Manual of Water Supply Practices

M45

Fiberglass Pipe Design



Third Edition

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Fiberglass Pipe Design

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Preface

This manual is the third edition of AWWA Manual M45, *Fiberglass Pipe Design*. It provides the reader with both technical and general information to aid in the design, specification, procurement, installation, and understanding of fiberglass pipe and fittings. The manual is a discussion of recommended practice, not an AWWA standard calling for compliance with certain requirements. It is intended for use by utilities and municipalities of all sizes, whether as a reference book or textbook for those not fully familiar with fiberglass pipe and fitting products. Design engineers and consultants may use this manual in preparing plans and specifications for new fiberglass pipe design projects.

The manual covers fiberglass pipe and fitting products and certain appurtenances and their application to practical installations, whether of a standard or special nature. For adequate knowledge of these products, the entire manual should be studied. Readers will also find the manual a useful source of information when assistance is needed with specific or unusual conditions. The manual contains a list of applicable national standards, which may be purchased from the respective standards organizations (e.g., American Water Works Association, American Society for Testing and Materials, etc.).

This third edition includes updates to soil classifications that unify the terminology for all piping materials, corrections to the pressure surge calculations, and editorial changes to improve understanding and clarity of content.

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Chapter 1

History and Use

1.1 INTRODUCTION

Fiberglass pipe is made from glass fiber reinforcements embedded in, or surrounded by, cured thermosetting resin. This composite structure may also contain aggregate, granular, or platelet fillers; thixotropic agents; and pigments or dyes. By selecting the proper combination of resin, glass fibers, fillers, and design, the fabricator can create a product that offers a broad range of properties and performance characteristics. Over the years, the diversity and versatility of materials used to manufacture fiberglass pipe have led to a variety of names for fiberglass pipe. Among these are reinforced thermosetting resin pipe (RTRP), reinforced polymer mortar pipe (RPMP), fiberglass reinforced epoxy (FRE), glass reinforced plastic (GRP), and fiberglass reinforced plastic (FRP). Fiberglass pipes have also been categorized by the particular manufacturing process—filament winding or centrifugal casting. Frequently, the particular resin used to manufacture the fiberglass pipe—epoxy, polyester, or vinyl ester—has been used to classify or grade fiberglass pipes.

Regardless of the many possible combinations, the most common and useful designation is simply "fiberglass pipe." This name encompasses all of the various available products and allows consideration as a unique and general class of engineering materials.

1.2 HISTORY

Fiberglass pipe was introduced in 1948. The earliest application for fiberglass piping, and still one of the most widely used, is in the oil industry. Fiberglass pipe was selected as a corrosion-resistant alternative to protected steel, stainless steel, and other more exotic metals. Product lines expanded to include applications of increasingly high pressure and down-hole tubing with threaded connections. In the late 1950s, larger diameters became

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available and fiberglass pipe was increasingly used in the chemical process industry because of the pipe's inherent corrosion-resistant characteristics.

Since the 1960s, fiberglass pipe products have been used for municipal water and sewage applications. Fiberglass pipe combines the benefits of durability, strength, and corrosion resistance, thus eliminating the need for interior linings, exterior coatings, and cathodic protection. Fiberglass pipe systems offer great design flexibility with a wide range of standard pipe diameters and fittings available, as well as an inherent ability for custom fabrication to meet special needs. Fiberglass pipe is available in diameters ranging from 1 in. through 144 in. (25 mm through 3,600 mm). Fiberglass pipe is available in pressure classes ranging from gravity applications through several thousand pounds per square inch (kilopascals). Few countries in the world have not used fiberglass pipe.

1.3 APPLICATIONS

Fiberglass pipe is used in many industries and for a myriad of applications, including

- chemical processes
- desalination
- down-hole tubing and casing
- ducting and vent piping
- geothermal
- industrial effluents
- irrigation
- oil fields
- potable water
- power plant cooling and raw water
- sanitary sewers
- seawater intake and outfalls
- slurry piping
- storm sewers
- water distribution
- water transmission

1.4 STANDARDS, SPECIFICATIONS, AND REFERENCE DOCUMENTS

Many organizations have published nationally recognized standards, test methods, specifications, and recommended practices on fiberglass piping systems and products. These organizations include the American Society for Testing and Materials (ASTM), the American Petroleum Institute (API), the American Society of Mechanical Engineers (ASME), the NSF International (NSF), Underwriters Laboratories (UL), Factory Mutual Research (FM), the American National Standards Institute (ANSI), and the International Organization for Standardization (ISO).

Following is a list of fiberglass pipe standards and specifications that are commonly used in specifying, testing, and using fiberglass piping systems.

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1.4.1 Product Specifications and Classifications

General

ASTM D2310	Standard Classification for Machine-Made "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
ASTM D2517	Standard Specification for Reinforced Epoxy Resin Gas Pressure Pipe and Fittings
ASTM D2996	Standard Specification for Filament-Wound "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe (Applicable to epoxy, polyester, and furan resins in sizes from 1 in. to 16 in.[25 mm to 400 mm].)
ASTM D2997	Standard Specification for Centrifugally Cast "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe (Applicable for 1 in. through 14 in. [25 mm through 350 mm] pipe of polyester or epoxy resins.)
ASTM D3262	Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer Pipe (Applicable for pipes 8 in. through 144 in. [200 mm through 3,700 mm] diameter, with or without siliceous sand, and polyester or epoxy resin.)
ASTM D3517	Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe (Applicable for pipes 8 in. through 144 in. [200 mm through 3,700 mm] diameter, with or without siliceous sand, and polyester or epoxy resin.)
ASTM D3754	Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer and Industrial Pressure Pipe (Applicable for 8 in. through 144 in. [200 mm through 3,700 mm] diameter, with or without siliceous sand, and polyester or epoxy resin.)
ASTM D4024	Standard Specification for Machine Made "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Flanges (Applicable for ½ in. through 24 in. [13 mm through 600 mm] ANSI B16.5 150 lb [70 kg] bolt circle flanges.)
ASTM D4161	Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Joints Using Flexible Elastomeric Seals
ASTM F1173	Standard Specification for Thermosetting Resin Fiberglass Pipe Systems to Be Used for Marine Applications
API 15LR	Specification for Low Pressure Fiberglass Line Pipe (Applicable to 2 in. through 24 in. [50 mm through 600 mm] diameter pipe of epoxy or polyester resin for use at cyclic pressures to 1,000 psi [6,895 kPa].)
API 15HR	Specification for High Pressure Fiberglass Line Pipe (Applicable to 1 in. through 10 in. [25 mm through 250 mm] pipe and fittings for operating pressures of 500 psi [3,500 kPa] to 5,000 psi [35,000 kPa].)
ANSI/AWWA C950	AWWA Standard for Fiberglass Pressure Pipe

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US military (MIL) specifications

MIL P24608	Specification for epoxy resin pipe from ½ in. through 12 in. (13 mm through 300 mm) diameters for 200 psig (1,379 kPa) service at 150°F (66°C) for US Navy shipboard applications
MIL P28584A	Specification for epoxy resin pipe and fittings from 2 in. through 12 in. (50 mm through 300 mm) diameter for use as Steam Condensate Return Lines in continuous service at 125 psig (862 kPa) and 250°F (121°C)
MIL P29206A	Specification for epoxy or polyester pipe and fittings 2 in. through 12 in. (50 mm through 300 mm) in diameter for POL services to 150°F (66°C) and 150 psig (1,034 kPa) with surges to 250 psig (1,724 kPa)

1.4.2 Recommended Practices

Dimensions

ASTM D3567	Standard Practice for Determining Dimensions of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings

Installation

ASTM D3839	Standard Guide for Underground Installation of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
API RP15TL4	Care and Use of Fiberglass Tubulars
API RP1615	Installation of Underground Petroleum Storage Systems

1.4.3 Standard Test Methods

Tensile properties

ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D1599	Standard Test Method for Resistance to Short-Time Hydraulic Failure Pressure of Plastic Pipe, Tubing and Fittings
ASTM D2105	Standard Test Method for Longitudinal Tensile Properties of Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube
ASTM D2290	Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe

Compressive properties

ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics

Bending properties

ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM D2925	Standard Test Method for Beam Deflection of Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Under Full Bore Flow

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Long-term internal pressure strength

ASTM D1598	Standard Test Method for Time to Failure of Plastic Pipe Under Constant Internal Pressure
ASTM D2143	Standard Test Method for Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe
ASTM D2992	Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings

Pipe stiffness

ASTM D2412	Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel Plate Loading

External pressure

ASTM D2924	Standard Test Method for External Pressure Resistance of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe

Chemical resistance

ASTM C581	Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass Fiber Reinforced Structures Intended for Liquid Service
ASTM D3681	Standard Test Method for Chemical Resistance of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe in a Deflected Condition
ASTM D5365	Standard Test Method for Long Term Ring Bending Strain of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe

1.4.4 Product Listings, Approvals, and Piping Codes

NSF International—Standard Numbers 14 and 61. Tests and lists fiberglass pipe, fittings, and adhesives for use in conveying potable water. Additionally, tests and certifies products as to their classification to an applicable national standard or for special properties (Standard 14 only).

Underwriters Laboratories Inc. Provides established standards for testing and listing fiberglass pipe for use as underground fire water mains and underground transport of petroleum products.

Factory Mutual Research. Has established an approval standard for plastic pipe and fittings for underground fire protection service.

ANSI/ASME B31.1—Power Piping Code. This code prescribes minimum requirements for the design, materials, fabrication, erection, testing, and inspection of power and auxiliary service piping systems for electric generation stations, industrial institutional plants, and central and district heating plants.

ANSI/ASME B31.3—Chemical Plant and Petroleum Refinery Piping Code. This code lists some ASTM, AWWA, and API fiberglass pipe specifications as acceptable for use within the code and establish criteria for their installation and use. These codes, in addition to other ASME codes, establish rules regarding the application of fiberglass piping and provide engineering guidance for the use of fiberglass materials.

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ANSI/ASME B31.8—Gas Transmission and Distribution Piping Systems Code. This code lists fiberglass pipe manufactured in compliance with ASTM D2517 as acceptable for use within the code.

Department of Transportation, Title 49, Part 192. This is a code of federal regulations that covers the transportation of natural and other gases by pipeline. Minimum federal standards are included.

ASME Boiler and Pressure Vessel Code Case N155. This code provides the rules for the construction of fiberglass piping systems for use in section III, division I, class 3 applications in nuclear power plants.

1.4.5 International Organization for Standardization Standards and Specifications (ISO)

ISO has issued many standards, test methods, and technical reports relating to fiberglass piping systems and products. Many of their titles, as well as the general content, are very similar to the US-issued standards covered previously.

Product specifications

ISO 10467	Plastics piping systems for pressure and non-pressure drainage and sewerage—Glass-reinforced thermosetting plastics (GRP) systems based on unsaturated polyester (UP) resin
ISO 10639	Plastics piping systems for pressure and non-pressure water supply—Glass-reinforced thermosetting plastics (GRP) systems based on unsaturated polyester (UP) resin

Test methods

ISO 7432	Glass-reinforced thermosetting plastics (GRP) pipes and fittings—Test methods to prove the design of locked socket-and-spigot joints, including double-socket joints, with elastomeric seals
ISO 7509	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes—Determination of time to failure under sustained internal pressure
ISO 7510	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) components—Determination of the amounts of constituents using the gravimetric method
ISO 7511	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes and fittings—Test methods to prove the leak tightness of the wall under short-term internal pressure
ISO 7684	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes—Determination of the creep factor under dry conditions
ISO 7685	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes—Determination of initial specific ring stiffness
ISO 8483	Plastics piping systems from pressure and nonpressure drainage and sewerage glass-reinforced thermosetting plastics (GRP) systems based on polyester (UP) resin—Test methods to prove the design of bolted flanged joints
ISO 8513	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes—Determination of longitudinal tensile properties

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ISO 8521	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes—Test methods for the determination of the apparent initial circumferential tensile strength
ISO 8533	Plastics piping systems for pressure and nonpressure drainage and sewerage glass-reinforced thermosetting plastics (GRP) systems based on unsaturated polyester (UP) resin—Test methods to prove the design of cemented or wrapped joints
ISO 8639	Glass-reinforced thermosetting plastics (GRP) pipes and fittings—Test methods for leak tightness of flexible joint
ISO 10466	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes—Test method to prove the resistance to initial ring deflection
ISO 10468	Glass-reinforced thermosetting plastics (GRP) pipes—Determination of the long-term specific ring creep stiffness under wet conditions and the calculation of the wet creep factor
ISO 10471	Glass-reinforced thermosetting plastics (GRP) pipes—Determination of the long-term ultimate bending strain and the long-term ultimate relative ring deflection under wet conditions
ISO 10928	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes and fittings—Methods for regression analysis and their use
ISO 10952	Plastics piping systems—Glass-reinforced thermosetting plastics (GRP) pipes and fittings—Determination of the resistance to chemical attack from the inside of a section in a deflected condition
ISO 14828	Glass-reinforced thermosetting plastics (GRP) pipes—Determination of the long-term specific ring relaxation stiffness under wet conditions and the calculation of the wet relaxation factor
ISO 15306	Glass-reinforced thermosetting plastics (GRP) pipes—Determination of the resistance to cyclic internal pressure

Technical reports

ISO/TR 10465-1	Underground installation of flexible glass-reinforced thermosetting resin (GRP) pipes—Part 1: Installation procedures
ISO/TR 10465-2	Underground installation of flexible glass-reinforced thermosetting resin (GRP) pipes—Part 2: Comparison of static calculation methods
ISO/TR 10465-3	Underground installation of flexible glass-reinforced thermosetting resin (GRP) pipes—Part 3: Installation parameters and application limits

1.5 TERMINOLOGY

Fiberglass pipe users may encounter some unique or unfamiliar terminology. A glossary of terms used in this manual and by those in the fiberglass pipe industry is provided at the end of this manual.

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Chapter 2

Materials, Properties, and Characteristics

2.1 GENERAL

Fiberglass pipe is a composite material system produced from glass fiber reinforcements, thermosetting plastic resins, and additives. By selecting the right combination and amount of materials and the specific manufacturing process, the designer can create a product to meet the most demanding requirements. The result is a material with a broad range of characteristics and performance attributes.

2.2 CHARACTERISTICS

The following is a list of general characteristics of fiberglass composite pipe.

Corrosion resistance. Fiberglass pipe systems are resistant to corrosion, both inside and out, in a wide range of fluid-handling applications. As a result, additional linings and exterior coatings are not required.

Strength-to-weight ratio. Fiberglass composite piping systems have excellent strength-to-weight properties. The ratio of strength per unit of weight of fiberglass composites is greater than that of iron, carbon, and stainless steels.

Lightweight. Fiberglass composites are lightweight. Fiberglass piping is approximately one-sixth the weight of similar steel products and one-tenth the weight of similar concrete products.

Electrical properties. Standard fiberglass pipes are nonconductive. Some manufacturers offer conductive fiberglass piping systems for applications that require dissipation of static electricity buildup when transporting certain fluids, such as jet fuel.

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Dimensional stability. Fiberglass composites can maintain the critical tolerances required of the most demanding structural and piping applications. The material meets the most stringent material stiffness, dimensional tolerance, weight, and cost criteria.

Low maintenance cost. Fiberglass piping is easy to maintain because it does not rust, is easily cleaned, and requires minimal protection from the environment.

2.3 THE MATERIAL SYSTEM

Fiberglass composites consist of glass fiber reinforcements, thermosetting resins, and additives, which are designed and processed to meet specific functional performance criteria. To aid understanding of the performance characteristics of a finished fiberglass pipe, the interrelationship of the system components is outlined in this chapter. The following is a list of terms used in describing the material system.

Fiberglass reinforcement. This term indicates the amount, type, location, and orientation of glass fibers in the pipe that will provide the required mechanical strength.

Resin system. Resin selection will provide the physical and chemical properties (e.g., the glass transition temperature, a measurement of resistance to heat, and softening or plasticization by solvents and gases).

Following is a brief review of the constituents of fiberglass pipe and how they influence the finished pipe product.

2.3.1 Glass Fiber Reinforcements

The mechanical strength of fiberglass pipe depends on the amount, type, and arrangement of glass fiber reinforcement. Strength increases proportionally with the amount of glass fiber reinforcement. The quantity of the glass fibers (and the direction in which the individual strands are placed) determines the strength.

2.3.1.1 Fiberglass types. Fiberglass materials are available with a variety of compositions. This allows for additional design flexibility to meet performance criteria. All fiberglass reinforcement begins as individual filaments of glass drawn from a furnace of molten glass. Many filaments are formed simultaneously and gathered into a "strand." A surface treatment (sizing) is added to maintain fiber integrity, establish compatibility with resin, and ease further processing by improving consolidation and wet strength. Sizing can also affect resin chemistry and laminate properties.

The glass fibers most commonly used in pipe are referred to as Types E, ECR, and C. Glass types ECR and C provide improved acid and chemical resistance. Type C glass fibers are generally only used to reinforce chemical-resistant liners.

2.3.1.2 Fiberglass reinforcement forms. Following is a brief description of the various forms of fiberglass reinforcements.

Continuous roving. These consist of bundled, untwisted strands of glass fiber reinforcement and come as cylindrical packages for further processing. Continuous roving typically is used in filament winding and unidirectional/bidirectional reinforcements and may be processed into chopped strand mat used to provide multidirectional reinforcement in pipe and fittings.

Woven roving. This is a heavy, drapable fabric, woven from continuous roving. It is available in various widths, thicknesses, and weights. Woven roving provides high strength to large molded parts and is lower in cost than conventional woven fabrics.

Reinforcing mats. These are chopped strands held together with resinous binders. Two kinds of reinforcing mats are used in pipe and fittings (i.e., chopped strand mat and woven roving combination mat). Chopped strand mats are used in medium-strength applications for pipe fittings and reinforcing where a uniform cross section is desired. Use of the combination mat saves time in hand lay-up operations.

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Surface veils. These lightweight fiberglass reinforcement mats allow layers with a high resin content with minimal reinforcement. The surface veil provides extra environmental resistance for pipe and fittings, plus a smooth appearance. (Some surface veils from polyester fibers are also used.)

2.3.1.3 Reinforcement arrangement. The three general types of fiber orientation include:

Unidirectional. The greatest strength is in the direction of the fibers. Up to 80 percent reinforcement content by weight is possible.

Bidirectional. Some fibers are positioned at an angle to the rest of the fibers, as with helical filament winding and woven fabrics. This provides different strength levels governed by the fiber quantity in each direction of fiber orientation. A combination of continuous and chopped fibers is also used to provide designed directional strength.

Multidirectional (isotropic). This arrangement provides nearly equal, although generally lower, strength and modulus in all directions. From 10 percent to 50 percent reinforcement content, by weight, can be obtained with multidirectional materials such as chopped roving or chopped strand mat.

2.3.2 Resins

The second major component of fiberglass pipe is the resin system. Manufacturers choose a resin system for chemical, mechanical, and thermal properties and processability.

The two basic groups of resin systems are thermosetting and thermoplastic. Fiberglass pipe, by definition, uses only thermosetting resin systems. Thermosets are polymeric resin systems cured by heat or chemical additives. Once cured, a thermoset is essentially infusible (cannot be remelted) and insoluble.

The thermosetting resins used in fiberglass pipe fall into two general categories—polyesters and epoxies.

2.3.2.1 Polyester resins. Polyester resins are commonly used to produce large-diameter water and sewage piping. Polyesters have excellent water and chemical resistance and are noted for acid resistance.

The base polyester resin is a solid. It is typically dissolved in styrene monomer, with which it cross-links to provide the final thermoset structure. Polyester resins are cured by organic peroxide catalysts. The type and amount of catalyst will influence gel time, cure time, curing temperature, and the degree of cure. Typical catalysts include methyl ethyl ketone peroxide (MEKP) and benzyl peroxide (BPO). Manufacturers may select from several different types of polyester resins that provide a wide range of performance characteristics. These include

- orthophthalic polyester
- terephthalic polyester
- chlorendic acid polyester
- novolac epoxy vinyl ester
- isophthalic polyester
- bisphenol-A fumarate polyester
- bisphenol-A vinyl ester

2.3.2.2 Epoxy resins. Epoxy resins are commonly used in the manufacture of smaller diameter piping (<30 in. [800 mm]) conveying water, condensates, hydrocarbons, caustics, and dilute acids. Fiberglass epoxy piping is used in oil fields at pressures up to several thousand pounds per square inch (kilopascals). Epoxy resins typically allow higher service temperatures than polyester resins, ranging up to about 225°F (108°C).

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Epoxy resins cannot be categorized by resin type as easily as polyesters. The type of curing agent, or hardener, is critical with epoxy resins because the agent influences the composite properties and performance. The two basic types are amine- and anhydride-cured bisphenol-A epoxies.

Bisphenol-A epoxy resins are commonly cured with multifunctional primary amines. For optimum chemical resistance, these mixtures usually require a heat cure and/or post cure. The cured resin has good chemical resistance, particularly in alkaline environments, and can have good temperature resistance. Bisphenol-A epoxy resins may also be cross-linked with various anhydrides by using a tertiary amine accelerator and heat. These cured polymers generally have good chemical resistance, especially to acids.

2.4 OTHER COMPONENTS

Glass fiber reinforcements and thermosetting resins are the major constituents in fiberglass pipe. However, other materials that influence processing and/or product performance are used, including fillers, promoters, accelerators, inhibitors, and pigments.

Fillers. Inorganic materials, such as hydrated alumina, glass microspheres, clay, talc, calcium carbonate, sand, and calcium silicate, may yield economic, appearance, or performance advantages in fiberglass pipe.

Promoters, accelerators, and inhibitors. Promoters and accelerators advance the action of the catalyst to reduce the processing time. Inhibitors provide control over the cure cycle and increase the shelf life of the resin mix.

Pigments. The pigment choice affects the difference in reflected and transmitted color, clarity of the resin mix, reaction between dyes and other additives, such as catalysts, and the end-product color fastness and heat resistance.

2.5 PHYSICAL PROPERTIES

The following is a description of the physical properties of fiberglass pipe.

2.5.1 Chemical Resistance

All fiberglass pipes provide excellent resistance to water and native ground conditions. They are not subject to general corrosion attack, galvanic corrosion, aerobic corrosion, pitting, dezincification, and graphitic and intergranular corrosion. Fiberglass pipes are subject to some environmental stress and aging effects, the determination of which is part of the fiberglass pipe design procedure (see chapter 5).

Fiberglass pipe resists a wide range of chemicals. The chemical resistance of fiberglass pipe depends primarily on the particular resin matrix material used. Although other factors such as liner construction, cure, and fabrication method may influence the chemical resistance of fiberglass pipe, the primary factor is the resin. The resins can be selected to provide chemical resistance to a broad range of materials. The fiberglass pipe manufacturer should be consulted for performance information for a particular chemical application.

2.5.2 Temperature Resistance

The temperature resistance of fiberglass pipe also depends largely on the resin matrix. The allowable upper limit of service temperature will also be influenced by the chemical environment and the stress condition of the piping system. In general, chemical agents are more aggressive at higher concentrations and elevated temperatures. However, for

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typical temperatures encountered in water supply systems (33°F to 90°F [1°C to 32°C]), fiberglass pipe is unaffected by service temperature, and the fiberglass pipe pressure performance does not need to be rerated or derated. Fiberglass pipe is virtually unaffected by colder temperatures. Therefore, normal shipping, handling, and storage procedures, as discussed in chapter 10, may be used in subzero weather. However, users and installers of fiberglass pipe should be aware that the coefficient of thermal expansion for fiberglass pipe is generally higher than that for metal pipes (see Table 2-1). This must be recognized and provisions made in design and installation to accommodate expansion and contraction, particularly in aboveground applications.

2.5.3 Abrasion Resistance

Fiberglass pipe provides generally good abrasion resistance and can be custom made for extremely abrasive service by lining the pipe with sand, silica flour, carborundum, or ceramic beads or tiles or by incorporating resilient liner materials such as polyurethanes. Special lining materials should match or exceed the hardness and abrasiveness of the contents being transported through the pipe or provide a high level of toughness and resilience.

2.5.4 Flame Retardants

The thermosetting resin systems used to fabricate fiberglass pipes are organic materials. Therefore, under the proper combination of heat and oxygen, a thermosetting resin, like any organic matter, will burn. If required, the fire performance of fiberglass pipe can be enhanced by using resin systems that contain halogens or phosphorus. Use of hydrated fillers also enhances flame resistance. Other additives, primarily antimony oxides, can also increase the effectiveness of halogenated resins.

Fire performance testing requires small samples and specialized test methods and may not indicate how a material will perform in a full-scale field or fire situation. The fiberglass pipe manufacturer should be consulted for specific information on the combustion performance of fiberglass pipe.

Table 2-1 Mechanical properties range

	Units		Resin		Glass Fiber		Fiberglass Pipe	
Property	*in.–lb*	*SI*	*in.–lb*	*SI*	*in.–lb*	*SI*	*in.–lb*	*SI*
Tensile strength	10^3 psi	MPa	9.0–13.0	62–90	250–350	1,725–2,400	2.0–80.0	14–550
Tensile modulus	10^6 psi	GPa	0.4–0.6	2.8–4.1	10.0–11.0	69–75	0.5–5.0	3.5–34.5
Flexural strength	10^3 psi	MPa	10.0–22	69–150	250–350	1,725–2,400	4.0–70.0	28–480
Flexural modulus	10^6 psi	GPa	0.4–0.6	2.8–4.1	10.0–11.0	69–76	1.0–5.0	6.9–34.5
Coefficient of thermal expansion	in./in./°F $\times 10^6$	mm/mm/°C $\times 10^{-6}$	11.0–55	20–100	3.0–3.3	5.4–6.0	8.0–30.0	14–54
Specific gravity			1.0–1.2	1.0–1.2	2.57–2.63	2.57–2.63	1.2–2.3	1.2–2.3
Compressive strength	10^3 psi	MPa	10.0–22	69–150	250–350	1,725–2,400	10.0–40.0	69–275

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2.5.5 Weathering Resistance

Most thermosetting resin systems used to fabricate fiberglass pipe are subject to some degradation from ultraviolet (UV) light. This degradation, however, is almost entirely a surface phenomenon. The structural integrity of fiberglass pipe is not affected by exposure to UV light. The use of pigments, dyes, fillers, or UV stabilizers in the resin system or painting of exposed surfaces can help reduce significanly any UV surface degradation. Surfaces exposed to UV light are generally fabricated with a resin-rich layer. Other weathering effects, such as rain or saltwater, are resisted fully by the inherent corrosion resistance of fiberglass pipe.

2.5.6 Resistance to Biological Attack

Fiberglass pipe will not deteriorate or break down under attack from bacteria or other microorganisms, nor will it serve as a nutrient to microorganisms, macroorganisms, or fungi. No known cases exist in which fiberglass pipe products suffered degradation or deterioration due to biological action. No special engineering or installation procedures are required to protect fiberglass pipe from biological attack. Some elastomers used in gaskets may be susceptible to this type of attack.

2.5.7 Tuberculation

Soluble encrustants, such as calcium carbonate, in some water supplies do not tend to precipitate onto the smooth walls of fiberglass pipe. Because fiberglass pipe is inherently corrosion resistant, tuberculation of the fiberglass pipe is not caused by corrosion by-products.

2.6 MECHANICAL PROPERTIES

2.6.1 Mechanical Property Range

The design flexibility inherent with glass fiber reinforced plastic materials and the range of manufacturing processes used preclude the simple listing of fiberglass pipe mechanical properties. For this reason, fiberglass pipe product standards are based on performance and detail product performance requirements rather than thickness property tables. Table 2-1 illustrates the broad range of mechanical properties available for resin, glass fiber, and fiberglass pipe.

This broad range of mechanical properties is further illustrated by the widely variable stress-strain curves possible with fiberglass pipe, depending on the amount, type, and orientation of the reinforcement as well as the manufacturing process. Figures 2-1 and 2-2 show the typical shape of the stress-strain curves for high- and low-pressure pipes for the circumferential and axial directions, respectively.

2.6.2 Mechanical Property Testing

The time dependence and wide range of mechanical properties of fiberglass pipe necessitate testing to develop data needed for design and analysis. Many test methods develop data over a moderate time range and then statistically extrapolate the data to establish long-term design values.

For example, the key long-term property test for fiberglass pipe is the development of a hydrostatic design basis (HDB) to establish the pipe pressure rating. This testing is conducted in accordance with ASTM D2992.

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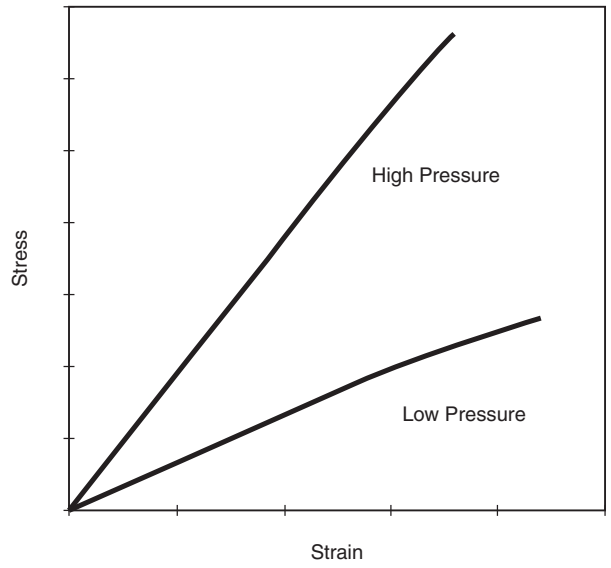


Figure 2-1 Typical circumferential stress-strain curves

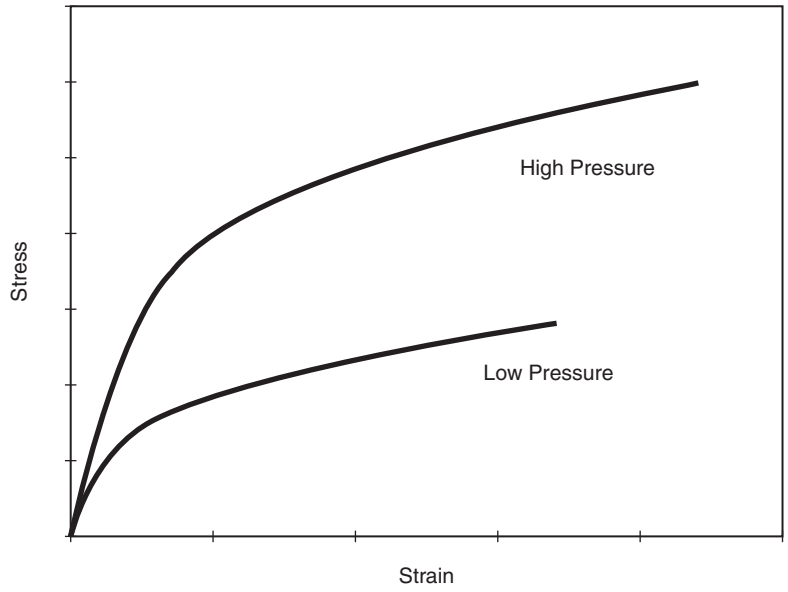


Figure 2-2 Typical axial stress-strain curves

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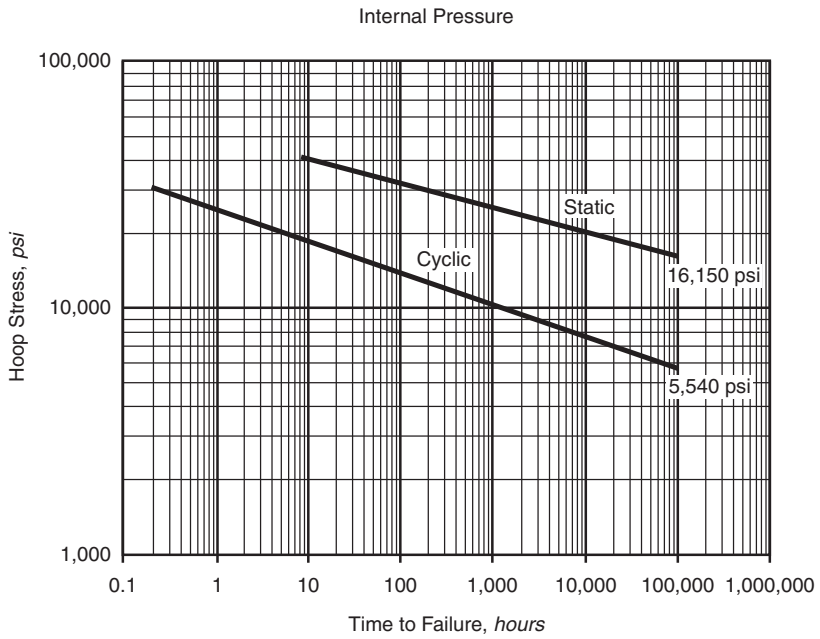


Figure 2-3 Static versus cyclic pressure testing

This method requires pressurizing a minimum of 18 pipe samples at pressures far exceeding the normal use range and monitoring the time to failure. Data must be collected over a range of time from 1 hour to beyond 10,000 hours. The pressure/stress/strain (all may be validly used) versus time to failure is statistically extrapolated to 50 years to establish a long-term HDB. To establish the pipe pressure rating, a safety factor is applied to this 50-year value. In ANSI/AWWA Standard C950, Fiberglass Pressure Pipe, the specified safety factor is 1.8 at 50 years (i.e., the extrapolated 50-year value is divided by 1.8 to establish the allowable design value).

This testing may be conducted using static pressurization (the standard for water piping) or cyclic pressure testing (which is common for small-diameter pipes used in the oil field industry). The same pipe tested in both static and cyclic pressure conditions will exhibit significantly different regression behavior. The cycling testing condition is far more severe (25 cycles per minute from 0 to test pressure). Because the test is so severe, the common practice is to use the 50-year value directly for design purposes (i.e., the safety factor applied to the extrapolated 50-year value is 1.0). To illustrate the comparison of the two procedures, Figure 2-3 shows the results of a filament-wound epoxy pipe tested both by static and cyclic pressure testing procedures.

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Chapter 3

Manufacturing

3.1 INTRODUCTION

Machine-made fiberglass pipe is produced using two basic processes: filament winding and centrifugal casting. Each process produces a pipe with characteristics that, although unique and advantageous for some applications, will meet the performance requirements of ANSI/AWWA Standard C950, Fiberglass Pressure Pipe.

3.2 FILAMENT WINDING

Filament winding is the process of impregnating glass fiber reinforcement with resin, then applying the wetted fibers onto a mandrel in a prescribed pattern. Fillers, if used, are added during the winding process. Chopped glass rovings may be used as supplemental reinforcement. Repeated application of wetted fibers, with or without filler, results in a multilayered structural wall construction of the required thickness. After curing, the pipe may undergo one or more auxiliary operations such as joint preparation. The inside diameter (ID) of the finished pipe is fixed by the mandrel outside diameter (OD). The OD of the finished pipe is variable and determined by the pipe wall thickness.

The filament winding process is illustrated in Figure 3-1. Within the broad definition of filament winding, several methods are used, including reciprocal, continuous, multiple mandrel, and ring and oscillating mandrel, each of which is described briefly. Figure 3-2 shows the application of impregnated glass reinforcement onto a mandrel during production of a filament-wound pipe.

3.2.1 Reciprocal Method

The reciprocal method is the most widely used filament winding production method. In this method, the fiber placement head with the associated resin bath drives back and

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forth past a rotating mandrel (see Figure 3-1). The angle of fiber placement relative to the mandrel axis is controlled by the synchronized translational speed of the bath and the rotational speed of the mandrel.

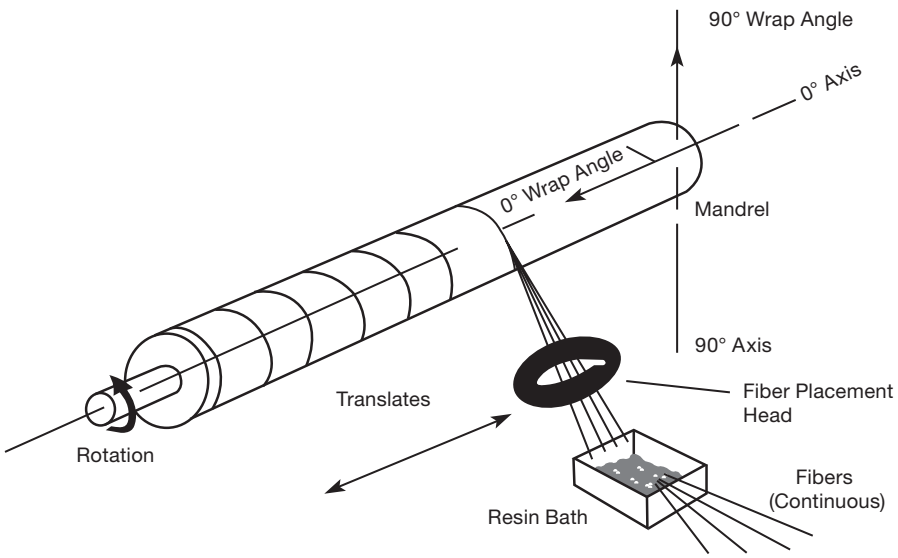
3.2.2 Continuous Methods

In one type of continuous process, pipe is made on one or more mandrels, which move past stations that apply fiberglass tapes preimpregnated with resin or glass fiber and resin. The winding angles are controlled through a combination of longitudinal mandrel speed, mandrel rotation (if used), or the rotation of planetary glass application stations. Once started, these methods produce pipe continuously, stopping only to replenish or change material components.

A second type of continuous process is the continuous advancing mandrel, which is composed of a continuous steel band supported by beams, which form a cylindrically shaped mandrel. The beams rotate, friction pulls the band around, and roller bearings allow the band to move longitudinally so that the entire mandrel continuously moves in a spiral path toward the end of the machine. Raw materials (continuous fibers, chopped fibers, resin, and aggregate fillers) are fed to the mandrel from overhead. Release films and surfacing materials are applied from rolls adjacent to the mandrel. After curing, a synchronized saw unit cuts the pipe to proper length. This method is illustrated in Figure 3-3. Finished pipe emerging from the curing oven is shown in Figure 3-4.

3.2.3 Multiple-Mandrel Method

In the multiple-mandrel method, a single materials-application system applies wetted glass reinforcement simultaneously to two or more mandrels. When the winding operation finishes, the mandrels are indexed to a new position for curing while another set of mandrels is wound.



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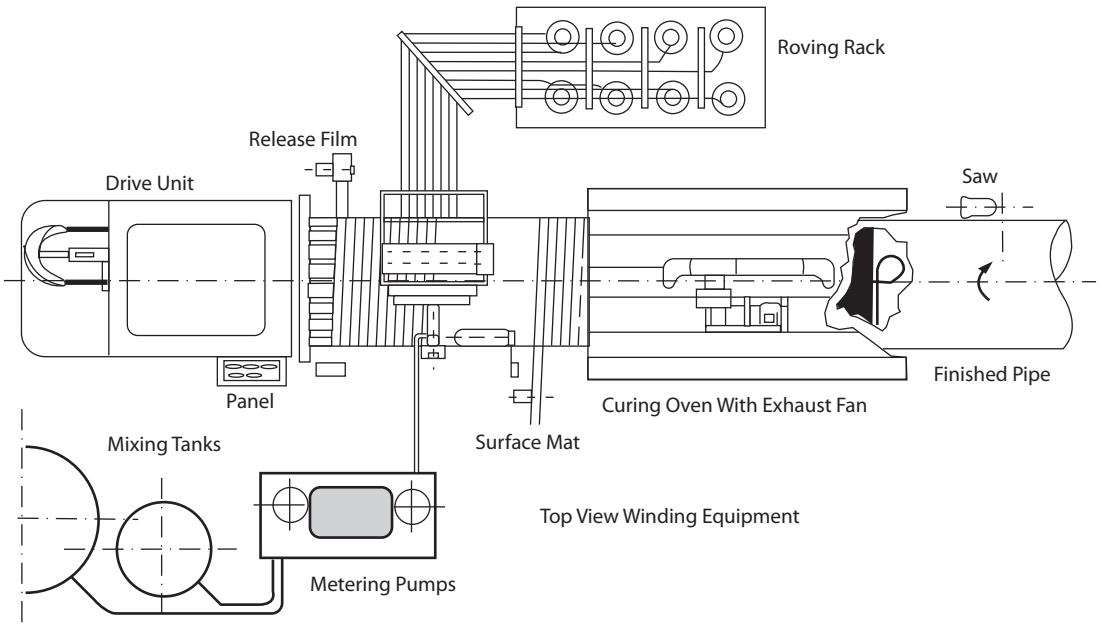
Figure 3-1 Filament winding process

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Figure 3-2 Application of impregnated glass reinforcement of a filament-wound pipe



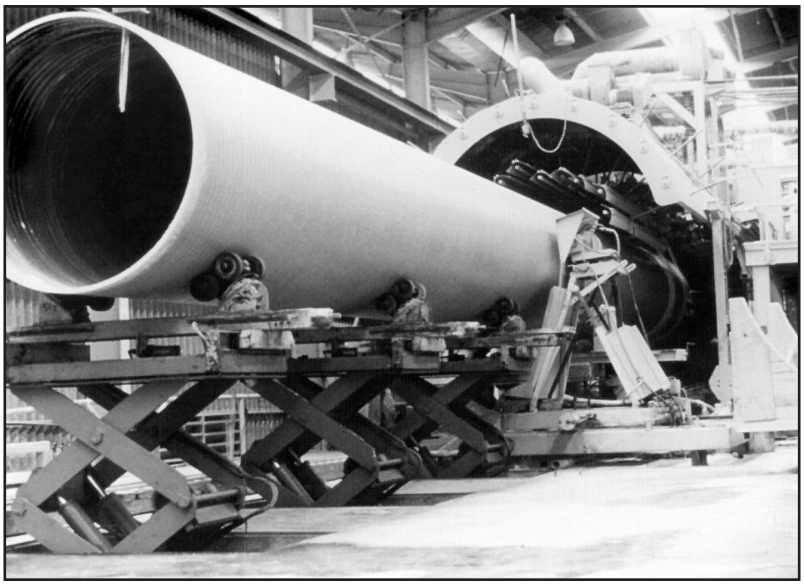
Source: Flowtite Technology, Sandefjord, Norway.

Figure 3-3 Continuous advancing mandrel method

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3.2.4 Ring and Oscillating Mandrel Method

The use of 360° glass delivery systems, sometimes in combination with an oscillating mandrel, allows production with both high- and low-winding angles as single circuit patterns (without interlayer crossovers).



Source: Flowtite Technology, Sandefjord, Norway.

Figure 3-4 Finished pipe emerging from curing oven

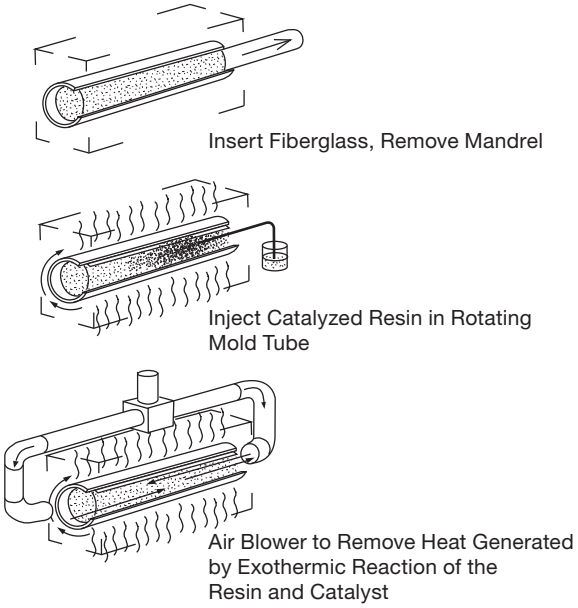


Figure 3-5 Preformed glass reinforcement sleeve method

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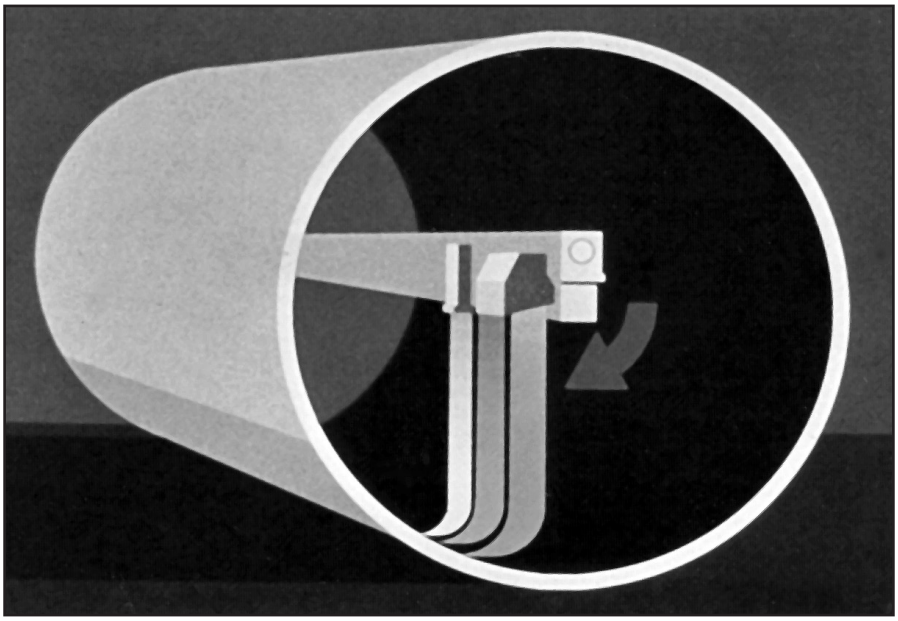
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3.3 CENTRIFUGAL CASTING

Centrifugal casting is used to manufacture tubular goods by applying resin and reinforcement to the inside of a mold that is rotated and heated, subsequently polymerizing (curing) the resin system. The OD of the finished pipe is determined by the ID of the mold tube. The ID of the finished pipe is variable and determined by the amount of material introduced into the mold. Other materials, such as sand or fillers, may be introduced in the process during manufacture of the pipe.

Two different methods of centrifugal casting are used and are described briefly.

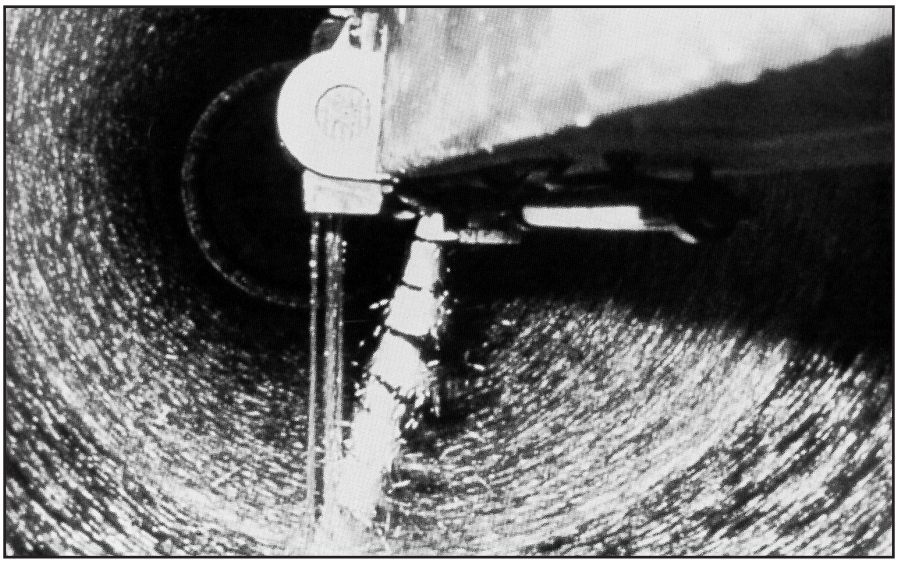
1. *Preformed glass reinforcement sleeve method.* A preformed glass reinforcement sleeve is placed inside a steel mold. As the steel mold rotates, resin and a filler, if used, are placed within the mold by means of a feed tube that moves in and out of the mold, thus wetting out the preformed sleeve. This method is illustrated in Figure 3-5.
2. *Chopped glass reinforcement method.* Varying proportions of chopped glass reinforcement, resin, and aggregate are introduced simultaneously, by layer, from a feeder arm that moves in and out of the mold. This method is illustrated in Figure 3-6. Application of glass, resin, and sand within a rotating mold is shown in Figure 3-7.



Source: Hobas Pipe USA Inc., Houston, Texas.

Figure 3-6 Chopped glass reinforcement method

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Source: Hobas Pipe USA Inc., Houston, Texas.

Figure 3-7 Application of glass, resin, and sand

3.4 REFERENCE

American Water Works Association. ANSI/AWWA C950, Standard for Fiberglass Pressure Pipe. Denver, Colo.: American Water Works Association.

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Chapter 4

Hydraulics

4.1 HYDRAULIC CHARACTERISTICS

The smooth interior of fiberglass pipe results in low fluid resistance, which could lower horsepower requirements for pumped systems. Because the interior pipe surface typically remains smooth over time in most fluid services, fluid resistance does not increase with age. In addition, the smooth interior allows the pipe diameter to be reduced while maintaining the desired flow.

This chapter provides a basis for analysis of the flow capacity, economics, and fluid transient characteristics of fiberglass pipe.

4.2 PRELIMINARY PIPE SIZING

The first step in designing a piping system is to determine the pipe size needed to transport a specific amount of fluid. Many engineers have adopted rules that are independent of pipe length but rely on typical or limiting fluid velocities or allowable pressure loss per 100 ft (30 m) of pipe. Once the fluid velocity or the pressure loss is known, a pump can be sized to provide the proper flow rate at the required pressure. The following equations are guidelines for the initial sizing of pipe. These equations are presented with inch-pound units in the left-hand column and metric units in the right-hand column.

4.2.1 Maximum Velocity

$$V = 48/\rho^{0.33}$$

Where:

V = fluid velocity, ft/sec

ρ = fluid density, lb/ft^3

= 62.4 lb/ft^3 for water

$$V = 37/\rho^{0.33} \quad \text{(Eq. 4-1)}$$

Where:

V = fluid velocity, m/sec

ρ = fluid density, kg/m^3

= 1,000 kg/m^3 for water

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4.2.2 Maximum Velocity for Corrosive or Erosive Fluids

$V = 24/\rho^{0.33}$ $V = 18.4/\rho^{0.33}$ (Eq. 4-2)

4.2.3 Minimum Pipe Diameter for Water

$d = 0.73[(Q)/(SG)]^{0.5}/\rho^{0.33}$ $d = 186[(Q)(SG)]^{0.5}/\rho^{0.33}$ (Eq. 4-3)

Where:
d = pipe inside diameter, in.
Q = flow rate, gpm
SG = specific gravity, dimensionless
= 1.0 for water

Where:
d = pipe inside diameter, mm
Q = flow rate, L/sec
SG = specific gravity, dimensionless
= 1.0 for water

4.2.4 Minimum Pipe Diameter for Corrosive or Erosive Fluids

$d = 1.03\ [(Q)/(SG)]^{0.5}/\rho^{0.33}$ $d = 262\ [(Q)/SG)]^{0.5}/\rho^{0.33}$ (Eq. 4-4)

4.3 TYPICAL PIPE DIAMETERS

The equations in Sec. 4.2 represent the minimum pipe diameters or maximum fluid velocities for water and corrosive (or erosive) liquid flow. Typical diameters for fiberglass pressure pipe and suction pipe can be calculated using the following equations.

4.3.1 Typical Diameters for Pressure Pipe Service

$d = 0.321\ [(Q)/(SG)^2]^{0.434}$ $d = 27.1\ [(Q)/(SG)^2]^{0.434}$ (Eq. 4-5)

4.3.2 Typical Diameters for Suction Pipe Service

$d = 0.434\ [(Q)/(SG)^2]^{0.434}$ $d = 36.6\ [(Q)/SG)^2]^{0.434}$ (Eq. 4-6)

4.3.3 Conversion of Flow Rate to Fluid Velocity

$V = 0.409\ (Q/d^2)$ $V = 1{,}274\ (Q/d^2)$ (Eq. 4-7)

4.4 PRESSURE REDUCTION CALCULATIONS

Reduction in pressure, expressed as head loss in feet (meters) or pressure loss in pounds per square inch (kilopascals), occurs in all piping systems because of elevation changes, turbulence caused by abrupt changes of direction, and friction within the pipe and fittings.

Different computational methods can be used to determine the head loss in fiberglass pipe. The most common methods are the Hazen-Williams, Manning, and Darcy-Weisbach equations. The suitability of each method depends on the type of flow (gravity or pumped) and the level of accuracy required.

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4.4.1 Hazen-Williams Equation

The Hazen-Williams equation is applicable to water pipes under conditions of full turbulent flow. Although not as technically correct as other methods for all velocities, the Hazen-Williams equation has gained wide acceptance in the water and wastewater industries.

The Hazen-Williams equation is presented in nomograph form in Figure 4-1, which is typical for small-diameter fiberglass pipe. Note, however, that graphical solutions usually are valid for water only. When fluids other than water are encountered, a more universal solution such as the Darcy-Weisbach equation should be used. The Hazen-Williams equation is valid for turbulent flow and will usually provide a conservative solution for determining the head loss in fiberglass pipe.

$$h_f = 0.2083\ (100/C)^{1.85}\ (Q^{1.85}/d^{4.87}) \qquad h_f = 240 \times 10^6\ (100/C)^{1.85}\ (Q^{1.85}/d^{4.87}) \qquad \text{(Eq. 4-8)}$$

Where:

h_f = friction factor, ft of water/100 ft
C = Hazen-Williams roughness coefficient, dimensionless (typical value for fiberglass pipe = 150)

Where:

h_f = friction factor, m of water/100 m
C = Hazen-Williams roughness coefficient, dimensionless (typical value for fiberglass pipe = 150)

Note: Graphs and examples use nominal pipe size for simplicity. The actual inside diameter (ID) should be used in hydraulic calculations.

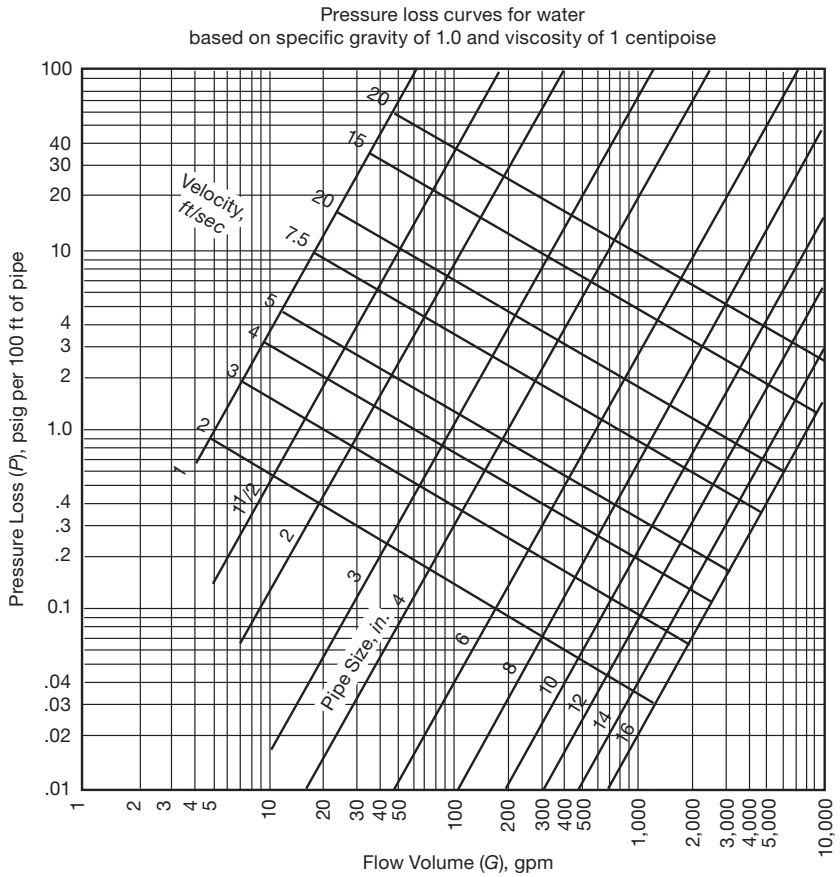


Figure 4-1 Friction pressure loss due to water flow through fiberglass pipe

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4.4.2 Simplified Hazen-Williams

Many engineers prefer a simplified version of the Hazen-Williams equation:

$$h_f = [42.7\ Q/(Cd^{2.63})]^{1.852} \qquad h_f = [3.35 \times 10^6\ Q/(Cd^{2.63})]^{1.852} \qquad \text{(Eq. 4-9)}$$

4.4.3 Head Loss Converted to Pressure Loss

Head loss for any liquid is converted into pressure loss using the following equation:

$$p = (H_f)(\text{SG})/2.31 \qquad p = (H_f)(\text{SG})/0.102 \qquad \text{(Eq. 4-10)}$$

Where:
- p = pressure loss, psi
- H_f = $(h_f)(L)/100$, ft
- L = line length, ft

Where:
- p = pressure loss, kPa
- H_f = $(h_f)(L)/100$, m
- L = line length, m

New fiberglass pipe has a Hazen-Williams roughness coefficient C value of 150–165. A design value of 150 is frequently used with fiberglass pipe.

4.4.4 Manning Equation

The Manning equation typically solves gravity flow problems where the pipe is only partially full and is under the influence of an elevation head only.

$$Qm = (1.486/n)(S)^{0.5}(A)(R)^{0.667} \qquad Qm = (1{,}000/n)(S)^{0.5}(A)(R)^{0.667} \qquad \text{(Eq. 4-11)}$$

Where:
- Qm = flow rate, ft^3/sec
- n = Manning roughness coefficient, = 0.009 for typical fiberglass pipe
- S = hydraulic slope, ft/ft = $(H_1 - H_2)/L$
  - H_1 = upstream elevation, ft
  - H_2 = downstream elevation, ft
  - L = length of pipe section, ft
- A = cross-sectional area of pipe, ft^2
- R = hydraulic radius (A/W_p), ft
  - W_p = wetted perimeter of pipe, ft

Where:
- Qm = flow rate, L/sec
- n = Manning roughness coefficient = 0.009 for typical fiberglass pipe
- S = hydraulic slope, m/m = $(H_1 - H_2)/L$
  - H_1 = upstream elevation, m
  - H_2 = downstream elevation, m
  - L = length of pipe section, m
- A = cross-sectional area of pipe, m^2
- R = hydraulic radius (A/W_p), m
  - W_p = wetted perimeter of pipe, m

4.4.5 Darcy-Weisbach Equation

The Darcy-Weisbach equation states that pressure loss is proportional to the square of the velocity and the length of the pipe. It is inversely proportional to the diameter of the pipe. The primary advantage of this equation is that it is valid for all fluids in both laminar and turbulent flow. The disadvantage is that the Darcy-Weisbach friction factor is a variable. Once preliminary sizing of the pipe diameter has been completed, the next step is to determine whether the flow pattern within the pipe is laminar or turbulent. This characterization of the flow is necessary in the selection of the appropriate friction factor to be used with the Darcy-Weisbach equation. The well-known Reynolds number equation is used to characterize the fluid flow:

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$$R_e = (\text{ID})\,(V)/\mu \qquad (\text{Eq. 4-12})$$

Where:

R_e = Reynolds number, dimensionless
ID = pipe inside diameter, ft
V = fluid velocity, ft/sec
μ = kinematic viscosity, ft^2/sec

Where:

R_e = Reynolds number, dimensionless
ID = pipe inside diameter, m
V = fluid velocity, m/sec
μ = kinematic viscosity, m^2/sec

This guideline determines the type of flow from the Reynolds number:

Flow Type	Reynolds Number
Laminar flow	$R_e \le 2{,}000$
Transition flow zone	$2{,}000 < R_e < 4{,}000$
Turbulent flow	$R_e \ge 4{,}000$

Simply stated, the Darcy-Weisbach equation is as follows:

$$H_f = [fL(V^2)]/2(\text{ID})g \qquad (\text{Eq. 4-13})$$

Where:

f = Darcy-Weisbach friction factor, dimensionless
g = gravitational constant = $32.2\ ft/sec^2$

Where:

f = Darcy-Weisbach friction factor, dimensionless
g = gravitational constant = $9.81\ m/sec^2$

If flow in the pipe is laminar (i.e., $R_e \le 2{,}000$), the friction factor f_l reduces to

$$f_l = 64/R_e \qquad (\text{Eq. 4-14})$$

Where:

f_l = friction factor for laminar flow

Where:

f_l = friction factor for laminar flow

Note: Friction factor for laminar flow is denoted as f_l, and f_t denotes friction factor for turbulent flow.

When the flow regime is turbulent (i.e., $R_e \ge 4{,}000$), the friction factor can be determined from the Moody diagram, which is found in most fluid mechanics texts (see Figure 4-2). Fiberglass pipe has a surface roughness parameter e equal to 1.7×10^{-5} ft (5.18×10^{-6} m). When divided by the pipe diameter (e/ID), the friction factor f_t for turbulent flow can be extracted from the smooth pipe segment of the diagram. The friction factor for turbulent flow can also be calculated from the Colebrook equation:

$$1/f_t^{0.5} = -2 \log [(e/\text{ID})/3.7] + 2.51/[(R_e)\,(f_t^{0.5})] \qquad (\text{Eq. 4-15})$$

Where:

f_t = Moody friction factor, dimensionless
e = surface roughness factor, ft
= 1.7×10^{-5} as typical for fiberglass pipe
ID = pipe inside diameter, ft

Where:

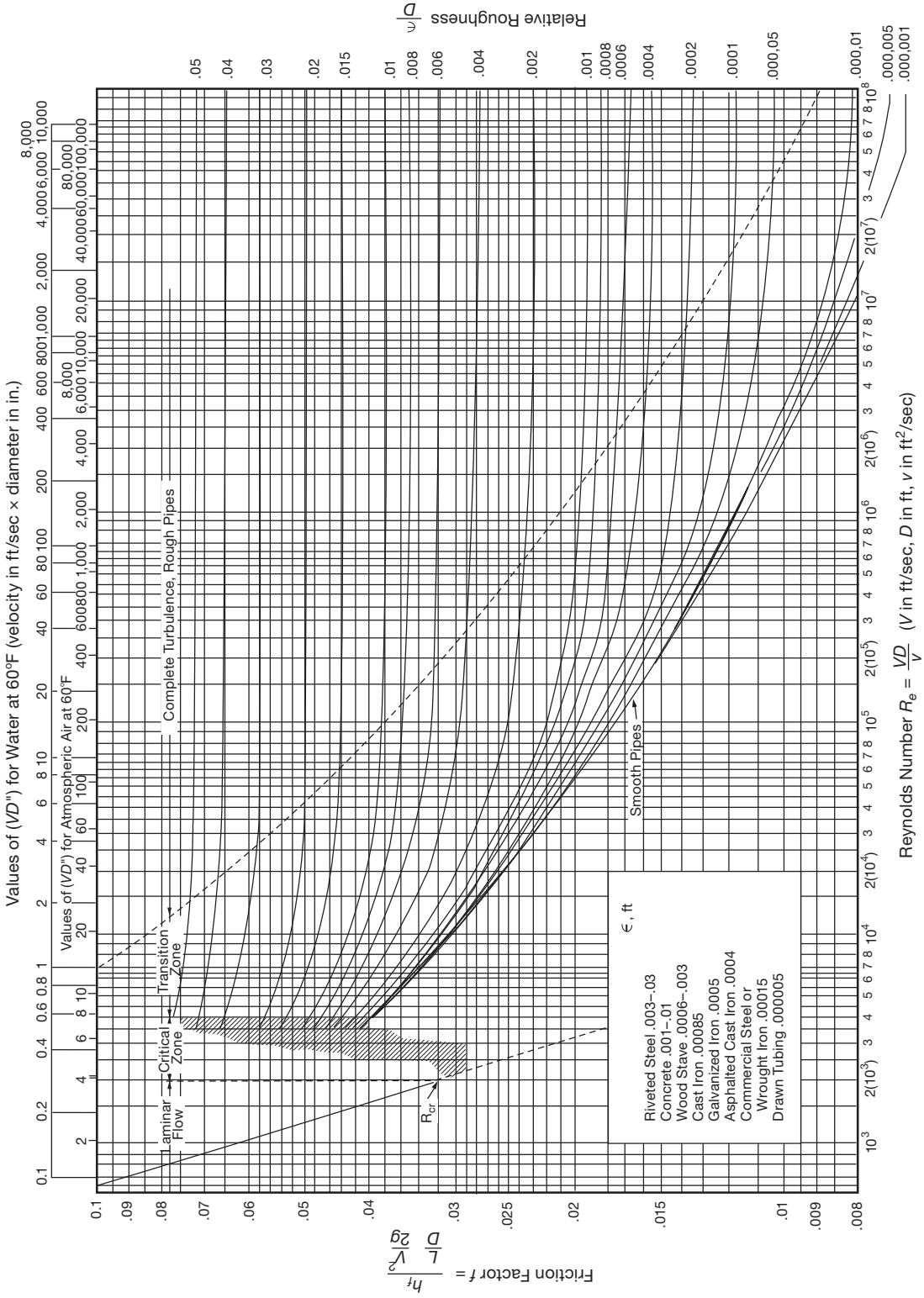
f_t = Moody friction factor, dimensionless
e = surface roughness factor, m
= 5.18×10^{-6} as typical for fiberglass pipe
ID = pipe inside diameter, m

This equation is difficult to solve because it is implicit in f_t and requires a trial-and-error iterative solution. The following simplified equation relates the friction factor to the Reynolds number and is accurate to within 1 percent of the Colebrook equation:

$$f_t = [1.8 \log (R_e/7)]^{-2} \qquad (\text{Eq. 4-16})$$

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Reprinted with permission from L.F. Moody, Friction Factors for Pipe Flow, *ASME, 345 E. 47th St., New York, NY 10017.*

Figure 4-2 Moody diagram for determination of friction factor for turbulent flow

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4.5 HEAD LOSS FITTINGS

Head loss in fittings is frequently expressed as the equivalent length of pipe that is added to the straight run of pipe. This approach has sufficient accuracy for many applications and is used most often with the Hazen-Williams or Manning equations. The approach does not consider turbulence and subsequent losses created by different fluid velocities. When tabular data are not available or when additional accuracy is necessary, head loss in fittings (or valves) can be determined using loss coefficients (*K* factors) for each type of fitting. Table 4-1 provides the typical *K* factors. In this approach the *K* factor for each fitting is multiplied by the velocity head of the fluid flow. Equation 4-17 illustrates the loss coefficient approach.

$$H_{ff} = K\,(V^2/2g) \qquad H_{ff} = K\,(V^2/2g) \qquad \text{(Eq. 4-17)}$$

Where:

H_{ff} = equivalent fittings head loss, ft
K = *K* factor for each fitting type from Table 4-1

Where:

H_{ff} = equivalent fittings head loss, m
K = *K* factor for each fitting type from Table 4-1

Many hydraulic handbooks provide *K* factors for various types of fittings and valves not included in this manual.

Table 4-1 Typical *K* factors for fiberglass fittings

Type of Fitting	*K* Factor
90° elbow, standard	0.5
90° elbow, single miter	1.4
90° elbow, double miter	0.8
90° elbow, triple miter	0.6
180° return bend	1.3
Tee, straight flow	0.4
Tee, flow to branch	1.4
Tee, flow from branch	1.7
Reducer, single-size reduction	0.7
Reducer, double-size reduction	3.3

The total head loss in a system includes, but is not limited to, losses from fittings, the head loss from the straight run pipe, and head losses due to changes in elevation.

4.6 ENERGY CONSUMPTION CALCULATION PROCEDURE

Pipeline operating costs are driven, in large part, by the frictional resistance of the pipe and the corresponding power consumption, and the pipeline design process should consider the operating economics of the pipeline material. This section outlines the basic procedure for determining the head loss due to friction and relative economic merits when considering different pipe materials.

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4.6.1 Pipeline Economic Analysis Procedure

Step 1. Calculate the head loss (Eq. 4-9):

$h_f = [42.7\ Q/(Cd^{2.63})]1.852$ $h_f = [3.35 \times 10^6\ Q/(Cd^{2.63})]1.852$

Step 2. Convert head loss to pump horsepower demand:

$HP = Q\ \rho_1\ H_f/33{,}000$ $HP = Q\ \rho_1\ H_f/102$ (Eq. 4-18)

Where:
- HP = water pumping power required, hp
  1 hp = 33,000 ft-lbf/min
- ρ_1 = fluid density = lb/gal
  = 8.34 lb/gal for water
- H_f = $(h_f)(L)/100$, ft
- L = line length, ft

Where
- HP = water pumping power required, kW
  1 kW = 102 kg-m/sec
- ρ_1 = fluid density = kg/L
  = 1 kg/L for water
- H_f = $(h_f)(L)/100$, m
- L = line length, m

Step 3. Calculate the annual energy usage:

(To demonstrate the calculations in a clear format, the following equations assume the pumps run 24 hours per day at full capacity. This is not a realistic assumption. In design situations, engineers must assess the actual expected operating conditions, e.g., 10 percent of the time at full power, 25 percent of the time at 75 percent power, etc.)

$Ec = (HP)(24)(365)(0.7457)/eff$ $Ec = (HP)(24)(365)/eff$ (Eq. 4-19)

Where:
- Ec = annual energy consumption, kW-hr per year
- 24 = hours per day
- 365 = days per year
- 0.7457 = kW-hr/hp-hr
- eff = overall (pump and motor) efficiency, typically 75%–85%

Where:
- Ec = annual energy consumption, kW-hr per year
- 24 = hours per day
- 365 = days per year
- eff = overall (pump and motor) efficiency, typically 75%–85%

Step 4. Calculate average annual energy cost (AEC):

AEC = (Ec) (UEC) AEC = (Ec) (UEC) (Eq. 4-20)

Where:
- AEC = annual energy cost, $
- UEC = unit energy cost, $/kW-hr

Where:
- AEC = annual energy cost, $
- UEC = unit energy cost, $/kW-hr

Techniques that consider the time value of money (net present value, life-cycle costing, etc.) can also be used to evaluate the relative economics of alternative pipe materials. These techniques consider the installed cost of pipe in the calculation, and future cash flows are discounted to present value.

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4.7 PRESSURE SURGE

Pressure surge, also known commonly as water hammer, results from an abrupt change of fluid velocity within the system. The pressure surge results from the rapidly moving wave that increases and decreases the pressure in the system depending on the source and direction of wave travel. Under certain conditions, pressure surges can reach magnitudes sufficient to rupture or collapse a piping system, regardless of the material of construction.

Rapid valve closure can result in the buildup of pressure waves due to the conversion of kinetic energy of the moving fluid to potential energy that must be accommodated. These pressure waves will travel throughout the piping system and can cause damage far away from the wave source.

4.7.1 Cause and Control of Pressure Surge

The magnitude of pressure surge is a function of the fluid properties and velocity, the modulus of elasticity and wall thickness of the pipe material, the length of the line, and the speed at which the momentum of the fluid changes. The relatively high compliance (low modulus of elasticity) of fiberglass pipe contributes to a self-damping effect as the pressure wave travels through the piping system.

In addition to rapid valve closure or opening, sudden air release and pump start-up or shut-down can create pressure surge. Pressure surges do not show up readily on conventional Bourdon tube gauges because of the slow response of the instrument. The net result of pressure surge can be excessive pressures, pipe vibration, or movement that can cause failure in pipe and fittings.

In some cases, anchoring the piping system may mitigate pipe vibration and movement problems. In other cases, mechanical valve operators, accumulators, rupture discs, surge relief valves, feedback loops around pumps, etc., may be required to protect against or remove the source of pressure surge.

Good design practice usually prevents pressure surge in most systems. Installation of valves that cannot open or close rapidly is one simple precaution. In addition, pumps should never be started in empty discharge lines unless slow-opening, mechanically actuated valves can increase the flow rate gradually.

4.7.2 Pressure Surge Calculation

The Talbot equation calculates surge pressure due to a change in velocity:

$$P_s = (a/g)\,(SG/2.3)\,(\Delta V) \qquad \text{(Eq. 4-21)}$$

Where:

$$a = 12/\left[(\rho/g)(1/k + d/(E(t))\right]^{0.5} \qquad \text{(Eq. 4-22)}$$

$$a = \frac{12}{\left[\left(\frac{\rho}{g}\right)\left(\frac{1}{k} + \frac{d}{Et}\right)\right]^{0.5}}$$

P_s = pressure surge deviation from normal, psig
SG = fluid specific gravity, dimensionless
ΔV = change in flow velocity, ft/sec
a = wave velocity, ft/sec
ρ = fluid density, lb/ft^3

$$P_s = (a)\,(SG)\,(\Delta V) \qquad \text{(Eq. 4-21)}$$

Where:

$$a = 1/\left[(\rho)(1/10^9 k + d/(10^9 E(t))\right]^{0.5} \qquad \text{(Eq. 4-22)}$$

$$a = \frac{1}{\left[\rho\left(\frac{1}{10^9 k} + \frac{d}{10^9 Et}\right)\right]^{0.5}}$$

P_s = pressure surge deviation from normal, kPa
SG = fluid specific gravity, dimensionless
ΔV = change in flow velocity, m/sec
a = wave velocity, m/sec
ρ = fluid density, kg/m^3

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g = gravitational constant, 32.2 ft/sec^2	
k = bulk modulus of compressibility of liquid, psi	k = bulk modulus of compressibility of liquid, GPa
= 300,000 psi for water	= 2 GPa for water
d = pipe inside diameter, in.	d = pipe inside diameter, mm
E = modulus of elasticity of pipe wall, psi	E = modulus of elasticity of pipe wall, GPa
t = pipe wall thickness, in.	t = pipe wall thickness, mm

The pressure class P_c must be greater than or equal to the sum of the working pressure P_w and surge pressure P_s divided by 1.4 (see chapter 5, Sec. 5.7.1.3).

Many fluid mechanics and hydraulic handbooks provide procedures such as the previous Talbot equation for calculating pressure surges as a result of a single valve closure in simple piping systems. Sophisticated fluid transient computer programs are also available to analyze pressure surge in complex multibranch piping systems under a variety of conditions.

4.8 DESIGN EXAMPLES

Example 4-1: Use of the Hazen-Williams equation

Compute the frictional pressure loss in a 1,500-ft long, 10-in. diameter fiberglass pipe transporting 2,000 gpm of water.

(C = 150 as typical)

Compute the frictional pressure loss in a 450-m long, 250-mm diameter fiberglass pipe transporting 130 L/sec of water.

(C = 150 as typical)

Step 1. Compute the head loss per unit length of pipe using Eq. 4-9:

$h_f = [42.7\ Q/(Cd^{2.63})]^{1.852}$

$h_f = [42.7(2{,}000)/(150)(10)^{2.63}]^{1.852}$

= 1.71 ft water/100 ft

$h_f = [3.35 \times 10^6\ Q/(Cd^{2.63})]^{1.852}$

$h_f = [3.35 \times 10^6\ (130)/(150)(250^{2.63})]^{1.852}$

= 1.95 m water/100 m

The total head loss for the length of pipe in this example is then:

H_f = 1.71 (1,500)/100 = 25.65 ft of water

H_f = 1.95 (450)/100 = 8.78 m of water

Step 2. Convert head loss to pressure drop using Eq. 4-10:

$p = (H_f)(SG)/2.31$

= 25.65(1.0)/2.31 = 11.1 psi

$p = (H_f)(SG)/0.102$

= 8.78(1.0)/0.102 = 86 kPa

Example 4-2: Determine the pipe diameter, working pressure, and pressure class on a pipeline

A pipeline requires 5,000 ft of pipe, four 90° elbows (double miter), and three 45° elbows (single miter) with an elevation change of 25 ft. Assume the kinematic viscosity μ = .00001. The flow rate is 8,000 gpm.

A pipeline requires 1,500 m of pipe, four 90° elbows (double miter), and three 45° elbows (single miter) with an elevation change of 7.5 m. Assume kinematic viscosity μ = 0.93 × 10^{-6}. The flow rate is 500 L/sec.

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Step 1. Determine minimum diameter (Eq. 4-3):

$d = 0.73\ [(Q)/(SG)]^{0.5}/\rho^{0.33}$
$d = 0.73\ [(8{,}000)/(1)]^{0.5}/62.4^{0.33}$
$= 16.7$ in.

Therefore, use the next larger available size, which is 18 in. for purposes of this example (ID 18 in. = 1.5 ft).

$d = 186\ [(Q)/(SG)]^{0.5}/\rho^{0.33}$
$d = 186\ [(500)/(1)]^{0.5}/(1{,}000)^{0.33}$
$= 425$ mm

Therefore, use the next larger available size, which is 450 mm for purposes of this example (ID 450 mm = .45 m).

Step 2. Calculate average fluid velocity (Eq. 4-7):

$V = 0.409\ (Q/d^2)$
$= 0.409\ (8{,}000/(18)^2)$
$= 10.1$ ft/sec

$V = 1{,}274\ (Q/d^2)$
$= 1{,}274\ (500/(450)^2)$
$= 3.15$ m/sec

Step 3. Calculate the Reynolds number (Eq. 4-12):

$R_e = (\text{ID})\ (V)/\mu$
$= (1.5)\ (10.1)/0.00001$
$= 1.52 \times 10^6$

$R_e = (\text{ID})\ (V)/\mu$
$= (.45)\ (3.15)/0.93 \times 10^{-6}$
$= 1.48 \times 10^6$

Because R_e is greater than 4,000, flow is turbulent.

Step 4. Calculate the friction factor (Eq. 4-16):

$f_t = [1.8 \log (R_e/7)]^{-2}$
$= [1.8 \log (1.52 \times 10^6/7)]^{-2}$
$= 0.0108$

$f_t = [1.8 \log (R_e/7)]^{-2}$
$= [1.8 \log (1.48 \times 10^6/7)]^{-2}$
$= 0.0109$

Step 5. Calculate system friction loss using Eq. 4-13 and Eq. 4-17:

Use a factor K for 90° double-miter elbows of 0.8 and for 45° single-miter elbows of 0.5. Consequently, the total K factor is 4(0.8) + 3 (0.5) = 4.7.

$H_f = K(V^2/2g) + [f_t\ L(V^2)]/(\text{ID})2g$
$= V^2/2g\ [K + f_t\ L/\text{ID}]$
$= (10.1)^2/2(32.2)\ [4.7 +$
$[0.0108\ (5{,}000)]/(1.5)]$
$= 64.5$ ft

$H_f = K(V^2/2g) + [f_t\ L(V^2)]/(\text{ID})2g$
$= V^2/2g\ [K + f_t\ L/\text{ID}] =$
$(3.15)^2/2(9.81)\ [4.7 +$
$[0.0109\ (1{,}500)]/(.45)]$
$= 20.8$ m

Step 6. Combine friction and elevation head:

$H_{\text{total}} = 64.5 + 25 = 89.5$ ft

$H_{\text{total}} = 20.8 + 7.5 = 28.3$ m

Step 7. Convert head loss to working pressure (Eq. 4-10):

$p = (H_f)(\text{SG})/2.31$
$= (89.5)\ (1.0)/2.31 = 38.7$ psi

The total working pressure of 38.7 psi would require a 50-psi pressure class. However, a higher pressure class may tentatively be selected to account for possible water hammer in the line. For these examples assume that a 100-psi class is selected. See example 4-4 to verify that this is adequate for pressure surge.

$p = (H_f)(\text{SG})/0.102$
$= (28.3)\ (1.0)/0.102 = 277$ kPa

The total working pressure of 277 kPa would require a 350-kPa pressure class. However, a higher pressure class may tentatively be selected to account for possible water hammer in the line. For these examples assume that a 700-kPa class is selected. See example 4-4 to verify that this is adequate for pressure surge.

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Example 4-3: Comparative power cost calculation

Assume a 10,000-ft long, 6-in. diameter pipeline is to deliver 500 gpm of water on a year-round basis. The engineer is considering using fiberglass pipe with an average Hazen-Williams coefficient C = 150 and another material that will have an average Hazen-Williams coefficient C = 100 over the life of the pipeline. Calculate the average AEC for each candidate material and the total energy cost over a 20-year service life using a unit cost of power of $0.06/kW-hr.

Assume a 3,000-m long, 150-mm diameter pipeline is to deliver 30 L/sec of water on a year-round basis. The engineer is considering using fiberglass pipe with an average Hazen-Williams coefficient C = 150 and another material that will have an average Hazen-Williams coefficient C = 100 over the life of the pipeline. Calculate the average AEC for each candidate material and the total energy cost over a 20-year service life using a unit cost of power of $0.06/kW-hr

Step 1. Calculate the head loss for each material (Eq. 4-9):

$h_f = [42.7\ Q/(Cd^{2.63})]^{1.852}$

$h_f = [3.35 \times 10^6\ Q/(Cd^{2.63})]^{1.852}$

For fiberglass pipe:

$h_f = [42.7 \times 500/(150 \times 6^{2.63})]^{1.852}$
$= 1.58$ ft/100 ft
$H_f = 158$ ft for the entire line

$h_f = [3.35 \times 10^6 \times 30/(150 \times 150^{2.63})]^{1.852}$
$= 1.55$ m/100 m
$H_f = 46.5$ m for the entire line

For alternate material:

$= [42.7 \times 500/(100 \times 6^{2.63})]^{1.852}$
$= 3.34$ ft/100 ft
$= 334$ ft for the entire line

$= [3.35 \times 10^6 \times 30/(100 \times 150^{2.63})]^{1.852}$
$= 3.29$ m/100 m
$= 98.6$ m for the entire line

Step 2. Convert head loss to horsepower demand (Eq 4-18):

$HP = Q\ \rho_1\ H_f/33{,}000$

$HP = Q\ \rho_1\ H_f/102$

For fiberglass pipe:

$= 500(8.34)(158)/33{,}000$
$= 19.96$ hp

$= 30(1)(46.5)/102$
$= 13.68$ kW

For alternate material:

$= 500(8.34)(334)/33{,}000$
$= 42.20$ hp

$= 30(1)(98.6)/102$
$= 29$ kW

Step 3. Calculate the annual energy consumption* Ec *using an 80 percent overall pump efficiency and Eq. 4-19:

(As previously noted, for simplicity in demonstrating the calculation procedure, this example assumes constant pump operation at full power. In design situations, engineers must assess actual operating levels.)

$Ec = (HP)(24)(365)(0.7457)/eff$

$Ec = (HP)(24)(365)/eff$

For fiberglass pipe:

$= (HP)\ (24)(365)(0.7457)/eff$
$= 19.96(24)(365)(0.7457)/0.80$
$= 163{,}000$ kW-hr

$= (HP)\ (24)(365)/eff$
$= 13.68(24)(365)/0.80$
$= 150{,}000$ kW-hr

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For alternate material:

= (*HP*) (24)(365)(0.7457)/*eff*
= 42.20(24)(365)(0.7457)/0.80
= 344,620 kW-hr

= (*HP*) (24)(365)/*eff*
= 29(24)(365)/0.80
= 318,000 kW-hr

Step 4. Calculate the AEC (Eq. 4-20) and calculate the total energy cost over 20 years:

AEC = (*Ec*) (UEC)

AEC = (*Ec*) (UEC)

For fiberglass pipe:

= 163,000 (0.06) = $9,780/yr
= $195,600 over 20 years

= 150,000 (0.06) = $9,000/yr
= $180,000 over 20 years

For alternate material:

= 344,620 (0.06) = $20,676/yr
= $413,000 over 20 years

= 318,000 (0.06) = $19,080/yr
= $381,600 over 20 years

Example 4-4: Surge pressure calculation

Determine if the maximum pressure surge for the pipe in example 4-2 is within the 40 percent surge allowance criteria. Assume a full instantaneous change in velocity equal to the flow velocity in the pipe. The fiberglass pipe has a tensile modulus of 3×10^6 psi and a pressure class of 100 psi. The pipe wall thickness t = 0.21 in. The bulk modulus of water is 300,000 psi.

Determine if the maximum pressure surge for the pipe in example 4-2 is within the 40 percent surge allowance criteria. Assume a full instantaneous change in velocity equal to the flow velocity in the pipe. The fiberglass pipe has a tensile modulus of 20 GPa and a pressure class of 700 kPa. The pipe wall thickness t = 5.3 mm. The bulk modulus of water is 2.07 GPa.

Step 1. Calculate the wave velocity (Eq. 4-22):

$a = 12/[(\rho/g)\,(1/k + d/(E(t)))]^{0.5}$
$= 12/[(62.4/32.2)\,(1/(3 \times 10^5) + 18/3 \times 10^6\,(0.21))]^{0.5}$
= 1,526 ft/sec

$a = 1/[(\rho)\,(1/10^9 k + d/(10^9 E(t)))]^{0.5}$
$= 1/[1{,}000(1/10^9(2) + 450/10^9(20)(5.3))]^{0.5}$
= 459 m/sec

Step 2. Calculate the surge pressure (Eq. 4-21):

$P_s = (a/g)\,(SG/2.3)\,(\Delta V)$
$= (1{,}526/32.2)(1/2.3)(10.1)$
= 208 psi

$P_s = (a)\,(SG)\,(\Delta V)$
$= (459)(1)(3.15)$
= 1,446 kPa

Step 3. Check compliance with the maximum system pressure requirement:

$P_c \geq (P_w + P_s)/1.40$

$P_c \geq (P_w + P_s)/1.4$

From example 4-2, P_w = 38.7 psi and the selected pressure class was P_c = 100 psi:

(38.7 + 208)/1.4 = 176 psi

From example 4-2, P_w = 277 kPa and the selected pressure class was P_c = 700 kPa:

(277 + 1,446)/1.4 = 1,231 kPa

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This exceeds the pressure class. The engineer has three options. The first would be to increase the pressure class to accommodate the surge, maintaining the same pipe diameter. The second would be to increase pipe diameter, which together with a more moderate increase in pressure class would satisfy the maximum system pressure requirement. The larger pipe diameter will lower operating pressure due to lower friction loss and will lower fluid velocity. The third option is to provide measures, such as a surge tank, to reduce the magnitude of the surge.

For this example, the second option will be used and a diameter of 20 in. (wall thickness of 0.23 in.) with a pressure class of 150 psi will be evaluated.

This exceeds the pressure class. The engineer has three options. The first would be to increase the pressure class to accommodate the surge, maintain ing the same pipe diameter. The second would be to increase pipe diameter, which together with a more moderate increase in pressure class would satisfy the maximum system pressure requirement. The larger pipe diameter will lower operating pressure due to lower friction loss and will lower fluid velocity. The third option is to provide measures, such as a surge tank, to reduce the magnitude of the surge.

For this example, the second option will be used and a diameter of 500 mm (wall thickness of 5.8 mm) with a pressure class of 1,000 kPa will be evaluated.

Step 4. Calculate the fluid velocity for the new pipe diameter (Eq. 4-7):

$V = 0.409(Q/d^2)$
$= 0.409[8{,}000/(20)^2]$
$= 8.18$ ft/sec

$V = 1{,}274(Q/d^2)$
$= 1{,}274[500/(500)^2]$
$= 2.55$ m/sec

Note: This velocity is lower than the 10.1 ft/sec (3.15 m/sec) in example 4-2.

Step 5. Calculate the new working pressure:

A. Reynolds number (Eq. 4-12):

$R_e = (\text{ID})\,(V)/\mu$
$= (20/12)\,(8.18)/0.00001$
$= 1{,}363{,}333$

$R_e = (\text{ID})\,(V)/\mu$
$= (500/1{,}000)\,(2.55)/0.93 \times 10^{-6}$
$= 1{,}370{,}967$

B. Friction factor (Eq. 4-16):

$f_t = [1.8 \log (R_e/7)]^{-2}$
$= [1.8 \log (1{,}363{,}333/7)]^{-2}$
$= 0.01103$

$f_t = [1.8 \log (R_e/7)]^{-2}$
$= [1.8 \log (1{,}370{,}967/7)]^{-2}$
$= 0.01102$

C. Friction losses (using Eq. 4-13 and Eq. 4-17):

Use a factor K for 90° double-miter elbows of 0.8 and for 45° single-miter elbows of 0.5. The total K factor is then 4(0.8) + 3(0.5) = 4.7.

$H_f = K\,(V^2/2g) + [f_t\,L(V^2)]/2(\text{ID})g$
$= V^2/2g\,[K + f_t\,L/\text{ID}]$
$= (8.18)^2/2(32.2)\,[4.7 + [0.01103\,(5{,}000)]/(20/12)]$
$= 39.3$ ft

$H_f = K\,(V^2/2g) + [f_t\,L(V^2)]/2(\text{ID})g$
$= V^2/2g\,[K + f_t\,L/\text{ID}]$
$= (2.55)^2/2(9.81)\,[4.7 + [0.01102\,(1{,}500)]/.5]$
$= 12.5$ m

Combine friction and elevation head:

$H_{total} = 39.3 + 25 = 64.3$ ft

$H_{total} = 12.5 + 7.5 = 20$ m

D. Convert to working pressure (Eq. 4-10) and using H_{total} for H_f:

$p = (H_f)(\text{SG})/2.31$
$= (64.3)\,(1.0)/2.31 = 27.8$ psi

$p = (H_f)(\text{SG})/0.102$
$= (20)(1.0)/0.102 = 196$ kPa

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