew point. This operating condition is usually for scrubber systems without reheat, with essentially saturated gas with temperatures from ambient to 140°F (60°C), or when there is insufficient reheat to raise the gas temperature above the acid dew point. Start-up conditions are covered by the operating conditions.

5.4 *Erosion/Abrasion Environment:*

5.4.1 *Condition 1*—Normal-velocity gas flow (45–100 fps (14–31 m/s)) with particulate removal equipment in service. Most particulate removal and flue-gas desulfurization (FGD) systems have velocities in this range.

5.4.2 *Condition 2*—Normal-velocity gas flow with particulate removal equipment out of service. This condition would be infrequent, such as when precipitator electric power is out or when bag houses are bypassed. The duration should be determined, as the plant may reduce load or shut down when such a condition occurs.

5.4.3 *Condition 3*—High-velocity gas flow (higher than 100 fps (31 m/s)), by design, or at sharp corners, turning vanes, and struts. Erosion will likely occur at these locations.

5.5 *Operating Temperature Environment:*

5.5.1 *Condition 1*—Saturated flue gas, ambient to 140°F (60°C). This is the usual operating condition for chimney liners on systems with wet scrubbers without reheat. Start-up conditions are covered by the operating conditions. Where bypass of scrubbers is provided, conditions are described in 5.6.

5.5.2 *Condition 2*—Normal gas temperature from 140 to 200°F (60 to 93°C), with moisture content and acid condensation determined by the individual conditions. This is the usual operating range for wet scrubber systems with reheat. Start-up, high-temperature, and by-pass conditions will be the same as described in 5.6.

5.5.3 *Condition 3*—Normal gas temperature from 140 to 200°F (60 to 93°C), with temperatures high enough for condensation not to occur during normal operation. This is the usual operating range for spray dryer-baghouse and spray dryer-precipitator combinations. Condensation at start-up is minimized by not introducing water to the spray dryers until coal firing is started. Temperatures during by-pass and for excursions are as described in 5.6.

5.5.4 *Condition 4*—Normal gas temperature from 200 to 330°F (93 to 166°C). This is the usual operating range for plants without scrubbers. This condition is also applicable to systems in which the particulate removal or flue-gas desulfurization (FGD) system, or both, can be bypassed, with temperatures determined by the gas flow that can be bypassed compared to the total gas flow of the system.

5.5.5 This guide covers FRP liners for Conditions 1, 2, and 3. Condition 4 is not covered in this guide, although applications over 200°F (93°C) operating temperature condition are in service. Condition 4 requires additional considerations in evaluating materials and composite designs.

5.6 *Abnormal Environments*—Abnormal environments, such as stoppage of an air preheater or malfunction of the scrubber sprays, or both, can result in short-term conditions more severe than those covered. The severity and duration of the abnormal conditions depend on the design and operation of the plant and should be determined for each project. In many cases, these conditions are of short duration because a major upset in the boiler draft system, or in the FGD or particulate removal system, means a reduction in load or plant shutdown to protect the equipment or stay within the emission criteria.

5.6.1 *Condition 1*—Flue-gas-temperature excursion of up to 250°F (121°C) maximum, maintained by a quench system.

5.6.2 *Condition 2*—Flue-gas-temperature excursion up to 400°F (227°C) maximum.

5.6.3 FRP liners may be used for abnormal Condition 1, but its use for Condition 2 is not considered in this guide.

5.6.4 The gas temperature shall be maintained by a quench system at or below a temperature of 250°F (121°C).

5.6.5 In case of a gas-temperature upset 25°F (–4°C) above the established operating temperature, an additional deluge system should be used to bring the gas temperature back to normal operating temperatures.

5.7 *Other Operating and Service Environments:*

5.7.1 Start-up of coal-fired units is usually accomplished with fuel other than coal, such as diesel oil, natural gas, or liquefied natural gas. These fuels, which result in flue-gas compositions different from that produced by coal-firing, should be considered in the design of the liner.

5.7.2 The temperatures given are average temperatures of flue gases entering the chimney liners. Gas temperatures vary as the gas rises up the chimney and at breaching openings, and they vary with the start-up condition of the unit.

5.8 *Static Electricity Build-Up*—FRP in a chimney-liner application is subject to the build-up of static electricity that may be a consideration in some installations. A static-charge dissipation system must be provided where considered necessary (see 6.3.6).

5.9 *Flame Spread*—FRP chimney liners are subject to conditions that propagate flame spread. Specific requirements will vary, depending upon operating and maintenance conditions. However, all FRP liners shall have a flame-resistant resin as in 6.3.5.

6. Materials

6.1 *Raw Materials:*

6.1.1 *Resin:*

6.1.1.1 The selected resin shall be either a polyester or vinylester that provides the properties necessary to withstand the conditions of the operating environment described in Section 5. Resins shall conform to the requirements of Specification C582.

6.1.1.2 FRP chimney liners are fabricated with a flame-retardant resin and, when required, additional flame-retardant synergist added. The resin shall, at minimum, have been demonstrated to withstand 25 % sulfuric acid at 180°F (82°C) for a duration of one year with a minimum retained strength of 50 %, in accordance with Practice C581, or under the actual anticipated environmental-service condition.

6.1.1.3 The resin in the corrosion barrier shall be chosen for its corrosion resistance and flame-retardant properties. Due to physical and mechanical requirements, a different corrosion-resistant resin may be used in the corrosion barrier than in the structural layer.

6.1.2 *Other Additives*—The resin may contain diluents such as added styrene, fillers, dyes, pigments, or flame retardants only when agreed upon between the fabricator and the owner. Such uses shall conform to the descriptions of diluents, resin pastes, and ultraviolet absorbers as explained in Specification C582. Additionally, carbon filler may be added for static-charge dissipation.

6.1.3 *Reinforcements*—Reinforcements shall conform to the requirements of Specification C582 for contact molding and Specification D3299 for filament winding. These specifications require the sizing and binder systems to be compatible with the resins selected.

6.1.3.1 Glass reinforcements shall be Type *E* or *E-CR* glass fibers having a sizing compatible with the resin.

6.1.3.2 The surface veil used in the corrosion barrier should be Type *C* glass fibers, or a synthetic material as approved by the owner. If specified by the purchaser, a carbon veil may be added for static-charge dissipation as in section 6.3.6.

6.2 *Laminate Composition*—FRP chimney-liner laminates consist of a corrosion barrier, a structural layer, and an exterior surface. The FRP composition shall include a thermoset polyester or vinylester resin, reinforced with glass fiber and containing various other raw materials to provide specific properties. The corrosion barrier provides primary corrosion resistance, flame retardant, and shall follow laminate construction described in Specification C582. The structural layer shall primarily provide the mechanical properties and strength of the design. The outer layer shall contain a paraffinated resin to prevent air from inhibiting the cure process and shall provide weather or environmental protection, or both. Liner extending above the chimney cap shall be protected against ultraviolet (UV) rays and in cold weather regions, against ice forming on the liner surfaces from freezing of water droplets in the gas phase.

6.2.1 *Corrosion Barrier*—The corrosion barrier shall be as described in Specification C582. Additional plies of surfacing mat and chopped-strand mat may be used in particularly severe chemical environments, but consideration shall be given to the effects of thermal and mechanical shock.

6.2.2 *Structural Layer*—The structural layer shall meet the physical properties required by the design in Section 7. The fabrication process is typically filament winding, as described in Specification D3299 and Section 8, but may include contact molding, as described in Specification C582, or a combination of both.

6.2.3 *Outer Layer*

6.3 *Laminate Properties:*

6.3.1 *Physical and Mechanical*—The following physical-property test methods are designed for use on entire laminates or individually on the corrosion barrier, the structural layer, or repeating structural units, and external overlays. The following test methods shall be used for determination of initial design data and QA/QC procedures:

6.3.1.1 *Tensile Modulus (Axial Direction)*—Test Method D638 shall be used; or the test results used in conjunction with laminate theory as in section 6.3.1.6.

6.3.1.2 *Flexural Modulus (Axial and Hoop Directions)*—Test Method D790 shall be used; or the test results used in conjunction with laminate theory as in section 6.3.1.6.

6.3.1.3 *Compressive Modulus*—The compressive modulus shall be obtained in accordance with Test Method D695, with the following modifications. The specimens shall be 2 in. (51 mm) in the test direction by 0.5 in. (13 mm) thick with the corrosion barrier removed by machining. Strain shall be measured by the use of an extensometer or other strain gages centered on the specimen in the 2-in. direction. The extensometer arms shall be spaced to 1.5 in. (38 mm) apart at their attachment points to the specimen. The test results may be used in conjunction with laminate theory as in section 6.3.1.6.

6.3.1.4 *Coefficient of Thermal Expansion*—Coefficient of thermal expansion shall be measured in accordance with Test Method E228, over an appropriate temperature range using specimens constructed with the same composition, resin, construction sequence, glass content, type and weight of reinforcement, and cure conditions used in the actual liner. The glass content of the test laminate should be within 5 % of the glass content of the actual chimney-liner laminate. The direction of measurement in relation to the orientation of glass shall be considered in interpretation of the results. Unidirectional roving may be used to approximate filament winding.

6.3.1.5 *Coefficient of Thermal Conductivity*—The coefficient of thermal conductivity shall be determined by Test Method C177 or C518 on representative laminate for either the entire liner laminate to be used, or for each of the following laminate components; that is, corrosion barrier, structure layer, and exterior coating, if any. The representative laminate shall be a flat laminate constructed with the same resin, construction sequence, glass content, type and weight of reinforcements, and cure conditions used in the actual laminate. The direction of measurement in relation to the orientation of glass shall be considered in interpretation of the results. Unidirectional roving may be used to approximate filament winding.

6.3.1.6 Laminate theory may be used instead of physical testing to determine axial tensile, flexural, and compressive moduli only. In such a case, the axial tensile and hoop flexural moduli computed from laminate theory shall be verified by comparison with the results obtained by physical testing. The test results shall be at least 90 % of the computed values.

6.3.2 *Chemical*—The corrosion resistance of the resins used shall have been characterized by either Practice C581 or Test Method D4398. Resins may also be evaluated for vapor exposure in accordance with Practice C581, except that specimens are exposed totally in the vapor space above the liquid returning from the condenser. The resin shall have been deemed acceptable for long-term use in the environments described in Section 5 (Conditions 1 or 2, or both), by either of the above test methods or verifiable actual field environments.

6.3.3 *Erosion/Abrasion*—In areas where Condition 3 erosion/abrasion is expected, resin additives such as silicon carbide may be considered.

6.3.4 *Temperature:*

6.3.4.1 The material properties of the laminate shall be suitable for operating-temperature environments as defined by normal Conditions 1, 2, and 3, and abnormal Condition 1. These conditions define only typical temperature environments. It is essential for the owner to fully provide specific temperature conditions in order to properly select the optimum resin.

6.3.4.2 The maximum operating temperature at the interface between the corrosion barrier and the structural layer shall not exceed the heat-deflection temperature (HDT) of the structural-layer resin. The HDT shall be determined in accordance with Test Method D648.

6.3.4.3 The temperature at the corrosion barrier/structural layer interface may be determined by a thermocouple embedded in the laminate or by correlating gas-stream temperature and thermal gradient through the laminate with the temperature at the corrosion liner/structural layer interface.

6.3.5 *Flame Retardancy*—Selection of the flame spread rating is governed by local building codes. The purchaser shall specify the rating for each location.

6.3.5.1 Flame spread is determined in accordance with Test Method E84 (see Note 2) by using a standard laminate construction as determined in accordance with 4.1.2 of Specification C582. The standard laminate is 0.125 in. (3 mm) thick, flat, reinforced with all mat and has a glass content of 25 to 30 % by weight. Flame-retardant synergists of the type and level used in the actual laminate construction shall be used in this test.

NOTE 2—This flame-spread rating is based on a laboratory test, which is not necessarily predictive of product performance in a real fire situation, and is therefore not intended to reflect hazards presented by this or any other material under actual fire conditions.

6.3.6 *Static-Charge Dissipation*—Operation of FRP chimney liners can build up significant static charges. This may be a safety hazard to personnel and appropriate grounding shall be considered.

6.3.7 *Grounding System*—Each can in the liner shall have at least two proof tested grounding patches. The patches shall be externally connected to a grounding system conforming to the requirements of NFPA 77 and 77-16. Patches should be approximately 2 feet square containing conductive carbon filler and carbon veil covering a ½ in. bolt that connects to the grounding system. Every bolt patch shall be proof tested (ohmmeter) to assure it will provide an appropriate path to ground.

7. Design

7.1 *Design:*

7.1.1 Standard guidelines and minimum requirements are provided for the structural design of fiber-reinforced plastic (FRP) chimney liners, based on load and resistance-factor design procedures.

7.1.2 The objective is to provide a uniform procedure for computing forces and displacements of the liner based on the present state of the art and science of design of fiber-reinforced plastic liners.

7.1.3 The design is limited to FRP chimney liners supported laterally and vertically by the concrete shell.

7.1.4 The design of a fiber-reinforced plastic liner is an iterative process and similar to most engineering designs, but with the following significant differences:

7.1.4.1 Fiber-reinforced plastic is a composite material and its behavior is different from isotropic materials.

7.1.4.2 The practical variation in the physical properties of the liner material in the thermal and chemical design environments are more than those encountered in most other structural materials.

7.1.5 The scope is limited to chimney liners designed to operate continuously in operating temperature environments defined by Conditions 1, 2, and 3 in Section 5 under normal operating conditions, and for Condition 1 for abnormal environments defined in Section 5. The design of liners operating in normal-temperature environment, Condition 4, or abnormal Condition 2, is not covered.

7.2 *Assumptions:*

7.2.1 The design procedure is based on the overall stress resultants acting on the wall and on the properties of the laminate.

7.2.2 For the purpose of analysis, the cross section is considered to consist of the average diameter and structural layer thickness. The thickness of the corrosion barrier is excluded. For structure design, properties of the material are based on centerline temperature of the section (that is, average through-wall thickness), except where variation through the thickness is being explicitly considered.

7.2.3 For analysis of the liner behavior due to dead load, wind, earthquake, and thermal loads, the liner may be treated as a beam column and beam theory used for calculating the resultant stresses and displacements.

7.2.4 For the beam-column analysis, the liner may be considered uncoupled (separate) or coupled (jointly) with respect to the concrete column.

7.2.4.1 For the uncoupled system, the liner is considered to be rigidly supported by the concrete column and shall be designed as a continuous beam column. The displacements at points of support or restraint shall equal the independently computed displacements of the concrete shell.

7.2.4.2 For the coupled system, the coupling of the liner and the concrete column system is achieved by incorporating the flexibility of the concrete column in the liner design. A larger combined structure must be analyzed to obtain forces in the liner member(s) as a beam column.

7.2.4.3 The flexibility of the supports and restraints between the liner and the concrete column and the local flexibility of the liner at lateral support points may be incorporated in the analysis of the coupled system.

7.2.5 If the frequency of vibration of the liner, based on beam theory, is within ±20 % of the concrete column frequency, a dynamic analysis of the coupled system shall be made. A dynamic analysis of the coupled FRP liner/concrete column system shall be made, unless it is demonstrated by evaluation of the mass frequency ratios that coupling effects are negligible.

7.2.6 At points of application of loads (that is, at supports and restraints) on the liner beam-column, the liner may be adequately stiffened locally so that the liner roundness is maintained and the liner indeed functions as a beam-column.

7.2.7 Resultant forces are computed from linear elastic analysis of the beam column.

7.2.8 Using the resultant forces from the analysis, the design of the liner is checked against the appropriate material properties of the laminate. The resistance in a certain direction is based on the strength of the laminate in that direction, determined either experimentally or derived from known properties of the constituents.

7.2.9 Most material properties used in the analysis and design are results of short-duration tests at room temperature. Factors are recommended to reduce these property values to a design life of 35 years of the liner in the range of operating temperatures given in Section 5.

7.2.10 The minimum structural-wall thickness of the liner shall be ⅜ in. (10 mm).

7.2.11 Wherever the design requirements for the concrete chimney are cited in accordance with ACI 307, it is implied that requirements of ACI 307, or of the project specification, whichever are more critical, shall be used.

7.2.12 Nothing in this section shall be deemed to prohibit the use of other properly substantiated technical data and procedures for the analysis and design of fiber reinforced plastic liners.

7.3 *Dead Loads (D):*

7.3.1 The dead load shall include the estimated weight of all permanent structures, including stiffeners and attachments. A unit weight of 140 lb/ft^3 (2243 kg/m^3) is recommended for the calculation of the dead load of the liner (including stiffeners and attachments) using its nominal dimensions.

7.3.2 Where fly-ash is expected to be deposited on the inside surface of the liner, the dead load of the fly-ash shall be considered in the design. Where a wet scrubber is in operation, or can be in operation upstream of the chimney liner, a fly-ash deposit shall be considered to be attached to the inside of the liner. The variation of the thickness of the fly-ash deposit along the height of the liner shall be as shown in Fig. 1. The dead load of the wet fly-ash shall be based on a unit weight of 80 lb/ft^3 (1281 kg/m^3).

7.3.2.1 Where a wet scrubber is not in operation and no quenching system is used, or used briefly or rarely, the dry

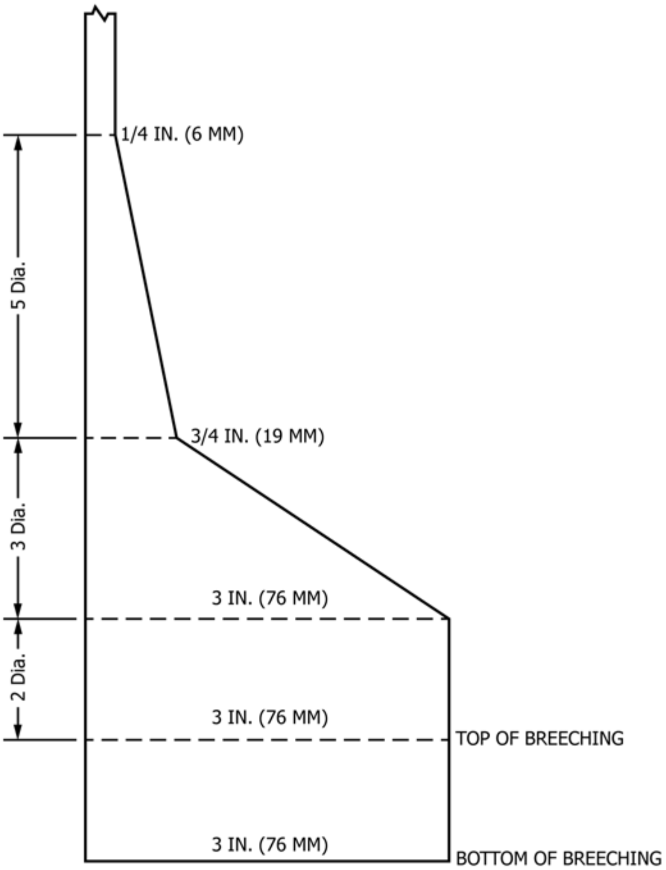


FIG. 1 Fly-Ash Deposit

fly-ash load [65 lb/ft^3 (1040 kg/m^3) dry-unit weight] shall equal 0.5 lb/ft^2 (2.5 kg/m^2) on the entire inside surface of the liner, or as specified.

7.3.2.2 When a quench system is used frequently and a wet scrubber is not in operation, the moist fly-ash load [80 lb/ft^3 (1281 kg/m^3) average moist-unit weight] shall equal 1.50 lb/ft^2 (7 kg/m^2) on the entire inside surface of the liner, or as specified.

7.3.3 The liner shall be designed to withstand the installation and handling stresses and the temporary loads during construction. Such loads should include self dead weight when the can is resting on its side prior to the installation of bracing. Temporary supports, lifting lugs, rigging, scaffolding, and other construction equipment shall be designed in accordance with accepted structural-engineering practices.

7.4 *Wind Loads (W)*—The liner shall be designed for all forces induced by the displacements caused by wind on the concrete column in accordance with ACI 307. The analysis for the dynamic wind loads shall be for along-wind or across-wind, whichever gives higher relative displacements in accordance with ACI 307.

7.5 *Earthquake Loads (EQ)*—It is recognized that the liner and chimney column interact under earthquake motion. Procedures for the dynamic analysis of the combined column liner system are outlined in 7.5.1. An alternative empirical procedure is outlined in section 7.5.2.

7.5.1 *Dynamic Analysis:*

7.5.1.1 The liner shall be designed for all forces or displacements, or both, resulting from a response spectrum analysis of the combined column liner system for the design response spectra in accordance with ACI 307.

7.5.1.2 Other dynamic analysis, based on properly substantiated technical data for establishing the magnitude and distribution of lateral forces, is also acceptable. In such analyses, the dynamic characteristics of both the column and liner shall be considered.

7.5.2 *Empirical Method*—The empirical method consists of computing, separately, the liner earthquake responses due to column deflections and due to liner inertia, and then combining them to obtain the total liner earthquake response. The restraints between the liner and the concrete column are considered rigid. The procedure is as follows:

7.5.2.1 Calculate the response of the liner to displacements induced by the concrete column due to earthquake. The column displacements shall be obtained from either method of earthquake analysis given in ACI 307, that is, from the design-response-spectrum analysis or the equivalent static-lateral-force analysis.

7.5.2.2 Calculate the response of the liner due to its inertia to the earthquake loads given in ACI 307 by either the design-response spectrum or by the equivalent static-lateral-force method.

7.5.2.3 Calculate the total liner earthquake response from:

$$R_t = (R_1{}^2 + R_2{}^2)^{1/2}$$

where R_1 and R_2 are the responses calculated from section 7.5.2.1 and 7.5.2.2, respectively. The response may be a typical quantity such as force, displacement, or stress.

7.6 *Thermal Loads:*

7.6.1 *Uniform Temperature Loading (T)*—The uniform temperature across the cross section normally does not cause any forces or stresses since the liner is not restrained in the longitudinal direction. This load is used to calculate the total thermal expansion of the liner due to the difference between the installation and operating temperatures.

7.6.2 *Non-Uniform Temperature Loading* (Δ*T*)—Thermal loading on the liner is created by non-uniform temperatures within the gas stream in both longitudinal and circumferential directions and by the variation of temperature through the liner wall thickness when combined with boundary restraint conditions.

7.6.3 *Longitudinal Stress Due to Thermal Loads*—The longitudinal thermal stress shall be taken as the sum of the flexural stress, the secondary stress, and the stress induced in the wall by the temperature differential through the wall.

7.6.3.1 *Thermal Membrane Stress*—A liner subject to circumferential temperature differential will rotate if free to do so. The resulting curvature may be expressed by 0.4 $\alpha_z \Delta T_m / r$. Thermal-membrane (direct) stresses result when rotational and translational supports restrain the curvature of the liner. The equivalent moment to be applied to the liner is 0.4 $E_z I \alpha_z \Delta T_m / r$.

7.6.3.2 Temperature differential of the liner across its diameter is calculated as follows:

$$\Delta T_m = \Delta T_g (1 - k_R) \qquad (1)$$

where:

ΔT_g = flue-gas temperature difference across the diameter, and

k_R = thermal resistance from gas stream to the middle of the liner wall relative to the total radial thermal resistance of liner.

In these calculations, the insulation effect of the corrosion-barrier thickness shall be used.

7.6.3.3 Temperature differential of flue gas across liner diameter is constant through the height of the breeching and attenuates with height as follows:

$$\Delta T_g = (\Delta T_g)_{\text{base}} e^{-0.2z/r} \qquad (2)$$

where:

z = distance from the top of breeching, and

$(\Delta T_g)_{base}$ = minimum of 25°F (−4°C).

7.6.3.4 Temperature differential across the structural layer, ΔT_w, should be considered in the design of the liner.

7.6.3.5 Thermally induced longitudinal secondary membrane stress resulting from ΔT_g shall be computed from:

$$f_z{}^{ct} = 0.1 E_z{}^{ct} \alpha_z (\Delta T_g) \qquad (3)$$

where:

$E_z{}^{ct}$ = modulus of elasticity (compression or tension) in the longitudinal direction, and

α_z = average coefficient of thermal expansion in the longitudinal direction.

7.6.3.6 Longitudinal bending stress due to temperature differential through the structural layer shall be computed from:

$$f_z{}^b = 0.5 E_z{}^b \alpha_z \Delta T_w \qquad (4)$$

where:

α_z *and* $E_z{}^b$ = average material properties of the wall in the longitudinal direction, and

ΔT_w = total temperature differential through the structural layer.

7.6.4 Temperature differential, ΔT_w, also induces bending stresses in the circumferential direction, which may be computed similarly using material properties in the circumferential direction.

7.6.5 Reverse-thermal-gradient loading (that is, during shutdown) where air temperature in the annulus is higher than inside the liner, shall be considered in the design of the liner.

7.7 *Circumferential Pressure Loads (CP)*—The circumferential loads on the liner result from the positive or negative pressure inside the liner and pressure fluctuations due to turbulent gas flow.

7.7.1 *Pressure in the Liner:*

7.7.1.1 The pressure within a liner is affected by changes in the unit operation (air preheater malfunction, forced draft, or induced draft fan changes) as well as the changes in the unit load.

7.7.1.2 When a liner is conveying hot flue gas of a specific weight less than that of the surrounding atmosphere, the pressure on the outside of the liner may be greater than on the inside. This negative pressure is commonly referred to as the chimney draft. The amount of negative pressure depends on the temperature and velocity of the flue gas, the height of the liner, as well as atmosphere pressure. When the flue-gas flow is supplemented by induced-draft fans, a reduction of the net negative pressure will result. For cases when an induced-draft fan is forcing the gas or cool air, or both, through the liner, the liner may be operating under a net positive pressure.

7.7.1.3 The theoretical negative static pressure, neglecting losses, shall be computed from:

$$D_s = 0.192H(\gamma_a - \gamma_g), \text{ inches of water} \tag{5}$$

where H = height from the center of breeching to top of liner.

7.7.2 *Liner Vibrations:*

7.7.2.1 There are situations where a liner may vibrate due to the movement of gas through it or due to resonance of the chimney column as a result of excitation by wind or earthquake. The lowest ovalling frequency of the liner, given in section 7.7.2.2 or 7.7.2.3 shall not be in the frequency range of the pressure fluctuation at the base of the liner. Where no specific data is available on the frequency range of pressure fluctuations, the lowest ovalling frequency shall not be less than 2 Hz.

7.7.2.2 The lowest ovalling or ring frequency for an unstiffened liner is calculated as follows:

$$f = \frac{t}{2\pi r^2}\sqrt{\frac{3E_\theta{}^b g}{5\gamma(1-\mu^2)}} \tag{6}$$

7.7.2.3 For a stiffened liner with ring stiffeners, the lowest frequency is calculated as follows:

$$f = \frac{3}{\pi R_c^2}\sqrt{\frac{E_\theta^b I_s g}{5L_1\gamma t_e(1-\mu^2)}} \tag{7}$$

$$t_e = \frac{W_L}{2\pi r L_L \gamma}$$

where:

R_c = radius of the liner to the centroid of the stiffeners,

$E_\theta{}^b$ = circumferential bending modulus of elasticity of the liner,

I_s = moment of inertia of one (1) stiffener,

g = acceleration due to gravity,

L_1 = spacing between full circumferential stiffeners,

γ = unit weight of liner,

t_e = equivalent liner thickness, including stiffener contribution, on basis of equal mass,

μ = average Poisson's ratio of the liner,

W_L = total weight of the continuous liner, including corrosion barrier, and stiffeners,

r = radius of the liner,

L_L = total length of the continuous liner, and

r_s = radius of the stiffener

7.7.2.4 For other liners not covered by section 7.7.2.2 and 7.7.2.3, rational procedures shall be used for computing the lowest frequency.

7.8 *Load Factors (LF)*—The load factors in the limit design approach are multiplicative factors used on dead, live, wind, earthquake, and temperature loads, as follows:

LF = 0.9 or 1.2 for dead load (*D*),
= 1.3 for wind or earthquake load (*W* or *EQ*),
= 1.1 for temperature load (*T* or Δ*T*),
= 1.1 for circumferential pressure loads (*CP*).

7.9 *Resistance Factor (RF)*—Resistance factor is the product of material resistance factor (*MRF*) and time-and-temperature-reduction factor (*TTRF*) (*RF* = *MRF* × *TTRF*).

7.9.1 *Material-Resistance Factor (MRF)*—The usable design strength is a fraction of the nominal material strength in the given mode.

7.9.2 The material-resistance factor for various types of loading is as follows:

MRF = 0.65 for direct tension or flexural, or both,
= 0.40 for direct compression.

7.9.3 *Time-and-Temperature-Reduction Factor (TTRF)*—The reduction in the mechanical properties of the liner material under load subjected to the operating environment of the liner is reflected in the time-and-temperature-reduction factor (*TTRF*). If no experimental data is available, the values of *TTRF* in section 7.9.5 shall be used.

7.9.4 The *TTRF* is affected significantly by the duration of the load. It is larger for short-term loads, such as those arising in abnormal operations or upset conditions, as compared to those for the long-term loads such as normal operation and dead loads.

7.9.5 The *TTRF* for the various types and durations of stresses at operating environments is given in Table 2.

TABLE 2 Time-and-Temperature-Reduction Factors (TTRF) for Long-Term Operation and Short-Term Abnormal Environments

Duration	Type of Stress		
	Membrane Tension	Membrane Compression	Bending
Long-term	0.2	0.7	0.7
Short-term	0.6	0.8	0.8

7.9.6 The values of the moduli used in sections 7.10 and 7.11 shall correspond to results from short-duration tests under the mean liner (T_m) temperature conditions.

7.10 *Loading Combinations*—Stresses shall be calculated for all three load combinations shown in sections 7.10.1 and 7.10.2.

7.10.1 Loading combination for the sustained or long-term loading are as follows:

$$\textit{Load Combination No. 1:} \qquad (8)$$

$$1.2D + 1.1T + 1.1CP$$

and where D reduces the effects of T and CP:

$$0.9D + 1.1T + 1.1CP \qquad (9)$$

where:

D = dead loads,
T = temperature loads, and
CP = circumferential pressure effects.

7.10.2 Short-duration-loading combinations are as follows:

$$\textit{Load Combination No. 2:} \, 1.2D + 1.1T + 1.3W/EQ + 1.1CP \qquad (10)$$

and where D reduces the effects of T, CP, and W or EQ :

$$0.9D + 1.1T + 1.3W/EQ + 1.1CP \qquad (11)$$

where W/EQ = effects of wind or earthquake, not taken at the same time.

$$\textit{Load Combination No. 3:} \qquad (12)$$

$$1.2D + 1.1AT + 1.1CP$$

and where D reduces the effect of AT and CP:

$$0.9D + 1AT + 1.1CP \qquad (13)$$

where AT = effect of the abnormal temperature condition.

7.11 *Allowable Longitudinal Stresses:*

7.11.1 *Compressive Stress*—Determine the maximum allowable longitudinal compressive stress in the cylindrical liner by the following equation:

$$F_z^{\,c} = RF \times F_z^{\,cr} \qquad (14)$$

$$= 0.28\, F_z^{\,cr} \text{ for long term loads, and}$$

$$= 0.32\, F_z^{\,cr} \text{ for short term loads.}$$

7.11.1.1 $F_z^{\,cr}$ in Eq 14 is calculated as follows:

$$F_z^{\,cr} = 0.6 \frac{k_n t}{r} \sqrt{E_z^{\,b} E_\theta^{\,c}} \qquad (15)$$

$$k_n = \text{knockdown factor} = 1.00 - 0.91 \left(1 - e^{-0.06\sqrt{r/t}}\right) \qquad (15A)$$

7.11.1.2 Lateral bracing such as stay rods or bumpers shall be provided so that L/r does not exceed 20.

7.11.2 *Tensile Stress*—Direct or membrane stress is that part of the total stress, which is uniform over the thickness of the structural layer, or which is almost uniform through the structural layer as in the case of beam bending of the liner. The remaining part of the total stress is caused by the bending of the structural layer.

7.11.2.1 The maximum allowable longitudinal direct tensile stress in the liner shall be determined as follows:

$$F_z^{\,t} = RF \times F_z^{\,tu} \qquad (16)$$

where:

RF = 0.13 for long-term loads,
RF = 0.39 for short-term loads, and
$F_z^{\,tu}$ = ultimate longitudinal short-term tensile strength of the structural layer at room temperature.

7.11.3 *Bending Stresses*—The allowable bending tension or compression in the longitudinal direction shall be determined from the following equation:

$$F_z^{\,b} = RF \times F_z^{\,bu} \qquad (17)$$

where:

RF = 0.45 for long-term loads,
RF = 0.52 for short-term loads, and
$F_z^{\,bu}$ = ultimate longitudinal short-term bending strength of the structural layer at room temperature.

7.12 *Allowable Circumferential Stresses:*

7.12.1 *Compressive Membrane Stress*—Determine the maximum allowable circumferential compressive membrane stress in the liner by the following equation:

$$F_\theta^{\,c} = RF \times F_\theta^{\,cr} = 0.28\, F_\theta^{\,cr} \text{ for long} - \text{term loads, and} \qquad (18)$$

$$F_\theta^{\,c} = RF \times F_\theta^{\,cr} = 0.32\, F_\theta^{\,cr} \text{ for short} - \text{term loads.}$$

where $F_\theta^{\,cr}$ is calculated by:

$$F_\theta^{\,cr} = 0.765 \frac{\left[(E_z^{\,c})^{1/4} (E_\theta^{\,b})^{3/4}\right](t/r)^{1.5}}{(L_1/r)} \qquad (19)$$

7.12.2 *Tensile Stress*—Direct or membrane stress is that part of the total stress which is uniform over the thickness of the structural layer. The remaining part of the total circumferential tension stress is caused by the bending of the liner wall.

7.12.2.1 Determine the maximum allowable circumferential direct tensile stress in the liner by the following equation:

$$F_\theta^{\,t} = RF \times F_\theta^{\,tu} \qquad (20)$$

$$= 0.13\, F_\theta^{\,tu} \text{ for long} - \text{term loads, and}$$

$$= 0.39\, F_\theta^{\,tu} \text{ for short} - \text{term loads.}$$

where $F_\theta^{\,tu}$ = ultimate hoop short-term tensile strength of the structural layer at room temperature.

7.12.3 *Bending Stresses*—The allowable bending tension or compression in the circumferential direction shall be determined from the following equation:

$$F_\theta^{\,b} = RF \times F_\theta^{\,bu} \qquad (21)$$

$$= 0.45\, F_\theta^{\,bu} \text{ for long} - \text{term loads, and}$$

$$= 0.52\, F_{\theta}^{bu} \text{ for short} - \text{term loads.}$$

where F_{θ}^{bu} = ultimate circumferential short-term bending strength of the liner wall, at room temperature.

7.12.4 *Circumferential Stiffener Requirements:*

7.12.4.1 *General*—Circumferential stiffening shall meet the minimum requirements given in this section when the unstiffened liner shell is unable to structurely support the circumferential pressures as described herein. In addition to providing structural resistance, stiffeners reduce the effect of imperfections built into the cross section.

7.12.4.2 The circumferential stiffeners shall be designed to resist the lateral loads arising from the positive or negative pressure inside the liner, pressure fluctuations due to turbulent gas flow, liner vibrations (see section 7.7.2) and the lateral restraints such as stay rods and bumpers.

7.12.4.3 *Stiffener Spacing*—Spacing of stiffeners shall not exceed 1½ diameters of the liner or 25 ft (8 m), whichever is less.

7.12.4.4 *Stiffener Size*—The size of stiffeners shall satisfy the following requirements:

(*a*) The ring stiffener shall have a bending stiffness equal to or greater than that determined by the following equation:

$$(EI)_s \geq \frac{PL_1 r^3}{1.15(RF)} \tag{22}$$

where:

$(EI)_s$ = transformed flexural stiffness of the ring stiffener, and

RF = reduction factor for flexural tension or compression for short-term loads. The MRF, of the RF, shall be selected based on the stiffener material used (that is, steel, plastic).

(*b*) In determining stiffener-section properties, a portion of the structural layer of the liner equal in width to $1.56\sqrt{rt}$ may be included, but the total area so added shall not exceed the transformed area of the stiffener.

(*c*) The stiffener shall be designed for the erection loads, including deflection considerations.

7.13 *Design Limits*—The liner shall be so proportioned that the actual or computed stress in a given direction of the liner, for a given loading condition, is less than the corresponding allowable stress. Thus, when one of the two computed stresses, namely, longitudinal or circumferential, is tensile, the requirement is expressed as follows:

$$\frac{f_z^{\,t}}{F_z^{\,t}} + \frac{f_z^{\,b}}{F_z^{\,b}} \leq 1 \tag{23}$$

or

$$\frac{f_{\theta}^{\,t}}{F_{\theta}^{\,t}} + \frac{f_{\theta}^{\,b}}{F_{\theta}^{\,b}} \leq 1 \tag{24}$$

7.13.1 As an alternative method to the requirements of section 7.13 for allowable tensile and bending stresses, the design professional may choose to use lamination analysis. If used then follow the procedure set forth in ASME RTP-1, a standard for reinforced thermoset plastic corrosion-resistant equipment. The elastic constants and strain limits selected shall account for the thermal environment of the liner.

7.13.2 When either the longitudinal or circumferential stress is compressive, the following requirements shall be satisfied:

$$\frac{f_{\theta}^{\,c}}{F_{\theta}^{\,c}} \leq 1 \quad \text{and} \quad \frac{f_z^{\,c}}{F_z^{\,c}} \leq 1 \tag{25}$$

7.13.3 When the longitudinal and circumferential stresses are both compressive, interaction shall be as follows:

$$\frac{f_z^{\,c}}{F_z^{\,c}} + \left(\frac{f_{\theta}^{\,c}}{F_{\theta}^{\,c}}\right)^2 \leq 1 \tag{26}$$

7.13.4 The design limits in section 7.13 shall be applied, separately, for long-term loads and for short-term loads.

7.14 *Tolerances*—The tolerances are based on those in Section 8.

7.15 *Deflections:*

7.15.1 *Short-Term Loads*—The loading combinations defined in section 7.10 with the loads defined in sections 7.3 through 7.7 shall be used to calculate deflections using the short-term moduli of elasticity at room temperature.

7.15.2 *Long-Term Loads*—The primary loads causing the long-term longitudinal deflection are the tension resulting from dead loads and the thermal growth of the liner.

7.15.2.1 The long-term longitudinal deflection shall be calculated from the following expression:

$$\delta = \left[f_z^{\,t}/E_z^{\,t} + \alpha_z \Delta T\right] 12H \tag{27}$$

7.16 *Critical Design Considerations and Details*—The following design considerations and details are critical to an FRP liner and will require careful consideration by the design professional:

7.16.1 Shear parallel to laminate,

7.16.2 Support shoulders,

7.16.3 Lateral-restraint locations,

7.16.4 Construction joints,

7.16.5 Reinforcement around openings,

7.16.6 Breechings,

7.16.7 Hoods, and

7.16.8 Expansion joints.

8. Fabrication

8.1 *Fabrication*—This section addresses minimum requirements of facilities, tooling, laminate construction, and procedures necessary for satisfactory fabrication of FRP chimney liner components.

8.2 *Responsibility of Fabricator*—The responsibility of the fabricator shall be to construct the equipment in accordance with the complete designs and details set forth solely by the design professional and shall warrant all workmanship to be in accordance with specified designs.

8.3 *Fabrication Facility:*

8.3.1 The fabrication process is considered to be a "shop" operation which can be performed in the "home-shop" of the fabricator, or the process can be performed in a "temporary shop" that is built at or near the project site.

8.3.2 The facility shall be enclosed and capable of maintaining a 60°F (16°C) minimum constant environment.

8.3.2.1 The facility shall maintain all materials and equipment during use at a minimum of 5°F (3°C) above dew-point temperature to avoid moisture condensation.

8.3.3 Special care and conditioning is required when materials are brought in from cold outside temperatures to warm work areas.

8.3.4 If fabrication is not a continuous operation, provisions shall be made to assure that condensation does not develop on the surface of an incomplete part.

8.3.5 All mechanical systems (heating, lighting, and ventilation) shall be designed and operated for adequate safety of materials and personnel.

8.3.5.1 The facility shall have adequate ventilation capacity to constantly maintain the proper number of air changes per hour, as required by OSHA (**1**).[7]

8.3.5.2 The styrene concentration at the working level shall not exceed that required by OSHA (**1**). Ventilation shall be designed to draw fumes from the floor of the facility. Floor-level exhaust fans are recommended.

8.3.6 Open-flame heating units shall not be allowed. Electric, steam, or closed-flame units are acceptable. The source of heat cannot generate any particles, moisture, or organic vapor to the environment.

8.4 *General Construction:*

8.4.1 The FRP chimney liners are normally constructed from individual cylindrical sections, called "cans," of the diameter set forth by the design.

8.4.2 The can should be fabricated in lengths to minimize the number of required erection joints.

8.5 *Fabrication Equipment:*

8.5.1 *Winding Machine:*

8.5.1.1 The winding machine shall maintain a wind angle within ±1 ½ ° throughout the length of the can.

8.5.1.2 The machine shall deliver the reinforcing strands in a continuous uniform flat band saturated with resin. Unsaturated glass is not acceptable.

8.5.1.3 The number of winding passes and the weight of resin and reinforcement applied shall be recorded for each can.

8.5.2 *Mandrel:*

8.5.2.1 The FRP cans shall be fabricated on mandrels with uniform outer surface to minimize flat spots or indentations. Mandrels may be of either collapsible or tapered design to allow removal of the liner can. The extraction method shall ensure safe removal without scratches.

8.5.2.2 The mandrel shall have a diameter within ±0.25 % of the specified diameter anywhere along its length.

8.5.2.3 The mandrel drive and related mechanisms shall be capable of maintaining the proper pattern(s) from can to can.

8.5.2.4 Suitable polyester film, or other release agents such as polyvinyl alcohol, or both, shall be used to provide a glossy inner surface to ensure extraction without damage to the inner surface.

8.5.2.5 Mandrel temperature must be 60°F (16°C) minimum during application of material.

8.5.3 *Resin Apparatus*—The resin-delivery equipment shall be commercial internal-mixing units which will accurately meter, dispense, and mix the proper ratio of catalyst to promoted resin in adequate volume to properly wet out (saturate) the glass reinforcement.

8.5.4 *Reinforcement Apparatus*—The machine apparatus should deliver glass strand, and other reinforcements, in a manner that is uniform, consistent and repeatable from part to part. Application of reinforcements that may cause gaps, voids or other structural impairments is not acceptable.

8.6 *Resin Systems:*

8.6.1 Resins shall be stored, promoted, catalyzed, and applied within the recommendations of the resin manufacturer.

8.6.1.1 The resins shall be maintained at a minimum temperature of 60°F (16°C) during mixing and application.

8.6.1.2 Resins can be supplied in drums or tank-car quantities. The mixing requirements apply equally to whatever quantities are being mixed.

8.6.2 Resin viscosity may be adjusted for manufacturing requirements by the addition of thixotropic agents such as fumed silica or styrene, or both. The addition of thixotropic agents or styrene shall be within the recommendation of the resin manufacturer and in no case shall these concentrations exceed 5 % by weight of the resin.

8.6.3 Resins containing dispersed solids shall be agitated after mixing and continuously throughout use during application.

8.6.4 Resins may be supplied with or without factory promoters added. When promoters or other additives are added at the fabrication site, adequate equipment shall be provided to assure accurate measurement and adequate mixing of resin.

8.6.5 Prior to application, a gel time test shall be performed on the resin. A suitable means shall be used to monitor the flow of catalyst to ensure that properly catalyzed resin is delivered to the mandrel.

8.7 *Reinforcement:*

8.7.1 Structural reinforcements shall be *E* or *E-CR*-grade fiberglass rovings and mat with sizings and binder systems compatible with the specified resin, as stated in the requirement in Section 6.

8.7.2 All reinforcement products shall be packaged, stored, and handled in such a manner that does not allow damage or contamination (that is, dirt, moisture, etc.).

8.7.3 Winding rovings shall be continuous strands having nominal yield of 200 yd/lb, or greater.

8.7.4 Chopped-strand mat shall consist of random fibers with a minimum length of 1 in. (25 mm) and maximum of 2 in. (50 mm). A nominal weight of 1.5 oz/ft^2 (458 g/m^2) is required. Mat may be applied as roll goods or by use of a chopper gun.

8.8 *Fabrication Procedures:*

8.8.1 *Mandrel Preparation:*

8.8.1.1 Liner cans shall be constructed over a smooth mandrel surface with a laminate consisting of: (*1*) a corrosion barrier that consists of a resin-rich inner surface reinforced with one or more veil layers and interior layer(s) reinforced with chopped-strand mat, both intended for optimum chemical

---

[7] The boldface numbers in parentheses refer to the list of references at the end of this guide.

resistance; (*2*) a structural layer reinforced with continuous-strand rovings and mat layers for structured requirements; and (*3*) an exterior outer surface for weather, erosion, and environmental protection.

8.8.1.2 The specific laminate sequence and number of layers shall be determined by the design professional and detailed on the manufacturing drawings.

8.8.1.3 The mandrel and any molds shall be examined prior to the start of fabrication to assure that their surfaces are clean and free of defects.

8.8.2 *Corrosion Barrier:*

8.8.2.1 The corrosion barrier shall be built-up on the mandrel in a sequential operation to achieve the requirements of the specified laminate.

8.8.2.2 A resin coat shall be applied to the rotating mandrel before application of any reinforcement. The mandrel shall be wetted with resin and the specified veil applied. The veil should be applied with sufficient overlap to ensure that no gaps are present. Additional wetting of the veil may be required to achieve proper saturation.

8.8.2.3 The inner surface shall be 0.010-in. (0.25-mm) nominal thickness reinforced with a minimum one-veil reinforcement.

8.8.2.4 The resin content of the inner surface shall be approximately 85 % by weight.

8.8.2.5 After a uniform wet-resin coat has been applied the veil shall be applied with a minimum overlap of 0.5 in. (13 mm) and no gaps shall be permitted. Another application of resin shall then be applied to assure complete wet-out of the veil.

8.8.2.6 The interior layers shall consist of chopped-strand mat or chopped rovings in one or more layers as specified.

8.8.2.7 Chopped strand and resin shall be applied with uniform thickness. If more than 1.5 oz/ft^2 (458 g/m^2) is required, it shall be applied in a minimum of two applications.

8.8.2.8 Each pass shall be adequately rolled to ensure proper wet-out and air pocket removal.

8.8.2.9 The resin content of the interior layer(s) shall be at least 70 %, but not more than 80 % by weight.

8.8.2.10 The mat shall be overlapped a minimum of 0.5 in. (13 mm) and no gaps shall be permitted.

8.8.2.11 After completion of the corrosion barrier (inner surface and interior layers), the laminate shall be allowed to exotherm and essentially cure prior to the application of the structural wall. The structural wall shall not be allowed to compress the thickness of the corrosion barrier.

8.8.2.12 After exotherm, the liner shall be inspected for rough spots, bumps, or depressions that may cause subsequent bridging of the filament winding.

8.8.2.13 The corrosion barrier shall be free of any contamination, including moisture, and shall be acetone-sensitive prior to start of filament winding.

8.8.3 *Structural Layer:*

8.8.3.1 Before starting the structural layer, the surface of the corrosion barrier shall be inspected for defects, air pockets, protruding glass fibers, ridges at abutted reinforcement, or other conditions which could lead to deficiencies in subsequent operations.

8.8.3.2 Such deficiencies shall be removed or corrected by grinding or sanding. Any pockets or depressions created by this operation shall be filled with chopped-strand laminate to a uniform flush surface.

8.8.3.3 The structural reinforcement should be applied with 24 hours after completion of the corrosion barrier. The surface of the corrosion barrier must be inspected for contamination and condensation, and an acetone sensitivity test performed. If no contamination or condensation is found, and the surface is acetone sensitive, the structural reinforcement may be applied.

8.8.3.4 If the surface does not become tacky with acetone, or if the surface becomes contaminated by any cause, the surface shall be thoroughly sanded to remove the surface gloss. The surface shall then be blown free of excessive dust. In no case shall the time between completion of the corrosion barrier and application of the structural layer exceed 72 h without sanding.

8.8.3.5 The structural layer shall consist of continuous wound strands at the specified winding angle. Strands shall be applied as a flat band in a helical pattern so as to provide full mandrel coverage of bi-directional layers without gaps or overlays. Patterns that may not allow butting bands next to the preceding band shall not be used.

8.8.3.6 As determined by the design professional, localized reinforcements may consist of circular wound rovings and weft unidirectional roving parallel to the axis and shall be detailed on the manufacturing drawings.

8.8.3.7 The winding angle shall be as specified in the project specifications and drawings. Allowable variation from the specified angle is ±3°.

8.8.3.8 Immediately before start of the structural layer application, a wet layer of chopped strand shall be applied to "bed" the continuous strand and compensate for any minor outer-surface irregularities.

8.8.3.9 The first complete cycle (closed-pattern layer) of winding shall be applied with sufficient resin to fill in minor surface irregularities to aid in and ensure good bedding onto the cured corrosion barrier.

8.8.3.10 The glass content of the structural layer shall be within ±3 % of that used to predict the design properties.

8.8.3.11 Not more than 5 % of the winding strand or two adjacent strands may be allowed to break out before the operation is stopped and the strands retied.

8.8.3.12 If the winding operation is not continuous to the final thickness, or if equipment breakdown occurs that delays completion, then the procedures in 8.8.3.3 and 8.8.3.4 shall be followed before the winding operation restarts.

8.8.4 *Outer Layer*—The outer exterior surface shall be coated with a layer of non-air-inhibited resin.

8.8.5 *Fittings:*

8.8.5.1 Fittings shall be fabricated by hand lay-up construction of alternate layers of mat and woven roving or by filament winding, or a combination of both. The precise sequence and number of layers shall be specified by the design professional and detailed on the manufacturing drawings.

8.8.5.2 All fittings, regardless of structural layer design, shall have a corrosion barrier equal to the liner requirements.

8.8.5.3 Flanges shall be fabricated by hand lay-up procedures. The stub wall reinforcing shall be continuous into the flange face.

8.8.6 *Structural Joints:*

8.8.6.1 Structural joints for shop fabrication and field installation shall be butt-and-strap type. The specific joint requirements shall be determined by the design professional.

8.8.6.2 Butt-and-strap joints may be on the inside only or inside and outside.

8.8.6.3 Butt-and-strap joints shall be constructed with alternating layers of mat and woven roving to the thickness specified.

8.8.6.4 The first and last layers of butt-and-strap joints shall be mat.

8.8.6.5 All structural joints 24 in. (610 mm) in diameter and larger shall have an internal sealing laminate at least equal in construction to the specified corrosion barrier.

8.9 *Handling and Transportation:*

8.9.1 All liner sections shall be properly handled in a safe manner that will not allow damage, scuffing, or over-stressing. The FRP components shall not be allowed to impact on any hard objects as nonvisible impact damage may occur.

8.9.2 All shipments shall be adequately packaged, braced, and cradled in order to prevent damage during transit. Ends and fittings shall be adequately protected from damage.

8.9.3 All handling of cans shall be by means of non-abrasive slings. The use of cables or chains is prohibited.

8.10 *Erection Appurtenances:*

8.10.1 Lifting lugs or similar attachments shall be provided on each liner section for ease of handling and erection.

8.10.1.1 The design of these attachments shall be incorporated into the overall design of the liner and shall take into account the method of handling and loads imposed.

8.10.1.2 Location of the lifting attachments shall be determined by the fabricator and reviewed by the design professional. Details of the attachments shall be furnished by the design professional.

8.11 *Tolerances:*

8.11.1 The design professional is responsible to set consistent tolerances for the manufacturing of the FRP cans and the steel components that are attached to the cans. Tolerances shall take into account limitations with respect to methods of manufacturing.

8.11.2 The tolerance of can diameter, based on internal measurement when the can is in the vertical position, including the out-of-roundness, shall be less than 1 %.

8.11.3 Flat spots on a can shall not cause a change in geometry in excess of that resulting in a radial offset of 0.2 in. (5 mm) over 2 ft (610 mm), 0.4 in. (10 mm) over 3 ft (915 mm), and 0.8 in. (20 mm) over 4 ft (1219 mm) of the circumference of the can.

8.11.4 Tolerance on the overall can height shall be ±½ % but shall not exceed ±½ in. (13 mm).

8.11.5 Tolerance on the thickness of total structural layer and of the corrosion-barrier layer at any point shall be −10 to +20 %. The tolerance on the average thickness of a can, based on thickness measurements of at least five randomly selected points, or on the weight of the can, however, shall be between −5 and +10 %. When based on weight, there shall be no limit on the tolerance on underweight as long as the thickness tolerances are achieved.

8.11.6 Control the total weight of the liner in order that the grillages not be overloaded.

9. Erection of FRP Liners

9.1 *Erection Scheme and Sequence:*

9.1.1 Prior to liner erection, a construction plan shall be formulated detailing the erection sequence and methods to be employed by the contractor.

9.1.2 Consideration shall be given to the loads imposed on the FRP liner during handling, storage, and erection. Stresses resulting from these loads shall be accounted for during the initial-design stage and incorporated into the final design. Conditions such as ovalling and localized stresses at lifting points are of particular importance.

9.1.3 All rigging materials and hoisting equipment shall be designed by a licensed engineer and made available to the owner for review, if requested.

9.2 *Handling and Storage on Site:*

9.2.1 Handling of liner cans shall be done with slings made of nylon or other similar materials to prevent damage to the exterior surface.

9.2.2 When repositioning the liner cans from the horizontal to the vertical position, take care to avoid bottom edge point loading conditions which may cause cracking of the interior corrosion-barrier surface.

9.2.3 Liner cans shall be stored in a manner that will minimize ovalling.

9.2.4 Stored liner cans shall be checked for wind effects and suitable anchorage or guy wires provided if required.

9.3 *Erection Appurtenances:*

9.3.1 The use of alignment lugs on each liner can is required to ensure proper fit-up and liner orientation during the erection phase. They shall be designed to accommodate any loads imposed during erection.

9.3.2 When the liner installation utilizes a temporary FRP lifting shoulder to support the liner during erection, it shall be similar in fabrication to any permanent support shoulders. The lifting shoulder shall be designed to accommodate all loads imposed during erection.

9.4 *Field Joints:*

9.4.1 Field joints shall be connected as shown on the erection drawings.

9.4.2 All field joints shall be designed to transmit the loads from each liner can to the next. The joint shall be equivalent in strength to the structural layer.

9.4.3 A butt-and-strap joint is preferred to other types. The width of the joint shall be a minimum of 16 in. (406 mm) with the sum of the exterior and interior overlay at least equal to the full-wall thickness of the thinner can.

9.4.4 All joint types shall be cured to at least 25 Barcol hardness, read at eight places equally spaced on each surface around the circumference, and averaged, eliminating the high and low readings, before moving the section. Barcol readings shall be made for both the interior and exterior joint surfaces.

9.4.5 The contractor shall provide methods to ensure proper alignment of joints, tolerances, and clearances to the design professional for review prior to erection.

9.4.6 The contractor shall provide an inspection and testing program, as well as safety recommendations, to the design professional for review prior to erection.

9.5 *Field Joint Lamination Procedure:*

9.5.1 *Joint Overlay Zone Preparation:*

9.5.1.1 The field weld overlay must be applied onto the surface of an FRP Liner Can which has been abraded to completely remove the glaze, and is clean and dry. The surface glaze (external post coat or internal corrosion barrier), must be abraded in the overlay zone by grinding using a 24 grit grinding disc, a 36 grit grinding disc can be used if it produces the required surface profile. The abraded surface should not have a polished finish appearance; it must remove the surface glaze exposing a clean abraded surface which has a roughened finish approximately a 0.15 mm (0.006) mil minimum texture.

9.5.1.2 The surface preparation should be done just prior to fabricating the weld overlay (no more than 12 hours maximum prior to overlay placement). If the surface has been pre-ground and left exposed to exterior environments (wet with dew or moisture) then acetone solvent wipe, allow to air dry, or dry with a heat gun, and regrind the overlay zone.

9.5.1.3 If the grinding dust and dirt has not been removed from the overlay surface, this will cause the overlay not to have the proper bond adhesion. Clean, dry air or a clean cotton rag maybe used to remove the surface dust.

9.5.1.4 If there is doubt about the surface preparation, re-prepare the surface for bonding.

9.5.2 *Weld Overlay Placement:*

9.5.2.1 Verify the proper weld kit materials are available. Overlay patches consist of multiple glass fabric plies; refer to project drawings for the fabric ply order and quantities.

9.5.2.2 Verify surface preparation is completed properly and proceed with lamination.

9.5.2.3 If required, a bonding coat of catalyzed resin may be applied to the section of the overlay zone to receive the overlay. This should be done before the application of the first plies.

9.5.2.4 Wet out the overlay plies on clean cardboard or non waxed Kraft paper. Be certain that all tools are clean and free of liquid solvent before using. Begin to wet out overlay plies starting with the widest ply first on the wet out table. Verify complete saturation of laminate plies with catalyzed resin. Do not use an excessive amount of resin to wet overlay patches.

9.5.2.5 Apply the overlay material. Application in patch form is recommended. Apply the completed package of plies which have been wet out to liner can joint area. The overlay package should be centered on the liner can joint. Use a serrated roller tool to remove entrapped air from the laminated patch after it is placed on the liner can surface. Continue applying overlay packages until the weld joint area has been closed completely.

9.5.2.6 If the patch begins to gel, (i.e. harden) prior to placement on the liner can surface or prior to all the air removal between the cans and the overlay, remove the patch and discard it.

9.5.2.7 Allow laminate package to completely exotherm and cool to ambient temperature.

9.5.2.8 Repeat procedure from step 9.5.1.1 for each following laminate sequence to apply the remainder of the overlay material as defined in the overlay kit (glass layers).

9.5.2.9 Visually inspect the weld overlay, remove and correct with additional overlay material any deficiencies exceeding the prescribed limit per square foot area Ishall not exceed the following. MoveMore][VB60] stringent requirements may take precedence over these requirements.

9.5.3 *Top Coat of Overlay Surface:*

9.5.3.1 After application of all overlay laminate packages, and all repairs have been completed prepare the overlay laminate for a final resin coat by grinding all loose edges and burrs. Use of a 36 grit grinding disc or higher is acceptable for this step, as the intent is to provide a smooth finished laminate surface profile.

9.5.3.2 Apply a coating or catalyzed resin to the entire overlay joint area. This final topcoat is intended to provide a resin rich surface, possibly with the addition of chemicals for ultraviolet protection and wax for providing a tack free surface.

10. Quality Assurance and Quality Control

10.1 *Quality Assurance and Quality Control:*

10.1.1 Minimum quality-control criteria are stated for the design, fabrication, erection, and inspection of the FRP chimney-liner system and accessories, and to ensure a system of high-operating reliability.

10.1.2 Minimum quality requirements shall be ensured through the entire process of design, fabrication, and installation. The components for the program may be defined by the fabricator or a designated representative of the owner. The procedures and practices shall be performed by persons with a demonstrated knowledge of FRP design and fabrication and the specific requirements of chimney liners.

10.2 *Quality-Assurance Program:*

10.2.1 The contractor's organization shall be established in such a manner that persons involved in the quality-assurance program have sufficient authority and organizational freedom to identify quality nonconformances. The quality-assurance program shall define the method(s) to initiate, recommend, or provide solutions, as well as to verify implementation of solutions.

10.2.2 The organization shall be established in such a manner that the individual or group assigned the responsibility for checking, auditing, inspecting, or otherwise verifying that an activity has been correctly performed is independent of the individual or group directly responsible for performing the specific activity.

10.2.3 The authority and responsibility of persons performing activities affecting quality shall be clearly established and documented in the contractor's quality-assurance manual.

10.2.4 The contractor shall establish and maintain a quality-assurance program for the control over the quality of the specific items being supplied or the work to be performed. The contractor shall require any subcontractors or suppliers to establish and implement a quality-assurance program for the work to be performed or the items to be supplied, or both.

10.2.5 The quality of all items under contract, whether supplied by the contractor or a subcontractor, shall be controlled at all points necessary to assure conformance with the requirements of this guide and associated codes and standards.

10.2.6 The quality-assurance program shall be documented in detail in a quality-assurance manual, subject to the owner's (or his designee's) review.

10.2.7 The contractor's quality-assurance manual shall include: written instructions, procedures, or drawings to direct and control activities affecting quality. Job specifications, instructions, job tickets, planning sheets, operating or procedure manuals, test and repair procedures, or other relevant documents shall be maintained to control quality.

10.2.8 The contractor's quality-control system shall provide procedures that will ensure that issued documents affecting quality, such as procurement documents, reports, drawings, calculations, procedures, and instructions, are adequately controlled. The control specified in the procedures shall assure that the documents are reviewed for adequacy and approved for release by authorized personnel. Changes to these documents shall be authorized and controlled in the same manner as the original documents.

10.2.9 The design professional shall ensure that applicable codes and standards have been included in his design. Measures shall be established to ensure that appropriate quality requirements are specified and included in the design documents.

10.2.10 Design-control measurements shall provide for verifying or checking the adequacy of design by performance of design reviews and calculational or test programs.

10.2.11 The design professional shall identify and control design interfaces, including coordination, review, and approval with participating organizations of all interfaces with the subject equipment.

10.2.12 The contractor shall ensure that purchased items and services, whether purchased directly by him or through his subcontractors, conform to the requirements of the procurement documents. The contractor's procedures shall include, as appropriate: (*1*) provisions for source evaluation and selection by means of historical quality-performance data, source surveys or audits, or source qualification programs; and (*2*) objective evidence of quality furnished by the equipment subcontractor, source inspection and audit, and inspection and test of item upon delivery.

10.2.13 The contractor shall maintain a system of receiving control which will assure that the material received is properly identified and has documentation, including required material certifications or material-test reports to satisfy code or standard requirements, as ordered. The material-control system shall ensure that only acceptable material is used for fabrication or construction. These procedures shall also identify the methods of marking and maintaining control on applicable parts and materials.

10.2.14 The contractor shall establish a program for in-process and final inspection of activities affecting quality to ensure conformance with documented instructions, procedures, and drawings. Examinations, measurements, or tests shall be performed for each activity, where necessary, to ensure quality. Inspection and test activities to verify that the quality of work shall be performed by persons other than those who performed the work being inspected.

10.2.15 Sufficient records shall be prepared as work is performed to furnish documentary evidence of the quality of items and activities affecting quality. The records shall be readily identifiable and retrievable for a period to be identified by contract.

10.3 *Quality-Assurance Surveillance:*

10.3.1 All activities performed by the contractor and subcontractors are subject to quality-assurance surveillance or audit, or both, by the owner. Surveillance or audit, or both, shall not relieve the contractor of any responsibility for the requirements of his contract and shall not be considered as waiver of warranty or other rights.

10.3.2 Compliance with the requirements of this guide does not relieve the contractor of his responsibility to ensure that all other contract requirements are met.

10.3.3 The owner shall have the right to establish inspection-hold points and be given prior notice to all inspections designated as inspection-hold points.

10.3.4 Prior to the start of fabrication activities, the owner may prepare a vendor-surveillance-check plan (VSCP) which will be forwarded to the contractor. The VSCP shall establish those points in the fabrication cycle that the owner will witness, verify, or perform.

10.3.5 The owner reserves the right to provide a quality-assurance representative in the fabrication shop. A mutually acceptable quality-assurance program that incorporates the intent of the requirements of 10.2.1, 10.2.2, and 10.2.3 shall be developed by the fabricator.

10.4 *Inspections:*

10.4.1 Inspections and approval of all critical, major, and minor quality attributes shall be clearly defined in the quality-assurance manual.

10.4.2 The acceptance and rejection criteria shall be clearly defined for materials and laminate construction. Laminates shall be inspected for visual defects such as pits, voids, blisters, cracks and other defects listed in Table 5 of Specification C582. Special consideration shall be provided for entrapped air in the bond area of the corrosion barrier as these may result in eventual blistering. Appropriate acceptance and repair procedures shall be written in the Quality Assurance Manual.

10.4.3 The quality-assurance procedures shall address inspections and approval of quality attributes which include, but are not limited to the following:

10.4.3.1 Completeness of approved drawings and specifications;

10.4.3.2 Material description of resins, reinforcements, putty, and additives;

10.4.3.3 *Surface Preparation:* (*a*) Mandrel.

(*b*) Corrosion barrier to structural winding.

(*c*) Ribs and shoulders.

(*d*) Nozzles and joints.

(*e*) Secondary bonding of any discontinuous operations that may occur.

10.4.3.4 *Hand Lay-Up Laminate (Including Attachments and Appurtenances):* (*a*) Thickness control.

(*b*) Laminate sequences.

(*c*) Exotherm limit.

(*d*) Critical ply intervals.

(*e*) Delay-and-restarting contingencies.

(*f*) Reinforcement staggering.

(*g*) Reinforcement overlap.

(*h*) Glass-to-resin ratios.

(*i*) Cure.

(*j*) Wax coat (where applicable).

10.4.3.5 *Filament-Wound Laminate (Including Attachments and Appurtenances):* (*a*) Thickness.

(*b*) Band width and strands per inch.

(*c*) Winding angle.

(*d*) Laminate sequence.

(*e*) Exotherm limit.

(*f*) Glass-to-resin ratio.

(*g*) Cure.

(*h*) Strand yield.

(*i*) Gapping tolerance.

10.4.3.6 *Environmental Constraints:* (*a*) Temperature (air and resin).

(*b*) Humidity.

10.4.3.7 *Mechanical Elements Non-FRP:* (*a*) Welding and steel fabrication.

(*b*) Bolt torques.

(*c*) Equipment lifting and handling.

(*d*) Shipment to the job site.

(*e*) Storage of completed equipment.

(*f*) Erection sequence.

10.4.3.8 *Dimensions and Weights:* (*a*) Length.

(*b*) Thickness.

(*c*) Inside diameter.

(*d*) Out-of-roundness.

(*e*) Weight of finished part.

10.4.4 A typical inspection checklist is contained in Annex A1.

10.5 *Submittals*—The following documentation shall be submitted for review prior to fabrication by the contractor, if requested by the owner:

10.5.1 The details of construction, including ply thickness and type of reinforcement, for all laminates.

10.5.2 The description of laminates shall include all plies of the corrosion barrier and structural wall, including the minimum allowable thickness for laminate sequences and the location of exotherm plies. The glass content of the corrosion barrier and structural wall of each laminate shall be provided.

10.5.3 Filament-wound laminates shall be described including the thickness of each cycle, wind angle, and band density. The yield of winding strand shall be listed.

10.5.4 Resin type with the type of catalyst and promotion system intended and the location of its intended use.

10.5.5 The manufacturer's general-arrangement drawings showing all dimensions, cross-sectional details of shell joints or slip-mold-type joints, nozzles or manways, lugs and supports, knuckles, pads, or other appurtenances. The width, minimum thickness, and composition of all laminates shall be included.

10.5.6 Description of the method of construction of flanges detailing the method of connection between the flange face and neck.

10.5.7 The materials of construction and dimension of all weldments.

10.5.8 Identification of areas to receive abrasion-resistant laminates, for the purpose of resisting localized abrasion or impingement.

10.5.9 All major design criteria including laminate physicals, maximum deflections, and safety factors.

10.5.10 The plan for production of the equipment including the expected rate of production, number of shifts per day, names of the production manager, and leaders of each shift (if known).

10.5.11 Details of assembly and field installation of the equipment including edge preparations, end gap tolerances, and detailed joint-overlay laminate description including the width and composition of each ply. The method for protection of the joint area during lamination shall be provided.

10.5.12 All inspection forms required to comply with this guide.

10.5.13 Quality-assurance manual.

10.5.14 All design bases including calculations, laminate design, and physical sample test data.

10.5.15 Shipping, handling, and storage recommendations and instructions.

11. Operation, Maintenance, and Start-Up Procedures

11.1 *Initial Start-Up or Start-Up After a Long-Term Shutdown:*

11.1.1 During start-up and shutdown, the temperature gradients shall be gradual. Any sudden temperature changes shall be avoided.

11.1.2 Prior to start-up, any temperature-moderation devices (that is, spray quench systems) shall be checked and operational.

11.1.3 Prior to start-up all expansion joints, counterweights, guides, etc. shall be checked, cleaned, and operating smoothly.

11.2 *Operation and Maintenance:*

11.2.1 *Inspections*—Inspections of critical stress areas (that is, supports) shall be inspected at least annually. A vertical interior and exterior full-height inspection of the liner shall be performed at regular intervals (maximum two years).

11.2.2 Inspectors shall be qualified to inspect FRP materials and any areas of stress shall be noted and mapped.

11.2.3 All moving parts (that is, expansion joints), shall be inspected regularly to ensure that all are operating satisfactorily. Additionally, any spray-quench system shall be tested. All drains shall be kept clear.

11.2.4 Written reports of inspections and unusual operating occurrences shall be recorded and a liner history maintained over the life of the liner.

11.2.5 During operation of the liner, the difference in temperature between the ambient temperature surrounding the liner shall be minimized. For instance, during cold weather, exterior chimney-column vents shall not be opened unless necessary.

11.2.6 Operation of the facility shall be such that buildup of fly ash on the liner is minimized. The spray-quench system shall not be operated continuously on a regular basis. Operation of the spray-quench system causes buildup of fly ash on the liner.

ANNEX

(Mandatory Information)

A1. TYPICAL INSPECTION CHECKLIST

Inspection Item	Inspection Frequency	Inspection Method	Reference	Procedure Requirement	Reference	Remarks	Documentation
(*1*) *Mandrel Prior to Start of Carbon Veil Application (Hold Point)*							
Smooth	each can	visual	. . .	. . .	. . .		not formally documented
Clean	each can	visual	. . .	. . .	. . .		not formally documented
Other Items to Verify							
Resin batch numbers	each can	visual	. . .	. . .	. . .		quality assurance manual (QAM)
Resin shelf life	each batch	visual (drums)	. . .	6 months	resin supplier	if exceeds 6 months, retest in accordance with procedure	not formally documented
Resin gel-time test	each batch daily	Test Method D2471	QC procedure	resin supplier specifications	procedure	. . .	QAM
Resin viscosity test	each batch daily	Test Method D2393	procedure	resin suppliers specifications	procedure		QAM
Glass receiving report	each can	visual	procedure	. . .	. . .	. . .	QAM
Air temperature in work area	every day	thermometer on mandrel	. . .	50°F (10°C), min	fabricator		material usage form
Resin temperature in point of use	each can	visual	. . .	min 60°F (16°C) max 95°F (32°C)	fabricator		material usage form
(*2*) *Carbon Veil (Witness Application)*							
Smooth—no wrinkles which cannot be rolled out before gel	each can	visual	. . .	. . .	. . .	. . .	not formally documented
Full wet-out	each can	visual	. . .	. . .	. . .	. . .	not formally documented
(*3*) *Surfacing Veil (Witness Application)*							
Smooth—no wrinkles which cannot be rolled out before gel	each can	visual	. . .	. . .	. . .	. . .	not formally documented
Full wet-out	each can	visual	. . .	. . .	. . .	. . .	not formally documented
(*4*) *Chopped Strand (Witness First Layer At Least)*							
Smooth—no wrinkles which cannot be rolled out before gel	each can	visual	. . .	. . .	. . .	. . .	not formally documented
Full wet-out	each can	visual	. . .	. . .	. . .	. . .	not formally documented
(*5*) *Ready to Start Filament-Winding (Witness Point)*							
Chopped-strand used	each can	visual	. . .	3 oz/ft^2 (915 g/m^2), min (2 layers min)	procedure		material usage
Chopped-strand layers gelled prior to winding	each can	visual	. . .	. . .	. . .	. . .	not formally documented

Inspection Item	Inspection Frequency	Inspection Method	Reference	Procedure Requirement	Reference	Remarks	Documentation
Rough spots ground smooth	each can	visual	. . .	. . .	. . .	. . .	not formally documented
During winding:							
Winding (helix) angle	each can	visual	. . .	55–65°	specification		QAM
(*6*) *After Fabrication is Complete, and Prior to Removal from Mandrel (Witness Point)*							
No gaps between glass strands	each can	visual	. . .	. . .	. . .	. . .	not formally documented
Proper number of filament-winding cycles based on specified wall thickness	each can	visual (check “counter”-passes/cycle)	. . .	. . .	. . .		QAM
All required stiffeners etc . . . added	each can	visual	. . .	various requirements	drawings	. . .	QAM
Outer surface coat applied (U.V. stabilizer/wax)	each can	visual	. . .	U.V. stabilizer and wax	procedure		QAM
Resin-glass ratio: interior layer (chopped strand)	each can	Test Method D2584	procedure	glass content 25 ± 5 % by weight	procedure		QAM
Exterior layer (filament-wound)	each can	Test Method D2584	procedure	glass content 55 − 0 + 15 % by weight	procedure		QAM
Total wall thickness	each can	cut-outs or ultra sonics, or both	. . .	minimum thickness for each can	procedure and drawings		QAM
Corrosion barrier thickness (veil plus 2 mat)	each can	cut-outs	. . .	0.096 in. (2.5 mm), nominal	specification		QAM
Barcol hardness (for surface cure)	each can	Test Method D2583	procedure	per resin manufacturer	procedure	Barcol hardness of corrosion barrier to be measured *after* can removed from mandrel	QAM
Visual inspection/repair requirements	each can	visual	. . .	visual	specification	Inspect corrosion barrier *after* can is removed from mandrel	grid preliminary inner

APPENDIX

(Nonmandatory Information)

X1. COMMENTARY

X1.1 *Reference 7.2*—The information presented in the ASCE report(**2**) is used extensively.

X1.1.1 *Reference 7.2.3*—The error introduced in the analysis of cylindrical shells by the beam theory is the assumption that plane surfaces remain plane, or that the bending stresses are proportional to the distances from the neutral axis.

X1.1.2 *Reference 7.2.9*—If experimental data is available or if other values of material properties are available, or both, they may be used, provided the various parameters defined in this section can be substantiated (**3**).

X1.1.3 *Reference 7.2.12*—It will be up to the user of the alternative design procedures to properly substantiate the rationality and the choice of the parameters used in the methods. Two examples of such design procedures are given as follows:

(*1*) Laminate theory may be used in arriving at the theoretical properties of the laminate section based on the glass ratio, angle of wind and the material properties of the resin and reinforcement.

(*2*) The entire formulation may be developed in terms of limiting lamina stresses and strains that constitute the design criteria.

X1.2 *Reference 7.3.1*—The recommended dead load is based on a statistical analysis of some liners. See also X1.3.6.

X1.2.1 *Reference 7.3.3*—The erection loads do not occur in conjunction with the thermal loads and hence will not normally control the design of the liner. However, the circumferential stresses and stability shall be investigated for handling procedures.

X1.3 *Reference 7.4*—The mass of the liner is usually not large enough to significantly affect the dynamic wind characteristics of the concrete column.

X1.3.1 *Reference 7.6.2*—An empirical method is presented in Ref (**2**). Field data was collected for temperature distributions along and across steel liners with different geometric configurations and flow characteristics. Recommendations are based on these measurements made in the early 1970’s. The operating conditions of some power plants have been altered since then. Also, the thermal characteristics of uninsulated fiber-reinforced liners are significantly different from the insulated steel liners considered in the reports.

X1.3.2 The ASCE report remains a primary publicly available resource on the thermal distributions in liners. However, caution is required in the present application of the ASCE report recommendations.

X1.3.3 *Reference 7.6.3*—The temperature nonuniformity is the result of incomplete mixing of different-temperature-level flue-gas streams. The nonuniform temperature distribution within the gas stream will impose a similar temperature distribution on the inside of the liner, resulting in varying temperatures around the centerline circumference of the liner. These differentials produce unequal longitudinal thermal expansion causing lateral deflection of the liner. Longitudinal stresses will develop when the liner is restrained.

X1.3.3.1 If the centerline temperature varies across the liner as a linear function of the diameter, the resulting deformation in the cylinder produces only beam-type stresses, if the liner is restrained from bending freely. This idealized temperature distribution along the centerline of the liner seldom occurs. Secondary thermal stresses develop when nonlinear temperature variations are imposed across the liner.

X1.3.3.2 *Reference 7.6.3.2*—In the calculation of the total thermal resistance, the temperature inside the liner may be considered as the average gas temperature:

$$\left(T+\frac{T_0}{2}\right). \qquad (X1.1)$$

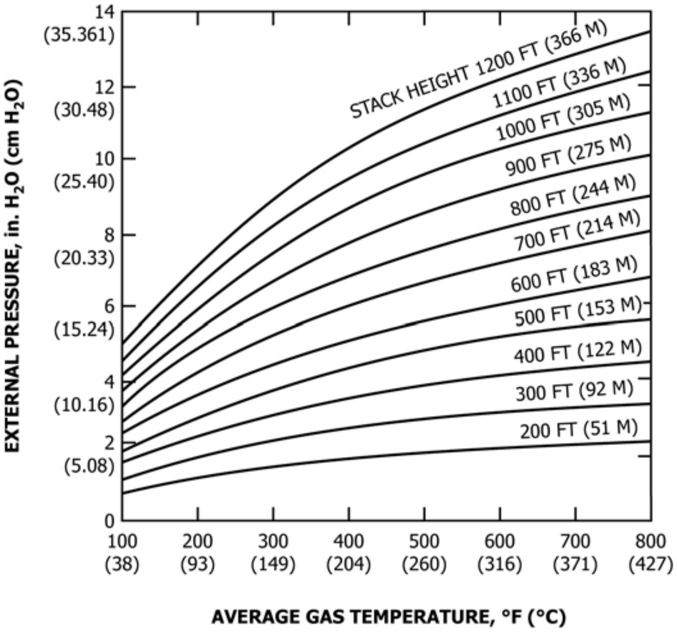
X1.3.3.3 *Reference 7.6.3.6*—The calculations for obtaining the temperature drop through the liner wall may be performed in accordance with the procedure outlined in ACI 307. Other substantiated heat-transfer models and the analysis thereof may be used.

X1.3.4 *Reference 7.7.1.3*—Considering the variation of pressure with elevation above sea level, the equation for D_s becomes:

$$D_s = 0.52Hp'\left(\frac{1}{T_a}-\frac{1}{T_g}\right) \text{ inches of water} \qquad (X1.2)$$

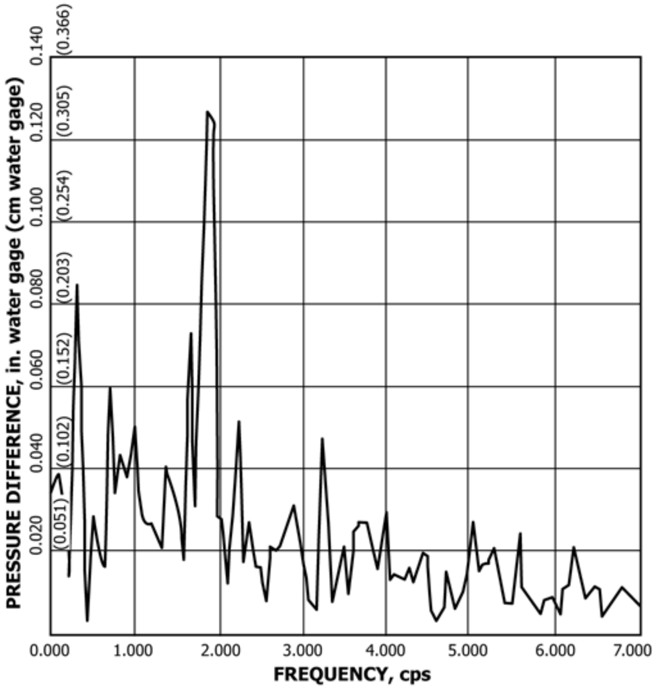
The negative pressure at the base of a chimney, computed in accordance with Eq X1.2 under natural-draft conditions, is shown in Fig. X1.1 in terms of average gas temperature for various chimney heights. The negative static pressure at the base of the stack is actually less than the plotted values because of flow losses, but for liner-design purposes, these values may be used.

X1.3.5 *Reference 7.7.3*—Gas movement through the liner is turbulent and may cause significant pressure fluctuation. At the present time there is little data available on the magnitude and frequency of pressure fluctuations, or their spatial distributions within the liner. The cause of the fluctuations may be associated with the uneven nature of the combustion process, turbulence induced when the gas stream changes direction or velocity, or both, and possible induced pulsation due to an imbalance in an induced-draft fan. Ovalling vibration of steel liners due to gas turbulence has been observed at several locations, and is a design criterion for steel liners. The FRP liners are as susceptible to vibration as steel liners. Measurements of steel liners have shown pressure pulsation of ½ to 2 in. of water and dominant frequencies of 1 to 2 Hz (cps). The spectrum shown in Fig. X1.2 shows a peak at 1.8 cps. Therefore, it is prudent to ensure a minimum natural frequency of 2 cps to avoid resonance. Note that ovalling frequency of liner is proportional to liner thickness, *t*, material factor $\sqrt[2]{E/[\gamma\,(1-\mu 2)]}$, and $1/r^2$. For chimney liners of the same radius, the material factor for FRP is about 50 to 60 % of that for steel; therefore, the thickness of the FRP liner must be 1.7 to 2 times that of the steel liner to result in the same natural frequency.



NOTE 1—Curves are based on atmosphere at −20°F (−29°C) and sea level.

FIG. X1.1 External Pressure Curves (1)



NOTE 1—Pressure difference measured by transducers located 180° apart.

FIG. X1.2 Pressure Difference Versus Frequency

X1.3.5.1 *Reference 7.7.2.2*—The formula given for ovalling frequency of an unstiffened shell is applicable to small diameter liners (approximately up to 6 ft (1.8 m)) in which the thickness is not substantially increased.

X1.3.5.2 *Reference 7.7.2.3*—If the shell is stiffened, appropriate computation of natural frequency must be made.

X1.3.5.3 *Reference 7.7.2.4*—Although natural frequency for circumferentially stiffened shell is not given, there is nothing that prevents the design professional from using an appropriate equation. The design professional can reference Forsberg for a discussion of natural frequency of a stiffened cylinder, or use the equations developed by Forsberg given in the steel chimney liner reference (**2**).

X1.3.6 *Reference 7.8*—The upper load factor on dead load was based on a statistical analysis of certain liners. A probability of failure of 1×10^{-5} was used with the normal distribution. The procedure given in Ref (**4**) was used in determining the load factor.

X1.3.6.1 *Reference 7.9.1*—The material-resistance factor (MRF) accounts for the usual variability in the room-temperature properties of the liner material manufactured under normal conditions of quality control, as specified in Section 10. It is based on a coefficient of variation of the measured property of less than 10 %. If the level of quality control is not sufficient to ensure a coefficient of variation of less than 10 %, then the MRF must be proportionally reduced.

X1.3.6.2 *Reference 7.9.3*—The time-and-temperature-reduction factor (TTRF) accounts for the loss of the mechanical properties of the liner material when subjected to the temperature and chemical environment of the liner for the duration of the load. When applied to long-term strength of laminate in direct tension, it is the ratio of the average strength of a loaded specimen in the chemical environment and temperature of the liner that would cause creep rupture only after the design life of the liner (35 years) to the strength of the specimen as determined by short-term tests at room temperature. The TTRF should be distinguished from the retained strength of the laminate, which is the percent of the short-term strength of the laminate that is retained after exposure of the unloaded specimen to the combined thermal and chemical environment of interest. The values of the TTRF presented in Section 7 were selected based on the engineering judgment of the members of Subcommittee D20.23 and the limited test results available (**5**).

X1.3.6.3 *Reference 7.10.2*—Wind loading is not considered in the sustained or long-term loading because the contribution of a factored-design wind load is very small, compared to other long-term loads on the liner.

X1.4 *Reference 7.11.1.1*—A more accurate longitudinal buckling strength of fiber-reinforced plastics may be determined from the following equation:

$$F_z^{cr} = \frac{2\sqrt{3}\,C\sqrt{D_x A_\theta}}{rt} \qquad \text{(X1.3)}$$

X1.4.1 For further explanation see Ref (**6**). For a uniform thickness of the shell and neglecting the shear deflection, the equation reduces to the one given in 7.11.2, with k_n = 1.0.

X1.4.2 The value of 0.6 in the equation in 7.11.1.2 corresponds to a Poisson's ratio of about 0.3.

X1.4.3 The above equation is based on the "long-shell" formulation. The longitudinal-buckling strength for the "short" shells is higher than that for the long shells. The effect of the length for" intermediate" shells can be incorporated in the knockdown factor k_n in the equation. The additional term of 1.5 $(r/L_1)^2$ (t/r) in the more exact semi-empirical equation for k_n is omitted because its contribution is not significant for the practical range of values of (r/L_1) and (t/r) for liners. Thus, its maximum value is estimated at about 0.03 when (r/L_1) is at its practical maximum of 1.0 and $t/r$is 0.02. Furthermore, dropping this term is more conservative.

X1.4.4 As the value of r/t is increased from 24 to 1160, the valuek_n in the formula given in 7.11 varies from 0.768 to 0.208. The latter value corresponds to the buckling stress of $0.125Et/r$used in(**2**).

X1.4.5 In addition to longitudinal buckling of the cylindrical shell, the combined flexural and longitudinal compressive stress should not be high enough to cause failure, local microbuckling, or delamination. Microbuckling occurs when fiber bundles buckle locally and delamination causes buckling of one or more laminate. Elastic buckling of a cylindrical shell liner is a bifurcation phenomenon in which two adjacent equilibrium configurations exist. The buckling occurs when the strain energy required for deforming the liner into the buckled configuration is less than the external work of the forces that maintain the liner in the unbuckled configuration. Therefore, the creep of the material in the unbuckled configuration does not affect the buckling strength directly, although it magnifies the imperfections and thus may affect the buckling strength indirectly.

X1.4.6 High negative pressure can occur in the liner as a result of the implosion effect following an explosion, or "puff" in the boiler. Several coal-fired units have experienced explosions during start-up which were severe enough to cause extensive damage to steel liners. Nonuniform circumferential negative pressures were estimated to exceed 10 in. of water.

X1.4.7 The sudden closing of flue dampers can also create a similar condition resulting in high negative pressures.

X1.4.8 There are two significant considerations that suggest that the reduction factors for buckling strength of fiber-reinforced plastic liners may be more than those for the steel liners. The normal thickness of the former is generally more than that of the latter; thus the ratio of the magnitude of the imperfections to the design thickness is likely to be less for fiber-reinforced plastic. Secondly the method of fabrication of most liners makes it less likely to have the deviation from the circular form, as compared to steel liners, where individual plates are field-welded.

X1.5 *Reference 7.12.1*—A more accurate analysis of the circumferential buckling strength of fiber-reinforced plastics may be determined from the following equation:

$$F_\theta^{cr} = \frac{5.5k_n(A_x)^{1/4}(D_\theta)^{3/4}}{L_1\sqrt{rt}} \qquad \text{(X1.4)}$$

X1.5.1 For further explanation, see Ref (**6**). For a uniform thickness of the liner, Eq X1.4 reduces to the one given in 7.11.1. The value of k_n is taken as 0.9.

X1.5.2 The circumferential compressive stress should not exceed the maximum compressive stress that causes microbuckling and delamination, as discussed in X1.4.

X1.5.3 If the test data for the material properties of the design laminate of the liner are not available, the moduli of elasticity of the liner in circumferential compression may be based on the following formula:

$$\left(E_z{}^{\mathrm{c}\,1/4}E_\theta{}^{\mathrm{b}3/4}\right) = W_{\mathrm{cm}}\ \sin^2 a \tag{X1.5}$$

X1.5.4 *Reference 7.12.4.4*—The stiffness of the stiffener should be large enough to resist ring buckling when subjected to radial load, even when the shell buckles and the pressure loads between stiffener rings are transferred to the rings. The factor of safety, FS, without the RF = 2.60. For a fiberglass stiffener with an RF = 0.52, the FS against buckling = 5.0. For a steel stiffener, an MRF = 0.85, the FS ≅ 3.0.

REFERENCES

(1) *Occupational Safety and Health Act* (OSHA).

(2) "Design and Construction of Steel Chimney Liners," American Society of Civil Engineers (ASCE), 1975. Discontinued; reproductions at: UMI, 3009 N. Zeeb Rd., Ann Arbor, MI 48106.

(3) Nielsen, L. E., "Mechanical Properties of Polymers and Laminates," Vol 1, Dekar, 1974, pp. 8–83.

(4) MacGregor, J. G., "Safety and Limit States Design for Reinforced Concrete," *Canadian Journal of Civil Engineering*, Vol 3, 1976, pp. 481–513.

(5) Kraus, H., *Creep Analysis*, John Wiley and Sons, Chapter 5 ("Creep Rupture"), p. 101, 1980.

(6) "Structural Plastics Design Manual," *ASCE Manual of Engineering Practice No. 63*, ASCE, New York, NY, 1984.

(7) Robinson, James, "Utility FRP Chimney Liner Survey," United Engineers and Constructors, Inc., Englewood, CO, May 1983.

(8) Zarghamee, Mehdi, S., Brainerd, M. L., and Tigne, D. B., "On Thermal Blistering of FRP Chimney Liners," *Journal of Structural Engineering*, ASCE Vol 112, No. 4, April 1986, pp. 677-691.

(9) Nespoli, O., and Osborne, A. D., "Predicting Elastic Properties of FRP Laminates at Elevated Temperatures," *1986 Canadian RP/C Corrosion Conference Proceedings*, SPI, Canada.

(10) *Manual of Professional Practice*, "Quality in the Constructed Project," American Society of Civil Engineers (ASCE), Vol 1.