Designation: D 5364 – 93 (Reapproved 2002)

An American National Standard

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

This standard is issued under the fixed designation D 5364; 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 scrubbers. 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. Appendix X4 is a partial listing of FRP-liner heights and diameters currently in the generating industry. The taller FRP structures and larger diameters (10–30 ft (3–9 m)) imposed new design, fabrication, and erection challenges.

A utility-industry survey of FRP liners was conducted in 1983 (**4**).[2] This survey summarized the 19 FRP liners constructed in the power-utility industry; including Owner/A-E/Contractor, overall configuration, fuel type, and specific operating experience.

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 bounding of attachments, appurtenances, and joints.

(*6*) Installation and handling.

Chimney components include an outer shell, an inner liner, 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 (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 transients affect material selection and design.

1. Scope

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

---

[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 Nov. 10, 2002. Published March 2003. Originally approved in 1993. Last previous edition approved in 1993 as D 5364 – 93.

[2] The boldface numbers in parenthesis refer to the list of references at he end of this guide.

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-assurance and quality-control procedures are developed for the design, fabrication, and erection phases. The quality-assurance program defines the proper authority and responsibility, control of material and fabrication, 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 similar or equivalent ISO standard.

1.10 *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:*

C 518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[3]

C 581 Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures, Intended for Liquid Service[4]

C 582 Specification for Contact-Molded Reinforced, Thermosetting Plastic (RTP) Laminates for Corrosion Resistant Equipment[4]

---

[3] *Annual Book of ASTM Standards*, Vol 04.06.

[4] *Annual Book of ASTM Standards*, Vol 08.04.

D 638 Test Method for Tensile Properties of Plastics[5]

D 648 Test Method for Deflection Temperatures of Plastics Under Flexural Load in the Edgewise Position[5]

D 695 Test Method for Compressive Properties of Rigid Plastics[5]

D 790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials[5]

D 792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement[5]

D 883 Terminology Relating to Plastics[5]

D 2393 Test Method for Viscosity of Epoxy Resins and Related Components[6]

D 2583 Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor[7]

D 2584 Test Method for Ignition Loss of Cured Reinforced Resins[7]

D 3299 Specification for Filament-Wound Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks[4]

D 4398 Test Method for Determining the Chemical Resistance of Fiberglass Reinforced Thermosetting Resins By One-Side Panel Exposure[4]

E 84 Test Method for Surface Burning Characteristics of Building Materials[8]

E 228 Test Method for Linear Thermal Expansion of Solid Materials With a Vitreous Silica Dilatometer[9]

2.2 *American Concrete Institute (ACI) Standard:*

ACI Standard 307 Specification for the Design and Construction of Reinforced Concrete Chimneys[10]

2.3 *NFPA Standard:*

NFPA 77 Recommended Practice on Static Electricity[11]

2.4 *ASME Boiler and Pressure Vessel Code:*

Fiberglass Reinforced Plastic Pressure Vessels [12]

2.5 *ANSI Standard:*

ASME/ANSI RTP-Reinforced Plastic Corrosion Resistant Equipment [13]

3. Terminology

3.1 *Definitions:*

3.1.1 Terms used in this guide are from Terminology D 883 unless otherwise indicated in 3.2.

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

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

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

3.5 *Barcol hardness*—measurement of the degree of cure by means of resin hardness. The Barcol impressor is the instrument used (see Test Method D 2583).

3.6 *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.

3.7 *blister*—Refer to Terminology D 883.

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

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

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

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

3.12 *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.

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

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

3.15 *chopper gun*—a machine used to cut continuous fiberglass roving to predetermined lengths (usually ½ –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.

3.16 *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.

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

3.18 *coverage*—see *winding cycle.*

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

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

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

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

3.23 *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.

3.24 *entrapped-air void*—see *void.*

3.25 *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.

---

[5] *Annual Book of ASTM Standards*, Vol 08.01.

[6] Discontinued. See 1994 *Annual Book of ASTM Standards* , Vol 08.02.

[7] *Annual Book of ASTM Standards*, Vol 08.02.

[8] *Annual Book of ASTM Standards*, Vol 04.07.

[9] *Annual Book of ASTM Standards*, Vol 14.02.

[10] Annual ACI Technical Committee Manual publication. Available from American Concrete Institute, P.O. Box 9094, Farmington Hills, MI 48333.

[11] Available from NFPA, 1 Batterymarch Park, Quincy, MA 02269.

[12] Available from American Society of Mechanical Engineers, New York, NY, 1989, pp. 187–202.

[13] Available from American Society of Mechanical Engineers, New York, NY, 1989, Subpart 3B and pp. 111–135.

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

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

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

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

3.30 *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.

3.31 *fiberglass roving*—see *roving.*

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

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

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

3.35 *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.

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

3.37 *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 E 84. The resins are not flame retardant in their liquid state.

3.38 *flame-spread rating*—index number for any laminate of definite composition resulting from testing in accordance with Test Method E 84.

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

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

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

3.42 *glass*—see *fiber(glass).*

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

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

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

3.46 *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 D 648 usually refers to a cured-resin casting, not a laminate.

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

3.48 *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.

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

3.50 *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.

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

3.52 *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.

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

3.54 *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 2.5).

3.55 *lamination theory*—see *lamination analysis.*

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

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

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

3.59 *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.

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

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

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

3.63 *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.

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

3.65 *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.

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

3.67 *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.

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

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

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

3.71 *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.

3.72 *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.

3.73 *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.

3.74 *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.

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

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

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

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

3.79 *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.

3.80 *strain*—elongation per unit length.

3.81 *stress*—load per unit area.

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

3.83 *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.

3.84 *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.

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

3.86 *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.

3.87 *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.

3.88 *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.

3.89 *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.

3.90 *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.

3.91 *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).

3.92 *Definitions of Terms Specific to This Standard:*

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

3.92.2 *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.

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

3.92.4 *quality control (QC)*—a system of measurements and checks employed to monitor the manufacture of the FRP chimney liner and to assess compliance of manufacture to the critical quality requirements.

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	$f_\theta^t f_\theta^c$	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	$E_\theta^t E_\theta^c$	E_θ^b	

3.93 *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/sf/in./h/°F
h_3 = film coefficient of thermal conductivity outside of liner, BTU/sf/in./h/°F
I = center-line moment of inertia of liner section, in.^{4}= $\pi r^3 t$
k = coefficient of thermal conductivity for FRP liner (in absence of data use k = 2), BTU/sf/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
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_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 Rankine
t_c = thickness of corrosion barrier, in.
T_g = flue gas temperature, Degrees Rankine
T_m = mean liner temperature, $^{(T1}$¼+ T2);2 , Degrees Rankine
T_n = annulus air temperature, Degrees Rankine
T_o = temperature at inside surface of corrosion barrier, Degrees Rankine
T_1 = temperature at interface between corrosion barrier and structural layer, Degrees Rankine
T_2 = temperature at outside surface of structural layer, Degrees Rankine
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_{oBASE}= 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
$TTRF$ = time and temperature reduction factor
W = wind load
W_{cm} = compressive modulus of elasticity of the winding material (glass), psi
W_{tm} = tension modulus of elasticity of the winding material (glass), psi
z = distance from top of breeching, ft
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/in.^{3}
γ_g = specific weight of gas, lb/in.^{3}
δ = longitudinal deflection, in.

4. Significance and Use

4.1 This guide provides information 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 unscrubbed 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 baghouses 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 440°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 is either a polyester or vinylester that provides the properties necessary to withstand the conditions of the operating environment described in Section 5. Resins conform to the requirements of Specification C 582.

6.1.1.2 Most FRP chimney liners are fabricated with a flame-retardant resin and 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 C 581, or under the actual anticipated environmental-service condition.

6.1.1.3 The resin in the corrosion barrier is 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 conform to the descriptions of diluents, resin pastes, and ultraviolet absorbers as explained in Specification C 582. Additionally, carbon filler may be added for static-charge dissipation.

6.1.3 *Reinforcements*—Reinforcements shall conform to the requirements of Specification C 582 for contact molding and Specification D 3299 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 *E* or *E-CR* type glass fibers having a sizing compatible with the resin.

6.1.3.2 The surface veil used in the corrosion barrier should be *C* type glass or a synthetic material. Additionally, a carbon veil may be required for static-charge dissipation as in 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 includes 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 follows laminate construction described in Specification C 582. The structural layer primarily provides the mechanical properties of the design. The outer layer contains a paraffinated resin to prevent air from inhibiting the cure process and providing weather or environmental protection, or both.

6.2.1 *Corrosion Barrier*—The corrosion barrier shall be as described in Specification C 582. Additional plies of surfacing mat and chopped-strand mat may be used in particularly severe chemical environments, but consideration should 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 D 3299 and Section 8, but may include contact molding, as described in Specification C 582, or a combination of both.

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 D 638 shall be used or laminate theory in conjunction with test results as in 6.3.1.7.

6.3.1.2 *Flexural Modulus (Axial and Hoop Directions)*—Test Method D 790 shall be used or the laminate theory in conjunction with test results in 6.3.1.7.

6.3.1.3 *Compressive Modulus*—The compressive modulus shall be obtained in accordance with Test Method D 695, with some 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. Laminate theory may be used in conjunction with test results in 6.3.1.7.

6.3.1.4 *Coefficient of Thermal Expansion*—Coefficient of thermal expansion is to be measured in accordance with Test Method E 228, 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 must 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 C 117 or C 518 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 must be considered in interpretation of the results. Unidirectional roving may be used to approximate filament winding.

6.3.1.6 *Specific Gravity*—The specific gravity shall be obtained in accordance with Test Method D 792 for measurement of specific gravity of plastics by displacement.

6.3.1.7 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 difference between the computed and the test results shall agree to within 10 %.

6.3.2 *Chemical*—The corrosion resistance of the resins used shall have been characterized by either Practice C 581 or Test Method D 4398. Resins may also be evaluated for vapor exposure in accordance with Practice C 581, 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 are to 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 is to be determined in accordance with Test Method D 648.

6.3.4.3 The temperature at the corrosion barrier/structural layer interface can 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. This procedure is described in Appendix X5.

6.3.5 *Flame Retardancy*:

6.3.5.1 Flame spread is determined in accordance with Test Method E 84 (see Note 2) by using a standard laminate construction as determined in accordance with 4.1.2 of Specification C 582. 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.

6.3.5.2 A maximum flame-spread index of 45 is recommended for the total laminate system.

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 must be considered.

6.3.6.1 *Static-Charge Dissipation Patch System*—An appropriate patch system should be a 2-ft^2 (0.2-m^2) laminate containing conductive carbon filler or carbon veil covering a ½-in. (13-mm) bolt that runs through the laminate and is connected to the chimney grounding system. The design of the bolt and patch should provide a 1-MΩ maximum path from the interior surface to the external ground.

6.3.6.2 *Continuous Conductive Liner-Material System*—This system could be an interior liner containing conductive carbon veil or carbon filler to provide continuous resistivity of no more than 1 MΩ throughout the interior surface of the liner. The interior surface is then connected to the ground, generally by a terminal patch, as described in 6.3.6.1.

6.3.7 *Grounding System*—Each can in the liner shall have at least one grounding point (patch), preferably two. Patches shall be proof tested using ohmmeters or spark testers. At the point of grounding, the resistance to ground shall be approximately 25 Ω. The grounding system shall be attached to a copper pipe embedded a minimum of 6 ft (2 m) into the ground, or an equivalent acceptable system. The grounding system shall conform to the requirements specified in the latest edition of NFPA 77 and 77-16.

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 temperature environments defined by Conditions 1, 2, and 3 in Section 5 for normal operating conditions and Condition 1 for abnormal environments. 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. 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. 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.

7.2.6 At points of application of loads (that is, at supports and restraints) on the liner beam column, the liner should 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 quantities to an expected life of 35 years 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 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.

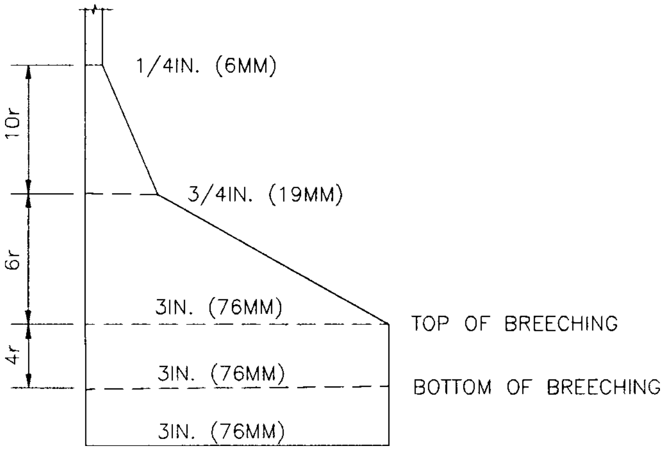

FIG. 1 Fly-Ash Deposit

7.3.2.2 When a quench system is used frequently and a wet scrubber is not in operation, the moist fly-ash load (73 lb/ft^3 1170 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 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: