Codification of Fiber Reinforced Composite Piping

Introduction

The goal of the overall project is to successfully adapt spoolable FRP currently used in the oil industry for use in hydrogen pipelines. The use of FRP materials for hydrogen service will rely on the demonstrated compatibility of these materials for pipeline service environments and operating conditions. The ability of the polymer piping to withstand degradation while in service, and development of the tools and data required for life management are imperative for successful implementation of these materials for hydrogen pipeline.

The information and data provided in this report provides the technical basis for the codification for fiber reinforced piping (FRP) for hydrogen service. The DOE has invested in the evaluation of FRP for the delivery for gaseous hydrogen to support the development of a hydrogen infrastructure. The majority for the effort in support of the FRP evaluation has been performed at the DOE National Laboratories. Savannah River National Laboratory (SRNL) and Oak Ridge National Laboratory (ORNL) have performed the bulk of the work presented in this report.

The plan for codification of the FRP was develop by SRNL and the American Society of Mechanical Engineers (ASME) [1]. The plan "Life Management Methodology Development for Fiber Reinforced Hydrogen Pipelines" presented a series of tasks to guide the direction for the research and testing needed to have FRP codified in the ASME B31.12 Hydrogen Piping Code[2]. The plan also provided the tasks needed for the post construction management of FRP to insure structural integrity through end of life. The plan calls for detailed investigation of the following areas:

- System design and applicable codes and standards
- Service degradation of FRP
- Flaw tolerance and flaw detection
- Integrity management plan
- Leak detection and operational controls evaluation
- Repair evaluation

The FRP codification process started with commercially available products that had extensive use in the oil and gas industry. These products have been evaluated to assure that sufficient structural integrity is available for a gaseous hydrogen environment.

The B31.12 Hydrogen Piping Code was developed specifically to address the needs for a hydrogen infrastructure. The B31.12 Code addresses industrial piping and pipelines. It is planned to develop an additional section in B31.12 for commercial and residential piping. The initial intent for the FRP product was for use as hydrogen delivery pipelines, but when addressing the codification effort the industrial and commercial application will also be considered to leverage the evaluation effort to it maximum extent.

ASME Methodology

The ASME methodology used in the pressure boundary structural integrity codes address seven key topics. These include

- Scope
- Materials
- Design
- Fabrication
- Examination
- Testing
- Inspection

The information and data provided in this codification report is organized to address these specific code elements. The presentation of the information by these topics will aid in its use by the ASME B31.12 Code Committee.

Scope

The DOE Hydrogen Delivery Program has identified spoolable FRP as a cost effective alternative to metallic piping for hydrogen service. The main advantage of the spoolable FRP product form is that it can be obtained in long sections, (1/2 mile), substantially reducing the fabrication cost associated with welding metallic piping.

The specific FRP construction method of interest uses a laminate of continuous filaments of a specified glass fiber with a specified resin wound in a systematic manner under controlled tension over a cylindrical non-metallic liner and cured. The glass filament is wound at a specified angle to provide both circumferential and longitudinal load carrying capacity to the piping. The test program evaluated FRP products with both single and multiple layers for fiber reinforcement. To assure a level of redundancy in the structural integrity of the pressure boundary the multiply layers of reinforcement are required.

The current FRP systems evaluated used metallic part for joints between the piping sections. Metallic load bearing pressure parts shall comply with the existing requirements for metallic piping in ASME B31.12.

The current ASME Piping Codes place a restriction on the use of plastic piping when used in flammable gas service. The provisions require that protective measures be taken to limit the risk in reinforced thermosetting resin piping in the event of a fire. The requirement stems from the concern that the plastic piping is flammable and will sustain burning in the event of an ignition. To provide the appropriate Codes required Safeguards, FRP will be restricted to underground application for hydrogen service.

Material

Product Form

The material used in the FRP products being considered consists of an inner polymer liner, multiple glass fiber reinforcement layers and an outer protective layer. The polymer liner is most commonly fabricated from High Density Polyethylene (HDPE) and is non-load bearing. The specific liner material evaluated during the DOE testing is PE-3408. PE-3408 is a Code listed material in ASME B31.3[3] and has been used in plastic pipe manufacturing for many years. The glass structural layer is fabricated from glass fiber in a resin matrix. The outer protective layer is a manufactured from polyethylene. The outer layer function is to provide shielding for the structural glass layer during transport and installation. The outer protective layer does not provide a structural integrity function for the pressure boundary.

The material evaluations that have been performed as part of the DOE testing program have specifically addressed degradation of an existing FRP product form in hydrogen service. Tensile strength following accelerated ageing of individual materials following hydrogen exposure has also been performed. The polyethylene liner provides the primary barrier for leakage control of the hydrogen to the environment. As part of the material evaluations the permeation of hydrogen through the FRP product form was measured. Additional permeation measurements were determined for polyethylene samples (PE 3408) and other possible candidate liner material.

To address concerns about the use of plastic materials in hydrogen service, ASME contracted a report to compile the available industry data on fiber reinforced composite tanks. This report was developed to support the effort to codify requirements for high pressure hydrogen tanks. The report[4] provide a comprehensive review of the available data for plastics in hydrogen pressure boundary applications.

Product Form Testing

SRNL and ORNL have collaborated on evaluating the service degradation of FRP in pressurized hydrogen. An accelerated aging process was used to evaluate hydrogen-induced damage in FRP pipelines (Fiberspar LinePipe™) and pipeline constituent materials. The process involves immersion of FRP pipeline specimens in hydrogen at 1000 psi (69 bar) at an elevated temperature 140°F (60°C) to promote an accelerated interaction of hydrogen with the pipeline structure. The hydrogen exposure for the FRP was performed by immersing the samples in hydrogen. The samples were placed inside a containment pressure vessel that was then pressurized with hydrogen. This allowed the samples to be exposed to hydrogen from both surfaces. The hydrogen exposure station is shown in Figure 1. Each containment vessel was wrapped with a resistance heater that was connected to redundant controllers to provide the increased temperature to promote the accelerated aging. The types of samples tested included pipe section, compression samples, and dog-bone tensile specimens. The dog-bone tensile specimens include both samples of the polyethylene liner and the epoxy matrix use for in the laminate. Photos of the tested samples are shown in Figure 2. Glass fiber specimens were also agee during the same experiment, but are not shown in Figure 2.

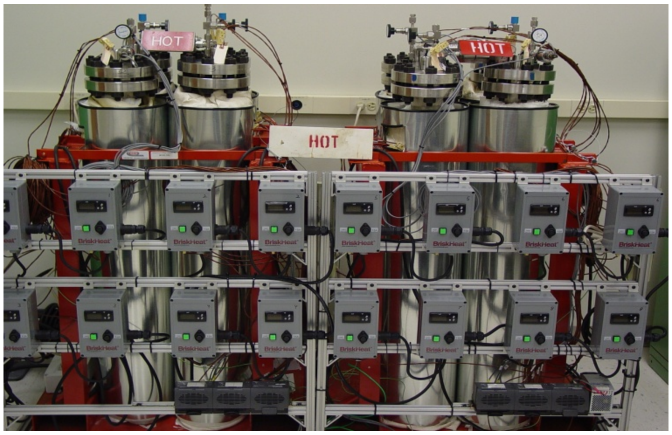

Figure 1 Hydrogen Exposure Station

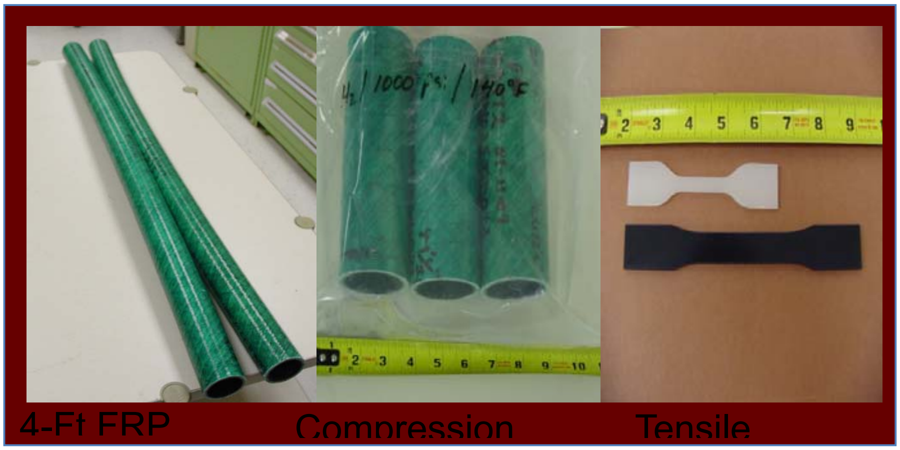

Figure 2 Types of Samples Exposed to Hydrogen

To assess specific effects on the component materials in the pipeline, specimens of fiberglass rovings, resin matrix and liner materials were immersed simultaneously with the pipeline specimens, and all specimens were subjected to either a one-month exposure or an eight-month exposure to this hydrogen environment. At the conclusion of the exposure interval, the pipeline specimens were evaluated by Fiberspar for degradation using hydrostatic burst pressure tests to assess the overall integrity of the structure, compression tests to assess the integrity of the polymer matrix, and bend testing to assess the integrity of the laminate. The results of these tests were compared to the results obtained from identical tests performed on un-conditioned specimens from the same manufacturing run. Tensile tests and dynamic mechanical analysis were performed at ORNL on multiple specimens of component materials. The results of the specimens conditioned in hydrogen were compared to specimens that were conditioned in ambient-air for identical intervals.

The results from the eight-month exposure were largely consistent with those from the one-month exposure; there were no statistically significant differences between the test results of off-the-shelf and hydrogen aged pipeline specimens and materials. A small difference between the tensile strengths of 1-month conditioned and 8-month conditioned glass fibers samples was observed. Although statistically significant, these results were not conclusive. Additional accelerated aging on a larger number of glass fibers, and using statistical analysis that reduces the large error bars due to extreme values in the data sets. The results of these tests are given below.

Glass Fiber Testing

An accelerated aging process was used to evaluate the possibility that hydrogen could weaken the load-bearing capability of the glass fibers that are used as reinforcement in glass fiber-reinforced pipelines being considered for hydrogen delivery. Designing a test to screen for hydrogen-induced failures in glass fibers is difficult because potential chemical incompatibilities are largely unknown (Need additional clarification from ORNL) and because the permeation of hydrogen into glass is typically 3 to 7 orders of magnitude smaller than it is in most polymers and metals. Previous studies of the effects of hydrogen on glasses have focused on the ability of the glasses to store hydrogen or on the tendency of hydrogen to produce attenuation centers in the glasses [5](Reference).

To assess possible hydrogen-induced changes in mechanical strength of the glass fibers, the fiber tensile strengths in boron-free e-glass fibers (Advantex® SE 1200 Type 30) before, during and after accelerated aging in a pressurized hydrogen reactor was measured. The accelerated aging protocol was based on the Arrhenius model for an activated process where the aging rate is proportional to $e^{-\lambda/kT}$, where λ is the activation energy, *T* is the aging temperature, and k is the Boltzmann constant. The fibers was aged in a 1020psi (70 bar) pressure of hydrogen at a temperature of 140°F (60°C), which are the maximum allowable working pressure and temperature of the FRP pipeline. There were no stressors to contribute to the degradation of the fiber other than hydrogen pressure (i.e., no oxygen, water, chemicals, untraviolet). From previous measurements done by others[6] (Reference), it has been shown that simply heating the fibers to 140°F (60°C) for long periods of time does not degrade their tensile strength when it is subsequently measured at room temperature. Tensile tests of untreated control specimens were included to compare with the specimens treated in hydrogen.

Fibers were removed from the reactor at intervals of 1, 5, 11, 20, 39 and 62 weeks of exposure to perform tensile tests on fiber specimens with gauge lengths of 25 mm. Each test included 30-100 fibers of both the hydrogen exposed and control groups at each time interval. The distribution of tensile strength can be approximated by the two-parameter Weibull distribution.

$P(\sigma) = 1 - \exp(-L/L_0[\sigma/\beta]\alpha)$

Where α is the shape parameter, β is the scale parameter, and *L* and L_0 are the fiber gauge and reference lengths. Figure 3 shows representative test results in Weibull coordinates for the shortest and longest hydrogen exposures.

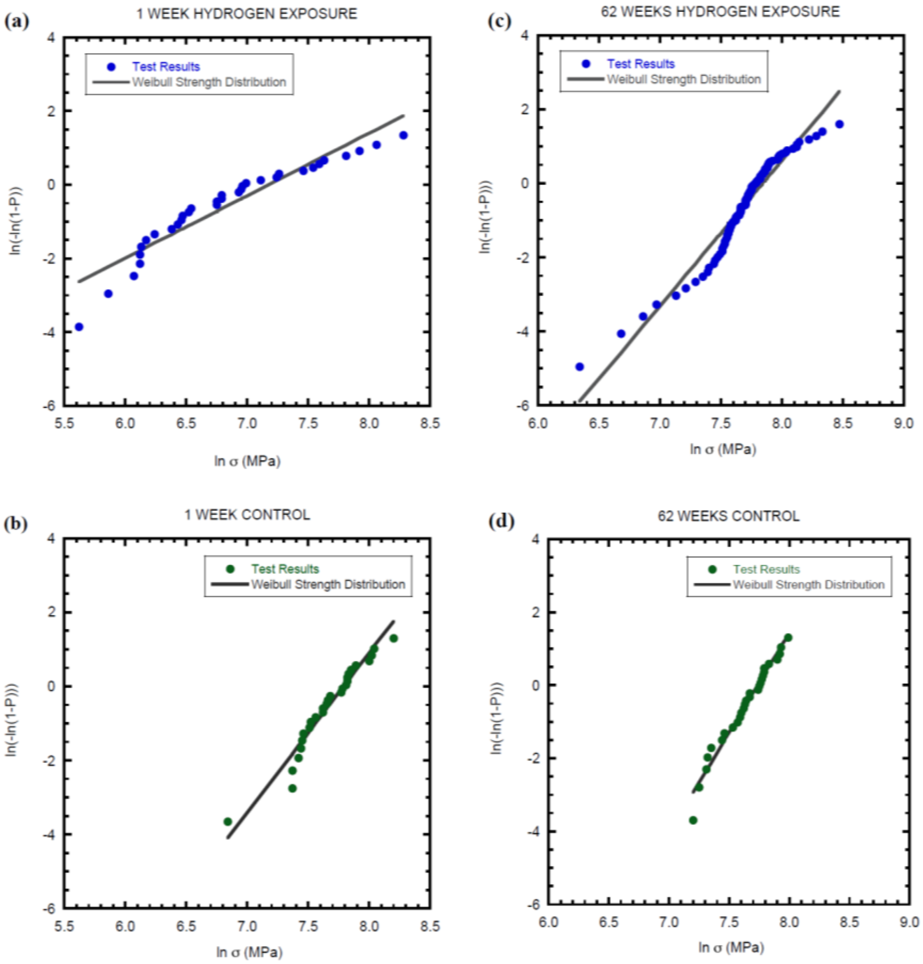

Figure 3 Representative test results in Weibull coordinates for fiber strengths measured following (a) 1-week and (c) 62-week hydrogen exposures.

Using the Weibull parameters determined from the tensile strength measurements performed at each exposure interval, the survival probabilities for the hydrogen-treated and control fibers were calculated. These survival probabilities are plotted versus exposure duration in Figure 4. The large error bars in the survival probabilities are likely due to the presence of both surface and bulk flaws in the fibers. Additional analysis would be required to censor the strength data by doing fractographic analysis to identify the type of flaw in each fiber tested. Fractographic analysis would have allowed the data to be separated by flaw type and thereby obtain Weibull distributions with straight-line slopes. Nevertheless, the survival probabilities for the treated and untreated fibers do not change qualitatively with aging, implying that there was no hydrogen-induced degradation in the fibers during the 62-week exposure duration.

The intensity of the glass-fiber exposure was significantly higher than the actual exposure of fibers in the pipeline epoxy matrix and exceeded even a worst-case scenario. The conclusion reached is that e-glass should be durable in hydrogen service and the glass fibers should retain their mechanical function in a glass-fiber-reinforced pipeline during the anticipated hydrogen service lifetime. E-glass fibers similar to those used as reinforcement in composite pipelines did not lose their tensile strength during a long-term exposure to high-pressure hydrogen gas.

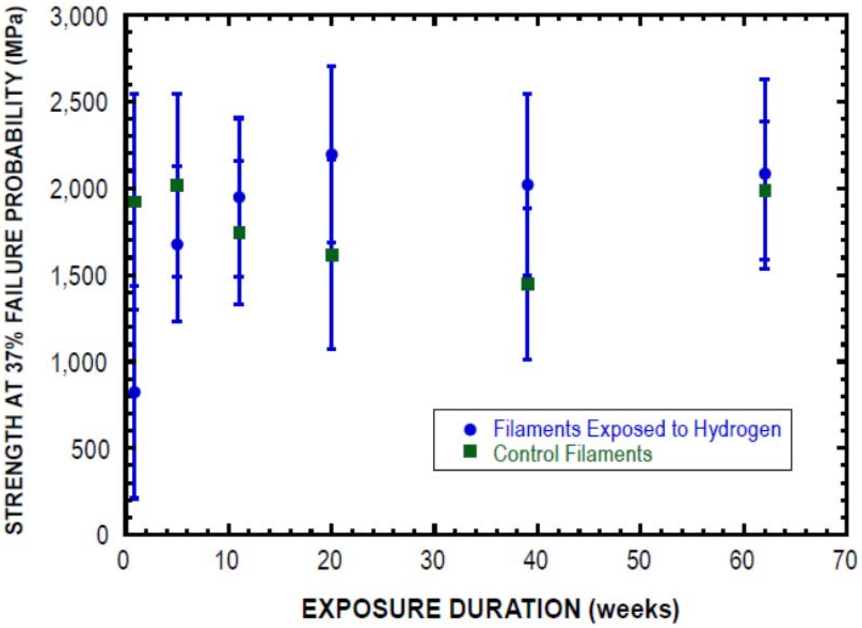

Figure 4 Survival probabilities of hydrogen-treated and untreated (control) fibers plotted versus accelerated aging duration.

Literature Review Potential Degradation of Polymers in Hydrogen[7]

The stability of a polymeric material during service is essential for reliability. It is for this reason that all possible polymer degradation processes during hydrogen pipeline operating conditions must be known and mitigated. Polymer degradation due to elevated heat and stresses is well documented; however, degradation due to gaseous permeation, specifically hydrogen, is not widely researched and is of major interest for the selection of materials for fiber-reinforced piping for hydrogen service. Polymer degradation can occur with exposure to normal environmental conditions, such as sunlight and oxygen. Samples exposed to UV light tend to continue to oxidize even when stored in darkness. In general, degradation usually occurs due to 1) irradiation and subsequent formation of free radicals within the polymer, 2) chemical attack of certain functional groups in the polymer chain possibly by changing pH conditions or humidity, or 3) thermal breakdown of polymers that are above Tm or do not have a melting temperature due to physical crosslinking. Often, a combination of these three factors leads to polymer breakdown

Polyethylene, for example, can be degraded by heating (in an inert atmosphere) to approximately 450°C. The breakdown is a result of random chain scission of the polymer backbone[8]. Random chain scission has been mentioned as the most important degradation mechanism, especially in polymers with aliphatic C-H bonds[9]. Chain scission also occurs due to irradiation. Polymers may experience degradation in the presence of water due to hydrolysis of the polymer molecules[10]. When chain scission occurs, by whatever catalyst, a ductile to brittle behavior change may be induced. This change is often termed as *embrittlement* and can drastically alter the properties of a polymer material. Embrittlement is due to many factors, including changes in crystallinity and molecular weight. However, degradation must occur before embrittlement takes place.

Crystallinity may change during the course of degradation. In the initial stages of photodegradation, chain scission often prevails, which reduces molecular weight. Shorter chains are more mobile and are thus able to crystallize more readily. Therefore, embrittlement of the polymer is driven by two associated processes: reduction of molecular weight and increased crystallinity. Additionally, degradation processes take place only in the amorphous regions of the polymer. Gaseous diffusion into the crystalline phases is restricted (if not prohibited completely), thus decreasing the potential for oxidation, and/or reaction with another permeating species, if the polymer has a high crystalline content.

The reaction pathway for radiation degradation of polyethylene (in the presence of O2) and the formation of free radicals is as follows [11]: First, polyethylene forms weakly-absorbing complexes with ground-state molecular oxygen, which, on UV exposure, generate hydroperoxides. Next, transition metal ions are known to catalyze hydroperoxide decomposition. Both high-density PE and low-density PE contain unsaturated hydrocarbon bonds. The presence of these unsaturations (vinylidene groups) leads to the formation of allylic hydroperoxides during the thermooxidative processes, and this becomes the major mechanism of initiation. The resultant structure can be further converted by heat, UV, or other radicals to free radicals and/or to structures containing UV-absorbing groups (e.g., carbonyl). Cross-linking can also occur, but the chain scission mechanism most often dominates.

With respect to the investigation of degradation of a polyethylene liner in a pipeline for hydrogen service, no mechanisms for degradation due to hydrogen alone has been reported. Little or no interaction between hydrogen gas (or any non-polar gas) and polyethylene should be expected. Additionally, hydrogen alone provides no mechanism for radical formation, as mentioned previously for chain scission. However, if the permeating gas stream contained contaminants in addition to hydrogen gas, then the mechanism for degradation would depend solely on the contaminant concentration and nature of the contaminant. In some cases, contaminant gases like sulfur dioxide actually decrease the amount of hydrogen to permeate the polymer by essentially “plugging up” all of the free volume available for diffusion.

Currently, specifications for the purity level of hydrogen gas transported via FRP pipeline have not been determined. However, it can be concluded that pure hydrogen gas will not promote polymer degradation, as mentioned previously. If, however, hydrogen gas is mixed with natural gas as a carrier (hythane), then the effects of natural gas on the stability of the pipeline liner material will become important. These findings have already been published elsewhere, although the main focus of these studies has been on the mechanical properties and not the degradation mechanisms[12]. Additionally, known gaseous contaminants, such as CO2, H2S, water vapor, chloride gas, and oxygen (among others) will also require further study into potential problems raised by the presence of these gases in the hydrogen stream.

Gas-Polymer Interactions

There is no mechanism for degradation of polyethylene in the presence of hydrogen unless some other reaction catalyst, such as heat, humidity, or radiation source is present. That is, any interaction between the hydrogen molecule and polyethylene chains would be very small, if at all. The concept of quantifying the degree of interaction between a polymer and another molecule (mainly a solvent or plasticizer) was first introduced by Flory and Huggins (simultaneously) in 1950[13]. The interaction parameter, χ, was proposed as a single parameter to quantify the interactions between components in a mixture, which is related to the change in energy when the polymer/polymer and molecule/molecule (molecule =solvent, plasticizer, permeant gas, etc) contacts are replaced by polymer/molecule contacts.

This change in interaction energy can be expressed in the form of cohesive energy density and is related to solubility parameters [14].

The χ parameter is usually expressed in terms of solubility of a polymer in a given solvent, but this parameter has been used recently to predict the solubility of a gas in the same way[15]. In the work of Kamiya [16], hydrogen gas was termed a “sparingly soluble” gas in both polyethylene and poly(dimethylsiloxane) polymers by way of sorption isotherm measurements. As mentioned previously, if solubility is small, then the gas-polymer interactions can be described by Henry’s Law. If not, then the Flory-Huggins theory of dissolution applies for rubbery polymers, while glassy polymers are described by the dual mode dissolution theory. In the case of hydrogen, Henry’s Law was found to apply and a linear isotherm was observed [17].

The χ parameter was estimated at around 3.1-3.5 for various grades of polyethylene, for the polyethylene/hydrogen interactions [14,15]. A value of 0.5 or below for the χ parameter indicates “good” solubility of the molecule in the polymer. An exact value of 0.5 indicates that the Flory theta (θ) condition was met. For this polymer-molecule pair, this means that the gas molecules are allowed to “flow” into and out of the polymer freely and with equal statistical probability without any thermodynamic restriction. A value of 0.5 and above indicates a poorly soluble molecule. The results of the work by the Kamiya group indicate that hydrogen is quantitatively very poorly soluble in polyethylene and other similar rubbery polymers.

A more rigorous investigation of the literature for generalizations on hydrogen interactions with polymers indicates that hydrogen interacts with rubbery polymers, in a similar manner as its interactions with a simple fluid, such as water. The solubility of hydrogen in water is well documented and known to be very low (Figure 5).

There are, however, a few instances when hydrogen can be thermodynamically “forced” to interact with a polymer. If hydrogenation takes place at or above certain critical conditions (temperature, pressure, etc), then the kinetic limitations to hydrogen solubility can be overcome. A “good” solvent that is hydrogenated can also be used to insert H2 molecules between polymer chains when the solvent is removed.

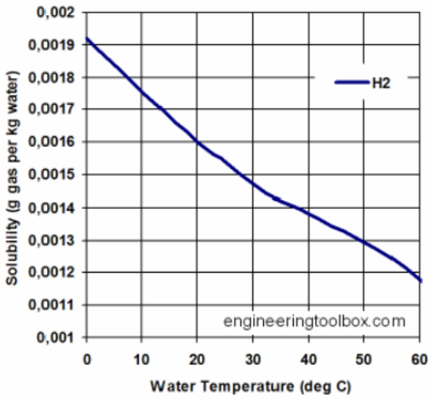

Figure 5 Solubility of hydrogen gas in water

Permeation Leakage through the Polymer Liner

Hydrogen leak rate measurements were determined and recorded in a short section of FRP pipeline. These measurements were designed to assess how well the pipeline contains pressurized hydrogen gas. The measurements were done on off-the-shelf 10-cm inside diameter specimens of Fiberspar LinePipe™. The pipeline liner was 0.526-cm-thick pipeline grade high-density polyethylene (PE-3408). The hydrogen pressurization in the pipelines was 1,500 psia (103 bar), which is the pipeline pressure rating, and all measurements were done at ambient lab temperatures. The pipeline was closed on each end using capped Fiberspar LinePipe™ connectors with elastomer (O-ring) seals. The leak rate was calculated from the temperature-corrected pressure decay curve. Changes in pipeline volume that occurred due to pressure-induced dimensional changes in the pipeline length and circumference were measured using strain gauge sensors. These volumetric changes occurred at the earliest measurement times and diminished to near zero at the long measurement times during which the steady-state leak rate was determined.

The equation below was applied to predict the hydrogen leak rate per meter of the liner:

$$\frac{dn}{dt} = \frac{2\pi P}{In\left(\frac{b}{a}\right)}(p_0 - p_1) \qquad \text{mol/s·m.}$$

Where *n* is moles of hydrogen, *P* is the permeation coefficient for hydrogen in PE-3408, *a*=5.05 cm and *b*=5.576 cm are the inner and outer radii of the liner tube, and *p*0=100 bar and *p*1=1 bar are the hydrogen pressures inside and outside the liner.

The measurement of the permeation coefficient for PE-3408 found that $P \approx 4\times10^{-10}$ mol/m.s.bar. Thus the predicted leak rate for a 2.7-meter long pipeline specimen is -2.4×10^{-2} mol H2/h, assuming the leakage through the seals on the steel end caps seals is negligible compared to the leakage through the polymer liner.

Figure 6 shows the results of a long-term measurement of the hydrogen gas leak rate d*n*/d*t* in a 2.7-meter-long pipeline. During the first 500 hours the apparent leak rate steadily decreased. We attribute this apparent leak rate, which is larger than the constant leak rate observed after 500 hours, to two phenomena. First, the pipeline volume initially increased slightly as the composite structure slowly expanded under the stress of pressurization. This volumetric expansion produced a slight reduction in pressure and yielded an apparent reduction the number of moles of gas. Second, the pipeline wall (liner and reinforcement layers) absorbed and retained hydrogen after it was pressurized. This also yielded an apparent decrease in the number of moles of gas. In the interval from 500 to 6,400 hours (20 to 270 days) the leak rate d*n*/d*t* was constant, and a linear least-squares fit to the leak rate in this interval gave a value of -5.4×10^{-4} mol H2/h. This leak rate is equivalent to a stored hydrogen loss of about 0.02% H2 per day at a pressurization of 1500 psi (100 bar).

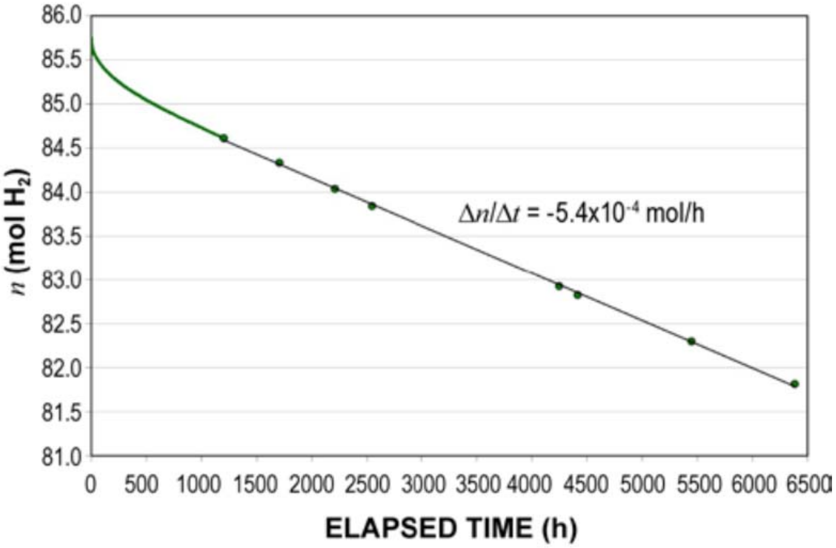

Figure 6 The leakage measured in a 2.7-m (9-ft) long specimen of 10-cm inside diameter Fiberspar LinePipe™

Table 1 shows the results of leak rate measurements of three lengths of pipeline. The three pipelines were identical with the exception of their lengths. The same pair of connector end caps was used on all specimens. In all three lengths the measured leak rate was significantly lower than the predicted rate. The leak rate should have increased in direct correspondence to the pipeline length, but for the two shorter lengths we probably terminated the measurement before the leak rate decreased to its steady-state (actual) value. (The pipeline wall might not yet have been saturated with hydrogen.)

Table 1 Results of H2 leak rate measurements in three Fiberspar LinePipe™ FRP pipeline specimens

Pipeline Length m (ft)	Nominal Pressure bar (psia)	Measurement Duration h	Measured Leakage Rate mol/h	Predicted Leakage Rate mol/h
0.9 (3)	100 (1,500)	145	-4.4×10^{-4}	-8.1×10^{-3}
1.8 (6)	100 (1,500)	285	-5.5×10^{-4}	-1.6×10^{-2}
2.7 (9)	100 (1,500)	6,400	-5.4×10^{-4}	-2.4×10^{-2}

Control of Material for Codification

The structural materials used to manufacture FRP will need to be controlled in a manner consistent with existing Codes and Standards. Metallic components used in the manufacture of joints for FRP must meet the current B31.12 requirements of metal pipe and fitting. All material used in the manufacture of the laminate must be traceable to an individual FRP lot and documented in the Manufactures Construction records. The laminate consists of fiber reinforcement in a resin matrix. Acceptable resin systems to consider include epoxy, polyester, or vinyl ester. Glass fibers to consider include Type S, Type E, or Type E-CR. The material supplier must certify that these fibers conform to the Manufacturer's specification.

Component ratios must be set for resin and curing agent in the resin formulation, and must be consistent between the FRP qualification test and the FRP production and a maximum use temperature must be established for the resin system. To insure that the laminate is properly cured a verification test by using Barcol hardness or equivalent, such as by checking a resin sample with a differential scanning calorimeter (DSC).

Since the application on FRP for hydrogen service will be underground the laminate must not the susceptible to degradation from moisture. The laminate must have a minimum interlaminar shear strength of 14 MPa (2,000 psi), determined in accordance with ASTM D 2344[18], following a 24-hour water boil. This verifies that the resin will likely not break down over the normal use cycle such that the fiber would start to unravel or such that it would not properly transfer load between fibers or layers.

The liner material must be compatible with the hydrogen. Properties of the liner must be confirmed and certified by the material supplier. Since the liner is a non-structural material, specific material specifications are not required unless needed to insure an adequate permeation boundary. The qualification tests will verify that the performance of the liner material is adequate.

Design

Piping Industry Design Margin Methodoloy

Two primary sources of information have been used to evaluate acceptable design margins for fiber reinforced piping. These include existing code and standards for composite pressure boundary components and creep rupture data from glass fiber testing. Stress rupture is a phenomenon in which tensile failure will occur in the fiber under stained load with no other phenomenon being present. Review of the available information in current codes and standards show that the two different methods have been applied to provide acceptable design margins for fiber reinforced components. I review of the most relevant standards that allow for the use of FRP was completed. The Codes and standards selected evaluation are shown below and the results of the review are shown in Appendix A. The reviewed showed that the most relevant standards available for FRP manufacturing are API 15HR and ASTM D2996[19]. API 15HR was not developed for hydrogen service so addition performance based testing will be required for hydrogen applications. ASTM D2996 provides the a basis for deterministic evaluation for FRP testing and dimensional control. At the present time ASME B31.12 does not allow for the use of polymer piping for hydrogen applications.

- Standards Reviewed
    - API 15HR, Specification for High Pressure Fiberglass Line Pipe[20]
    - AWWA C950 Fiberglass Pressure Pipe[21]
    - ASME Code Case N-155-2 Fiberglass Reinforced Thermosetting Resin Pipe[22]
    - ASME B31.3 Process Piping
    - ASME B31.8 Gas Transmission and Distribution Piping[23]
    - ISO 14692 Petroleum and Natural Gas Industries Glass-Reinforced Plastics (GRP) Piping[24]

In the fiber reinforced piping industry the design margin has been determined through the application of ASTM Standard D 2992[25]. The ASTM provides an established practice for determining the hydrostatic design stress for piping and piping components. The term hydrostatic design stress is the maximum tensile stress in the wall of the pipe in the hoop direction due to internal pressure that can be applies with a high degree of certain that failure of the pipe will not occur. The codes and standards review showed that methodology similar to ASTM D2992 (Hydrostatic Design Basis) are used to establish an allowable design margin when stress rupture is a concern for many of the relevant FRP codes and standards. The ASTM D2992 procedure addresses both constant and cyclic loadings conditions. Eighteen samples are required to be tested to develop the regression line for to calculate the hydrostatic design stress. In performing these tests at least one of the test specimens must fail following 10,000 hours of applied pressure. The data must also be shown to be statically relevant using a least squares curve fitting procedure as specified by the ASTM standard.

A data set show the application of ASTM D2992 is shown in Figure 7. The data was provided by Fiberspar Inc. The figure shows the failure data as a function of time and illustrates the regression line used to determine the hydrostatic design stress.

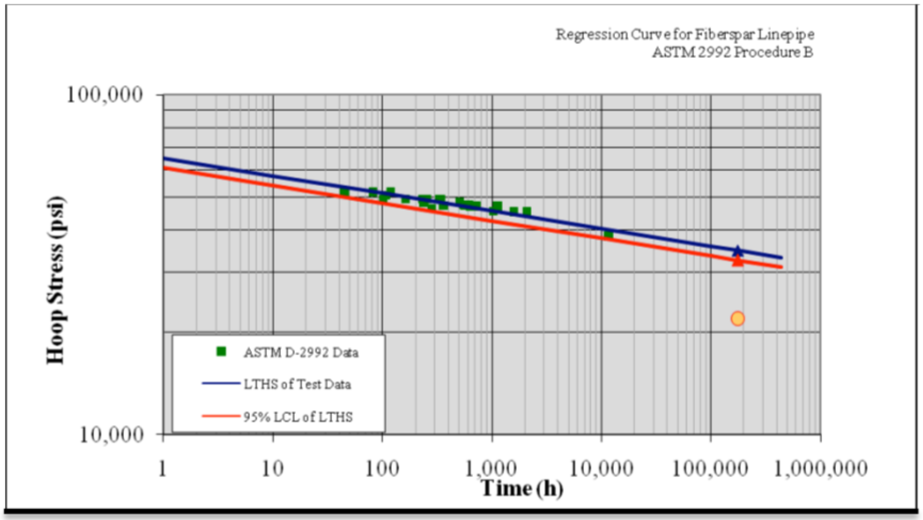

Figure 7 Example of ASTM 2992 Data Set for Development of Hydroststic Design Basis

Glass Fiber Stress Rupture Data

In the pressure vessel industry performance based standards have been the methodology used to address the technical issue with fiber reinforced components. The performance based methodology specifies a series of qualification tests to assure an acceptable design margin for all loading cases. The performance based standards are needed for fiber reinforced vessels because unlike metal tanks, there are not accepted analytical methods the address all the current composite failure modes. A performance-based standard is needed to address all the technical issues for composite hydrogen piping. Where the current FRP industry has used the ASTM D2992 standard to address stress rupture the pressure vessel industry has relied on fiber test data to set design margins in performance based standards.

Stress rupture is a phenomenon in which tensile failure will occur in the fiber under sustained loading below the material tensile strength. In glass fiber stress rupture will occur at ambient temperature with no other phenomenon being present. Investigators of stress rupture characteristics of glass fiber include Outwater[26] and Glaser, Moore, and Chiao[27]. The data presented by Outwater was of relatively short duration. The data presented by Glaser, Moore, and Chiao of Lawrence Livermore National Laboratory (LLNL) was gathered over a longer period of time on impregnated strands under constant load. This study was interrupted after about 10 years by an earthquake, and there was some evidence of UV light influence on the specimens later in the study. Robinson[28] evaluated the data from LLNL with results as shown in Figure 9. Figure 9 shows the stress rupture data for glass fibers over a range of failure probabilities. The data provided by Robinson, Aerospace Corporation has shown that a margin of 3.5 on the burst pressure (.28 Stress Ratio) will provide a stress rupture life of 25 years.

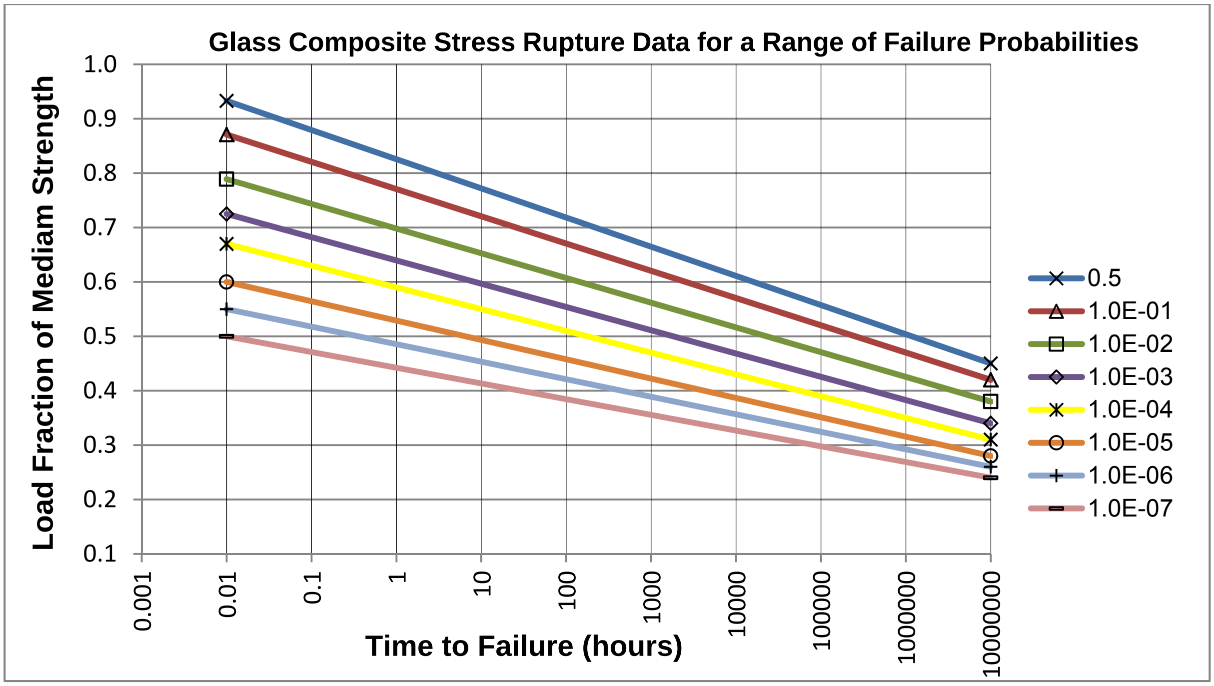

Figure 8 Stress Rupture Trends for Glass Fiber

A design analysis is required to determine the stress level in the fibers to utilize the stress rupture data directly. Minimum material conditions and geometric irregularities such as out-of-roundness must be modeled in the analysis to determine the maximum stress level in the fiber.

One of the key aspects of the design analysis is to confirm that the design does not place the fibers above limits that could result in stress rupture of the fibers. The maximum fiber stress is limited to 28.5% for glass fiber of the tensile strength of the fiber at design conditions. The fiber stress limits correspond to stress ratios of 3.5 for glass fiber and is intended to provide reliability with respect to stress rupture in excess of 0.999999 over the life of the vessel. The stress ratio is the ratio of the minimum strength of the fiber determined through testing divided by the stress in the fiber at the design conditions. The tensile strength of the fiber must be determined through the use of a burst test of a FRP sample, and not by using quoted values or strand tensile test results, in order to be valid for stress ratio calculations.

ASME Experience with Composite Vessels in Hydrogen Service

ASME recognized a need to develop Code requirements for both composite reinforced and totally composite vessels to provide vessels that could support hydrogen storage at 15000 psi (1030 bar). The experience with composites from design and use of ASME Section VIII and Section X vessels, cylinders to transport compressed gases, and fuel containers for natural gas and hydrogen powered vehicles was applied to develop composite hydrogen vessel code requirements. The composite vessel code rules are the most relevant within ASME to use as a starting point for development for B31.12 Code requirements composite hydrogen pipelines.

Code rules for composite vessels have been incorporated into ASME Section X[29], and the requirements for composite reinforced (hoop wrapped) vessel have been incorporated into ASME Section VIII Division 3[30]. When the effort started the ASME Section X scope only allowed for vessel with a maximum design pressures of 20 MPa (3,000 psig). These new composite vessels, are designated as Class III vessels, with design pressure ranging from 3,000 psi (20. MPa) to 15,000 psi (100 MPa). The change of scope to Section X to allow for the Class III vessel construction was published in the 2010 edition of ASME Section X in Appendix 8. The design condition of the vessel code is much higher than those proposed for fiber reinforces piping. The current proposed maximum design pressure for piping is in the range of 1500 to 2500 psi. The experience with the development performance based requirements of the ASME hydrogen can be leveraged for the requirements for hydrogen piping.

The temperature ranges allowable for the ASME hydrogen storage vessel are from -54°C (-65°F) to +85°C (+185°F). These temperatures are generally recognized as the extreme ambient limits to which vessels would be exposed during transportation or operation. The maximum temperature must also be at least 19°C (35°F) below the maximum use temperature of the resin. The temperature range for the current accepted vessel rules is broader than the current proposed need for FRP. The current maximum temperature for hydrogen piping 140 °F and the minimum design temperature will be controlled by the ground temperature. The current piping Code recommendation minimum temperature for FRP on the B31.3 Code is -20°F (-29°C). This value is warmer than current value used in the vessel code. Because FRP will be limited to underground service the warmer lower temperature limit should not be a concern. Additional investigation into the technical basis for both limits needs to be performed. The upper temperature limit in current B31.3 Code rules ranges from 200°F (93°C) to 300°F (149°) depending on the type of resin used with the glass fiber. Epoxy and Phenolic resins have the hotter maximum temperature limit where Polyester and Vinyl Ester have the colder maximum temperature limit. The current Code recommended upper temperature limit is hotter the current planed design temperature for hydrogen pipelines.

Current rules in ASME Section X apply to stationary composite pressure vessels. However, composite pressure vessels and composite hydrogen piping are clearly needed for transport and transmission applications to support a hydrogen delivery infrastructure. For applications in the US these pipelines will require DOT approval. Qualification testing for FRP products need to address input from the DOT if transmission pipelines are codified

The new code requirements for high pressure hydrogen storage vessels were written to support the U.S. Department of Energy recommendation to develop codes and standards needed to support an infrastructure for a hydrogen economy. The assumption was that hydrogen powered vehicles would have a tank capacity of 10,000 psi (70 MPa). The need for hydrogen storage vessels was set at 15,000 psi (100 MPa) to meet the need for high pressure refueling cascades. The current natural gas pipeline network operates in range of 1000 to 2000 psi. The FRP products evaluated to dates have focuses on maintaining the spoolable product form which at the time limits the design pressure to 2500 psi and the nominal diameter of FRP to 6 inches. The work to evaluate the spoolable FRP products has been directed at application for hydrogen service through codification into ASME B31.12. Specific rules and testing are needed for hydrogen because of small molecule size promoting an increased propensity for leakage. While hydrogen is the motivation of this effort the work can be leveraged for other fuel sources.

Control of Design Margins

The Manufacturer is responsible for preparation of a Manufacturing Specification to control materials and essential variables during the manufacturing process. The Manufacturing Specification is the controlling document for all material specifications, liner components and laminate materials. While the metallic components are required to be fabricated from code approved material, the non-metallic components are not code listed materials. Therefore, the required chemistry and physical and mechanical properties for the material forming the laminate are required to be documented in the Manufacturing Specification. The Manufacturing Specification also has a parallel function to the ASME Section IX welding procedures and welding qualification process in controlling the essential variables for the filament winding process.

It is also the Manufacturer's responsibility to conduct all Qualification Tests. Because the FRP standard will be performance based, these qualification tests form the design basis for a specific FRP design. Most ASME Codes are based on design by rule or design by analysis methods that do not require performance testing. The FRP performance is also a function of the essential variables defined in the Manufacturing Specification. To maintain quality control during production the essential variables defined in the manufacturing specification must be monitored during production. The Qualification Test Report, including the results of testing and examinations, is prepared and certified by the Manufacturer. Test results are included in the Manufacturer's Construction Records.

FRP Flaw Tolerance

To address third party damage the sensitivity of FRP to flaws must be established. The flaw testing was performed over a range of flaw sizes to determine the flaw tolerance of the FRP. FRP with single layer reinforcement and multi-layer reinforcement were evaluated. Stress rupture data on glass fiber was also reviewed to evaluate the effect of creep life on the glass fiber. The results indicate that a design margin of at least 3.5 is required to address long-term creep effects for a 25 year design life. The use of the fiberglass stress rupture data has been effective in evaluating the effect of flaw tolerance using a short-term burst test. Multiple tests have been completed to evaluate the effect of flaw tolerance on FRP samples for FRP designed to a recognized national consensus standard were used in the evaluation. Flaws for various depths were machined into the samples and burst tests have been performed.

The results of the single layer FRP tests are shown in Figure 8. A reduction in burst pressure from unflawed condition to a 2-inch long flaw cutting the reinforcing layer of 75% was observed. With the 2-inch long flaw cutting the reinforcing layer the burst pressure drops below the rated pressure for the single-layer product The single layer reinforced piping does not provide sufficient redundancy to tolerate third party damage. Following a review of the results from the piping with the single layer reinforcement, it was determined that this type of fiber-reinforced piping was not an acceptable option for hydrogen piping.

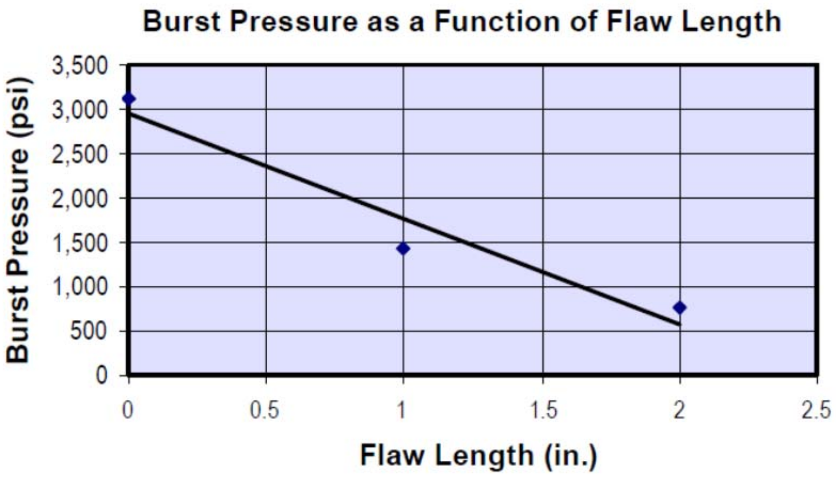

Figure 9 Single-Layer FRP Burst Test Data

The results of the multi-layer FRP tests are provided in Figure 9. Tests were conducted for increasing flaw depths up to 40% through wall. A 28% reduction in burst pressure from the unflawed condition to a 40% through wall flaw was observed. With the 40% through wall flaw there is still a margin of approximately 3 above the rated pressure of the FRP multi-layered product. The margin on burst of 3 provides an acceptable remaining product life to detect and repair flaws in FRP systems. Additional burst tests were conducted in on FRP samples with 40% through wall flaws to determine the variability between different samples. The results of the additional tests show that the variability between the tests is low and that all tests provide an acceptable design margin. The results for increasing the flaw length and width are also shown in Figure 9. The flaw with increased length showed no additional loss in design margin above the base flaw length. The flaw with increased width showed a small additional loss in design margin above the base flaw width.

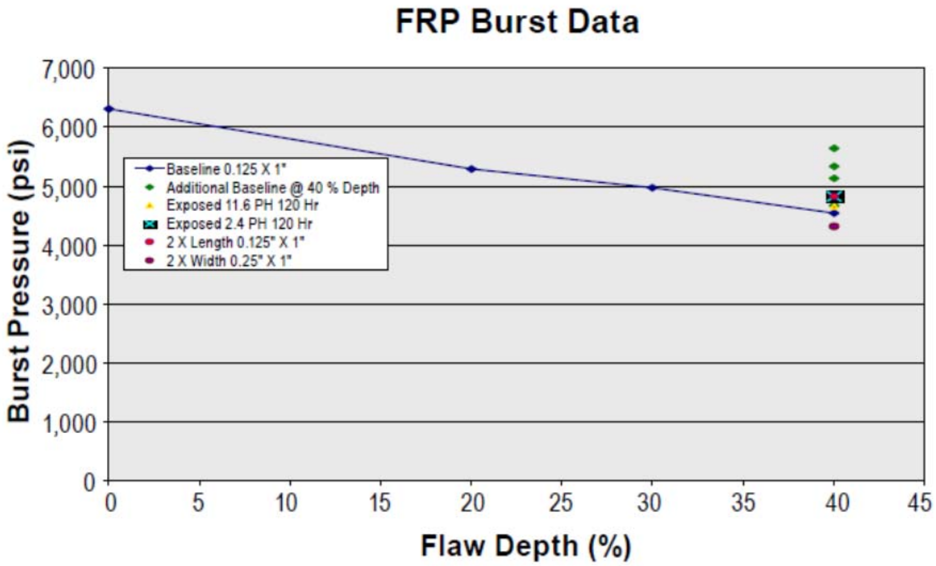

Figure 10 Multi-layer FRP Burst Test Data

From the flawed samples, it was observed that as the flaw depth increased the failure mode changed from a local failure to a more global failure mode. The series of photos shown in Figure 10 illustrates these failure modes. The first photo from the left shows the failure of the unflawed sample indicating a global failure of the pipe. The next three photos illustrate how the failure mode changed as the flaw depth increased. The last photo on the right shows the 40% through wall flaw. In the 40% through wall photo, the failure encompasses most of the pipe circumference. Based on this data it was determined that the 40% through flaw was a reasonable upper limit to set for flaw detection.

Failure mode changes from global to local and then move back towards global as flaw depth increases

Figure 11 Failure Mode for Burst Tested Flawed FRP with Increased Flaw Depth

Environmental Testing

Tests have also been performed to evaluate the effect of chemical environment on the FRP. The purpose of the chemical exposure tests is used to determine a measure of soil pH on the FRP materials. The first series of tests measured the chemical resistance of S- and E-type fiberglass strands that are typical of those that are used to fabricate the load-bearing overwrap used for the composite pipeline segments. Type S and E glass fiberglass strands were exposed to aggressive chemical environments in order to determine bounds on the base mechanical properties of tensile strength and chemical resistance. These bounds were comparable to technical literature on the subject[31], which have not been chemically exposed. These samples were subjected to solutions of pH 2.4, 7 and 10.6 for periods of either 24 hours or 120 hours (5 days) and then subjected to tensile strength testing using an Istron 4507 Electromechanical System with a strain rate of 200 µm/sec per ASTM C 1557[32].

The test results for glass fiber strands exposed to high and low pH solutions are shown in Figure 11. The red and blue curves in Figure 11 show the results for the untreated E- and S-type samples. As can be seen, mechanical failure typically occurred for the untreated samples below the 3% strain threshold, with the both samples showing reproducibility in the strain point of the initial point of failure. These tests were performed using thread grips and the samples were inspected after testing to ensure that failure occurred in a position not associated with applied stress or pinching at the grip surfaces.

The data in the blue circle provides the failure strain for the chemically exposed samples. It can be seen from a review of the chemically exposed data that the aggressive chemical environments can have a deleterious effect on their mechanical properties of the uncoated glass samples. Additional testing on chemically exposed uncoated glass sample indicated the effect of the chemical environment had resulted in corrosion of glass. Because the glass fibers are epoxy coated in the actual FRP product form, chemical exposure tests were conducted on flawed FRP samples.

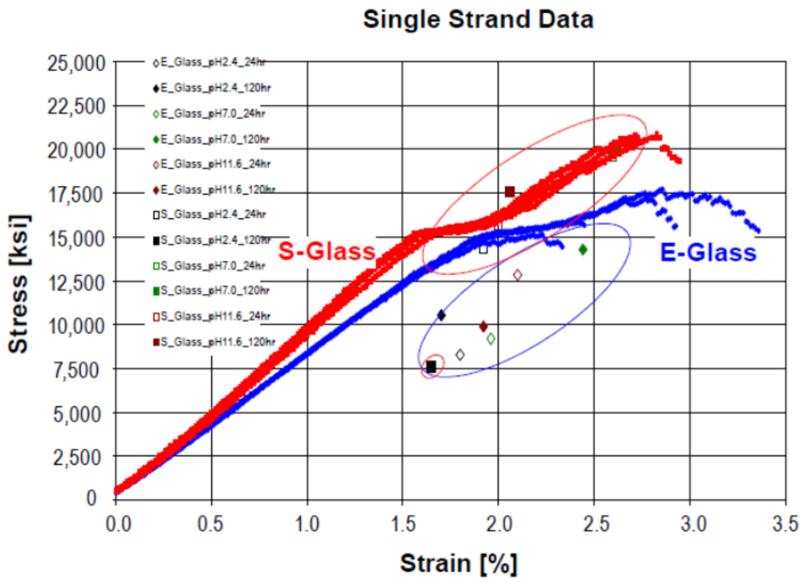

Figure 12 **Environmental Testing Results for Fiber Glass Strand Tensile Testing**

Two FRP samples were exposed to the exposed to the same pH levels for 120 hours and burst tested. The results are shown in Figure 9. The failure pressure for the chemically exposed samples fell within the variability of the unexposed data. The failure pressure for the chemically exposed samples fell within the variability of the unexposed data.

Battelle[33] evaluated fluids found in automotive service, likelihood of exposure, and severity of exposure, and recommended five environmental fluids as a representative worst case exposure for fiber reinforced composite environmental testing. Based on the Battelle report, the automotive fuel container industry developed tests where the container is periodically exposed to sulfuric acid, sodium hydroxide, methanol, gasoline, ammonium nitrate, a surfactant (window washer fluid), and a salt solution with a pH of 4, which is an extreme seen in acid rain. The fluid used in the FRP environmental testing done to date are more extreme in PH levels but to not represent a wide range chemical exposure. The intent of this testing is to provide extreme ends on soil PH levels since FRP will be in underground applications The API 15HR Specification provides recommendation for environmental testing on an as needed basis. Environmental testing should be considered as a requirement for FRP in hydrogen service unless the soil environment is shown to be benign.

Fatigue Testing

Fatigue Testing Fatigue testing of FRP was initiated for FRP during FY 2012 and it is planned to continue this effort during FY 2013. The fatigue testing is directly tied to the FRP life management plan. During FY 2012 fatigue tests were performed on flawed and unflawed specimens

Two fatigue tests have been performed on flawed FRP samples. The FRP samples were cycled with compressed nitrogen at 1,500 psi, which is the rated pressure of the FRP product. The flaw size used for fatigue testing was 1 inch long, 0.125 inch wide, and at a 40% depth into the structural layer. This was the same flaw size as used for the previous flawed burst test. The pressure cycle interval was a minimum of 1 minute with a 30 second hold time at 1,500 psi. The hold time was specified at rated pressure to ensure that the test specimen had a portion of load at levels affecting the creep rupture strength of the fiber. The two flawed samples failed after 2,830 and 4,862 full design pressure cycles.

The failure of the flawed specimen occurred when the existing flaw propagated through the structural glass layer. The specimen started to delaminate at the bottom of the engineered flaw, as shown in Figure 12. When the flaw depth reached the polyethylene liner, loss of the pressure boundary occurred. The thin polymer liner is not intended to be pressure retaining. The pressure load in supported entirely by the glass composite.

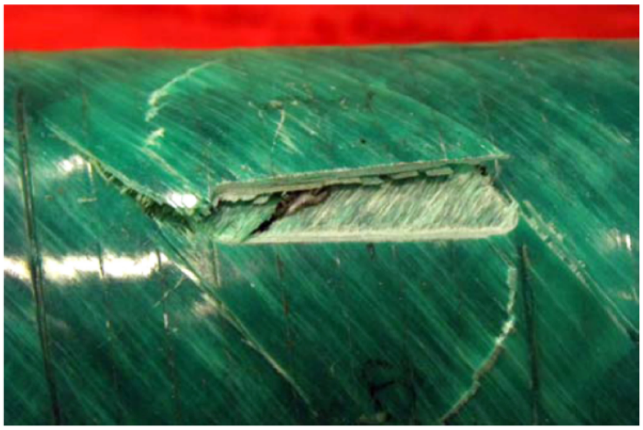

Figure 13 Fatigue Failure Mode on Flawed FRP Fatigue Test

An additional fatigue test was performed on an unflawed FRP sample. The unflawed sample was cycled for 8,077 full design pressure cycles. An 8,000 cycle limit was chosen because it represents a bounding value above the design current fatigue cycle limit for FRP of 20 years at 1 cycle per day. The unflawed sample was then burst tested and failed at 4,935 psi which shows a 22% reduction as compared to previously burst tested unflawed sample without fatigue damage. A photo of the failure location is shown in Figure 13.

The results of these tests show that FRP is susceptible to some level of fatigue damage. At the levels initially measured FRP still offers a viable alternative to metallic piping. The additional tests proposed for FY 2013 will focus on data needs for FRP piping design and codification.B31.12 Codification

Figure 14 Burst Test of FRP Following 8000 Full Pressue Cycle Fatigue Test

Evaluation of Piping Joints

The joints used to connect adjoining section of fiber reinforced piping have been evaluates as part on the DOE project. The connectors are all metallic with elastomer O-ring seal. The photo of the connector is shown in Figure 14. To form the connection the internal diameter of the polyethylene liner is machined to a specified diameter. The machined portion of the liner is where the O-rings in the metallic connector interfaces with the composite piping to form the fluid seal. The outer nut of the connector is tightened to mechanically compress the piping to compress the seals. Testing of the joints has shown that the leak rate is approximately an order of magnitude below permeation rate of the material in a per meter basis.

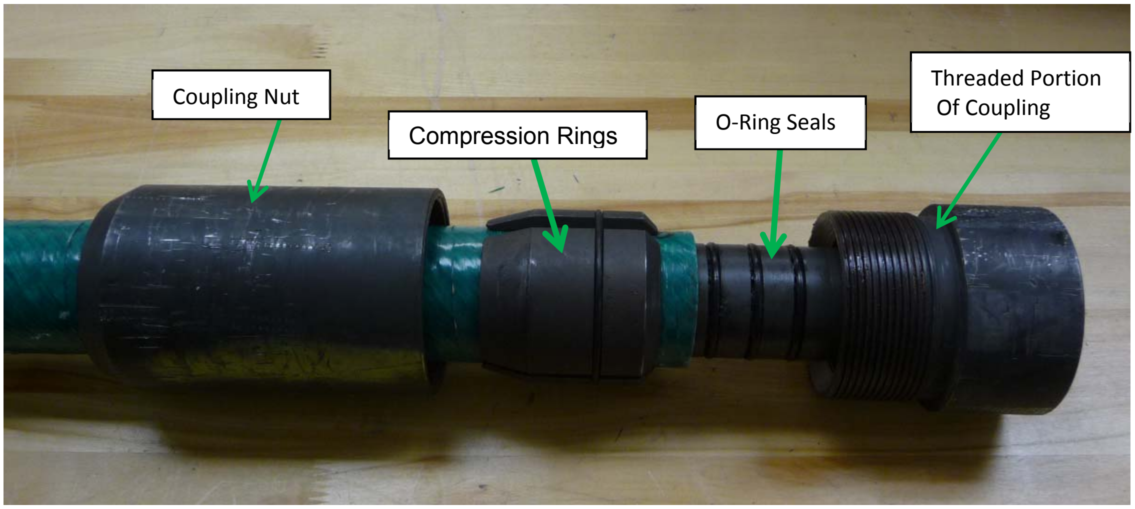

Figure 15 Components of FRP Compression Connector

The metal components are robust with burst strength much higher than the composite piping. When FRP is codified the metallic portions of the connector will be controlled by the existing Code requirements for metallic piping and fittings. Additional evaluation of the structural integrity of the metallic components is not required because the current B12.12 requirements for metal components are acceptable for the FRP metallic joints. The available option for connection of the FRP to metallic piping includes butt welded and ASME B16.5[34] flange connections. There will not be an issue with the available standard connections interfacing with B31.12 piping components.

Extended Design Life for FRP

Current FRP standards are limited to a 20-year design life. Because pipelines are a large capital investment a 20-year design life could be a limiting factor in the FRP application. SRNL has started to investigate extending the current accepted 20-year service life for FRP. Based on the results of the data from the burst test and review of the available creep rupture data for glass fiber there appears to be sufficient design margin to extend the design life for some FRP product from 20 to approximately 50 years. A comparison of the difference in the required design margin between 20 and 50 years is shown in Figure 15. The required decrease in fiber stress is from 0.32 to 0.3, a change of approximately 6%. Other standards are also starting to address increased design life for glass composite. The current draft International Organization for Standardization Standard 15399[35] is proposing a design life of up to 50 years for composite components.

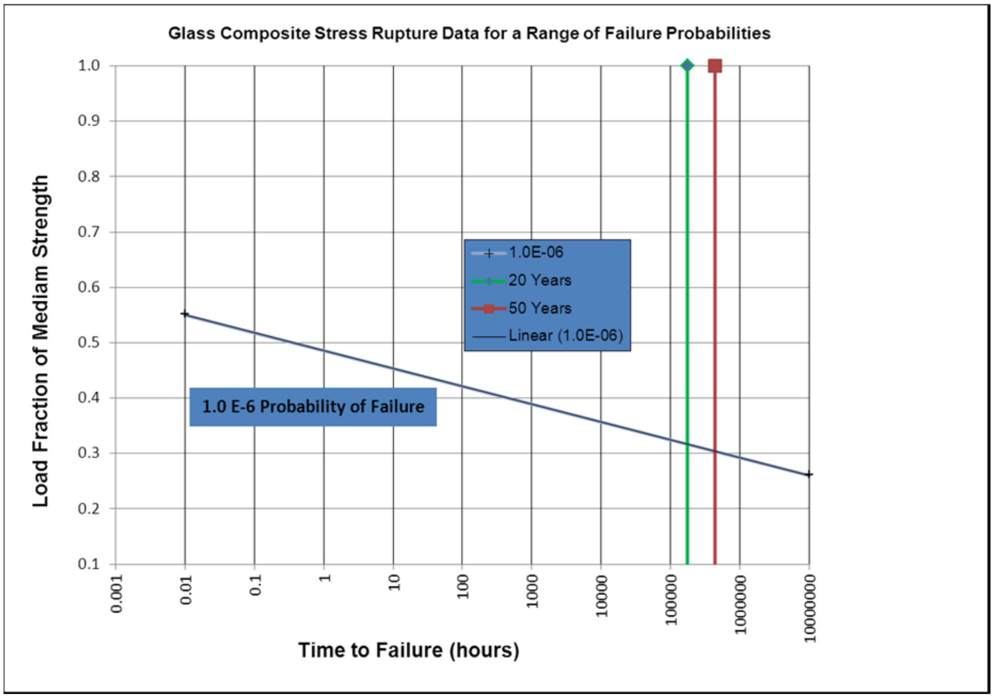

Figure 16 Illustration of Additional Failure Margin requires for Life Extension of FRP

Fabrication Requirements

Additional requirements will not be required in the Code for field fabrication of FRP System if mechanical joints are applies. Current codes and standards recognize the used for manufacturer specific components and the need have specific training and instructions when these types of components are used. ASME B31 Code have generic wording to address these conditions in the sections on special joints. The manufactures supplying proprietary components recognize the need to provide training and instructions specific for their produce and they provide the required training and materials to meet these needs.

If bonded joints are developed for FRP applications then additional requirements will be needed in B31.12. Currently the B31.3 Code, Process Piping Code, contains requirements for bonders. These rules could be used as a basis for any needed requirements on B31.12. The need for bonder qualification requirements would have to be consider for addition onto the Hydrogen Piping Code is bond joints are developed for FRP

Examination Requirements

The Manufacture is responsible for conducting examinations of the fabricated FRP. The FRP must be visually examined for imperfections, including burned areas, chips, cracks, foreign inclusions, pimples, pits, porosity, scratches, wrinkles and creases, and winding defects. The FRP must also be examined for conformance with dimensions, minimum thickness requirements, and tolerances as provided for in the FRP product design. The manufacture's examiner performing visual tests for the FRP manufacture should be qualified to the requirements of ASME B&PV Section V, Article 9. Examiners may also need specific training in concerns specific to fiber reinforced products and specifically defects in fiber reinforced products. Both API 15HR specification and ASME Section X have visual examination acceptance criteria for the fabricated FRP. These criteria can form the basis for the ASME visual examination requirement for FRP at the manufacture's facility.

In addition to the standard examinations required by the ASME B31.12 Code, FRP will need a visual examination of the external surface. The external surface examination is required to ensure that the external surface is free of defects in the structural layer of the fiber reinforcement. The flawed fatigue tests described above indicates that FRP has some vulnerability for surface defects in a fatigue environment. Examination or specific installation procedures will be need to ensure the structural defects eliminated for FRP in cyclic service.

Testing Requirements

Because the FPR Standard is performance based qualification testing is required to confirm the design and manufacturing process of the piping. Qualification test samples must be representative of FRP production. These tests subject the FPR to conditions that may be seen in service. The results of testing and examinations should be documented in the manufactures Qualification Test Report. The following performance tests are proposed for FRP in hydrogen service.

- Hydraulic Proof Pressure Test
- Burst Test
- Fatigue Test
- Temperature Creep Test
- Flaw Test
- Gas Permeability Test
- Leak Test
- Environmental Test

Production tests will be required to ensure that the FRP quality is maintained during manufacturing. A Burst testing to ensure production quality is proposed to be conducted on random samples of FPR. Test failures must be investigated. If there is evidence of a fault in conducting the test, it may be repeated. If the test procedure was proper, the cause of failure must be investigated and corrective action taken, including, if appropriate, removal of some or all FRP since the previous production test.

Inspection

No specific changes are needed to the requirements for the Owner's Inspector function in the B31.12 Code. The Inspectors should have experience with FRP to ensure that the piping system is acceptable for service.

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Appendix A Codes and Standards for Fiber Reinforced Pipe

Standard: API 15HR-2001

TOPIC	DISCUSSION	Section
SCOPE		
*Anything Industry Specific	Pipe used for production of oil and gas	1.2.1
*Above Ground/ Underground/surrounding media	Salt water fluid environment	1.2.2
DESIGN CONDITION		
*Pressure	Standard ratings in 250psi increments over the range of 500-5000psi	4.2
*Temperature	Service temperature is 150F, but higher temperature rating is possible if tested.	1.2.2, 5.1.1
MATERIALS		
*Type of Fiber	Glass Fibers (filament winding or centrifugal casting), No reference Specs listed.	6.1
*Type of Resin	Thermosetting polymers (epoxy resins, polyester resins, vinyl ester resins). No reference Specs listed.	6.2
*Liners	Nothing listed	NA
DESIGN MARGIN		
*Factor on Pressure	0.67 multiplied by composite service design factor composed of factors due to A. Cyclic Pressure, B. Environment, C. Design Life, D. Temperature, E. Axial Loads.	5.1.1, App.G
*How Qualified-Analysis or Performance test	All components, pipe and jointers, are hydro tested to 1.5 times the rated pressure. Performance testing done on components per ASTM D1599.	5.1.4
*Hydrostatic Design Basis (Cold Creep)	95% of Long Term Hydrostatic Strength (LTHS) at 20 years per ASTM D2992 procedure B.	5.1.1
FABRICATION		
*Construction Type continuous or chopped fiber	Joined with fittings that must meet same test criteria as pipe.	5.1
*Bend Radius	not listed	NA
*Joint Types	Threaded and coupled, Threaded ends without couplings, Integral joints, Alternate Pipe Threads.	5.2.3, 5.3

EXAMINATION		
*Anything special for FRP	Visual examination. Defects (pipe and components, threads) described and maximum size listed for acceptance criteria	7.4.1, 7.4.4
*Base material qualification	Degree of Cure determined with Differential Scanning Calorimetry (DSC)	7.4.2
*Joint exam	Visual exam for leaks during hydro.	7.4.1
TESTING		
*Test Type	1.5 times pressure rating used for hydrostatic test	7.4.1
*Leakage Criteria	Acceptance based on no visual weeps or leaks in pipe or components. Additional time based testing used for a statistical population to qualify for long term data.	7.4.4
INSPECTION		
*Specific Training for FRP	None listed for DSC or material properties measurement. ASTM standards listed for other tests would likely have specific training requirements.	NA
MISCELLANEOUS		
*	Service Life is 20 Years and includes cyclic pressure variation	1.2.2
	Other materials than those listed above will be considered for use in the standard when evidence is presented indicating that they are suitable	6.2
	Significant QC tests required based on population including Degree of Cure (1 in 100), Hydro of Joint (1 in 50 held for 10 minutes), short time failure pressure (1 per lot pipe and components), thread gaging (1 per lot)	7.4

Standard: AWWA C950-07

TOPIC	DISCUSSION	Section
SCOPE		
*Anything Industry Specific	Water Distribution/ Gaskets and lube materials should not grow bacteria or affect potable water quality.	1.1/4.4
*Above Ground/ Underground/surrounding media	Above and underground	1.1
DESIGN CONDITION		
*Pressure	50-450psig pressure class based on max sustainable working pressure	4.6
*Temperature	Design based on water temperature of 73.4F (23C), with temperature derating factors to be provided by manufacturer.	4.6

MATERIALS		
*Type of Fiber	Commercial-Grade E-Type glass is reinforcement for pipe wall	1.1
*Type of Resin	Epoxy-resin & Polyester resin	1.1
*Liners	Thermosetting or thermoplastic resin, reinforced or unreinforced, with or without fillers/ type A=no liner, B=thermoplastic, C=reinforced thermoset polyester, D=unreinforced thermoset polyester, E=reinforced thermoset epoxy, F=unreinforced thermoset epoxy.	1.1/4.3
DESIGN MARGIN		
*Factor on Pressure	Design factor of 1.8 used to determine pressure class with elevated temperature and surge pressure accounted for when used in these applications.	4.6
*How Qualified-Analysis or Performance test	Qualified per performance tests	5.1
*Hydrostatic Design Basis (Cold Creep)	Long-term ring-bending strain Sb, based on ASTM D5365 and results extrapolated to 50 years, ASTM D3681 or ASTM D2992 procedure B extrapolated to 50 years.	4.8
FABRICATION		
*Construction Type continuous or chopped fiber	Glass fiber reinforced thermosetting resin pipe (RTRP), glass fiber reinforced polymer mortar pipe (RPMP)/Cell classification given based on type, Grade and Liner. Grade 1=Glass-fiber-reinforced epoxy (RTRP epoxy), Grade 2=Glass-fiber-reinforced polyester (RTRP polyester), Grade 3=Glass-fiber-reinforced epoxy mortar (RPMP epoxy), Grade 4=Glass-fiber-reinforced polyester mortar (RPMP polyester)	1.1/4.3
*Bend Radius	None listed.	NA
*Joint Types	Restrained, unrestrained (can't take longitudinal tension), flexible or rigid, examples include flanged, mechanical couplings, Laminated overlays, etc.	4.9
EXAMINATION		
*Anything special for FRP	Seal of Lab examining pipe used for transporting potable water is required to be on pipe.	4.4
*Base material qualification	None given. QC performance based qualification	4.4 and 5.1.2
*Joint exam	Joint tightness shall meet lab performance requirements of ASTM D4161 section 7, and gaskets shall conform to ASTM F477.	4.9.3
TESTING		
*Test Type	Hydro/Stiffness/Hoop Tensile Strength (ASTM D2290-A, D638, D1599)/Axial Tensile Strength (ASTM D638 or D2105)/Beam Strength (ASTM D3517 or D695)	5.1.2.1/ 5.1.2.2 / 5.1.2.3 / 5.1.2.4 / 5.1.2.5
*Leakage Criteria	No visual leakage or weep when held at twice pressure class for 30 sec.	5.1.2.1.1
INSPECTION		
*Specific Training for FRP	None listed, but that required for ASTM spec implementation would apply.	NA

MISCELLANEOUS		
*	Stiffness classes of 9, 18, 36, 72psi	1.1, 4.7
	Design, Hydraulics and installation reference per AWWA Manual M45	1.1
	Permeation of low molecular weight petroleum products should be considered where this type of pipe is exposed to these contaminants per research obtained for polyethylene, PVC, etc.	
	Construction is similar to API where filament wound, and centrifigully cast are the only two methods listed.	4.3
	Circumferential bending should be accounted for in selection by hydrostatic design pressure class.	4.6

ASME Case N-155-2

TOPIC	DISCUSSION	Section
SCOPE		
*Anything Industry Specific	Class 3 piping, subassemblies, and appurtenances at temperatures limits listed. Materials can't be using in continuous steam service with pressure >5psig	1110
*Above Ground/ Underground/surrounding media	pipe classes in accordance with ASTM D2310, Type I, Grades 1 and 2; classes A, C, E, F and H are permitted./ Buried and aboveground piping applications are permitted per external pressure design parameters	2111.1 / 3133
DESIGN CONDITION		
*Pressure	500psi max for T< 180F, and 250psi max for T up to 250F / Allowable Stress Values provided for straight pipe and fittings.	1110 / 3611.1
*Temperature	180F max for polyester structural wall, and 250F max for epoxy structural wall materials	1110
MATERIALS		
*Type of Fiber	Structural wall shall contain reinforcement embedded in or surrounded by cured thermosetting resin. Composite structure may contain granular or platelet fillers, thixotropic agents, pigments or dyes. / Exterior may be thermosetting resin, thermosetting or thermoplastic coatings or other materials as given. / Glass fiber and organic fiber veil	2211/ 2212 / Appendix II
*Type of Resin	Thermosetting resin for pipe and fittings.	Appendix II
*Liners	thermosetting or thermoplastic resin with minimum of 75% resin by weight per ASTM D2584	2210
DESIGN MARGIN		
*Factor on Pressure	Allowable stress based on internal pressure, weight, thermal expansion and other sustained loads. Allowable tensile design stress is approximately 50% of the Hydrostatic Design Basis strength per table 3611-1.	3611.2b /
*How Qualified-Analysis or Performance test	Qualification test requirements based on bounding assemblies of pipe-to-pipe joints and pipe-to-fitting joints as applicable, and based on pipe diameter.	4220
*Hydrostatic Design Basis (Cold Creep)	Based on code A-Z where A-H are based on min stress to failure in 150M cycles per ASTM D2992 Method A, Q-Z based on min stress to failure in 100K hours by ASTM D2002 Method B.	Table 3611-1

FABRICATION		
*Construction Type continuous or chopped fiber	Pipe has continuous glass roving in circumferential and axial directions, but for axial may also have chopped glass or unidirectional glass tape/ Fittings have many fabrication possibilities. / Mandatory Appendix II gives additional requirements for RTRP.	2111.1 / 2111.2 / Appendix II
*Bend Radius	No restriction listed	NA
*Joint Types	Numerous fitting types allowed, but pressure laminated specifically not allowed / Mandatory Appendix I gives details specifications for fittings	2111.2 / Appendix I
EXAMINATION		
*Anything special for FRP	Fittings per -4000 must be inspected by an authorized Nuclear inspector/ Tables 2900-1A to 2900-4 give visual examination and and repair requirements based specific to inside, structural wall, outside of pipe, and also based on diameter	1210c
*Base material qualification	CMTR required for all materials, and special RTRP-1 form completed for constituent materials / Indication depth <+ 12.5% of required structural wall thickness	2700/ 2900
*Joint exam	Table 2900-4 includes visual exam and repair criteria for fittings 16"D and smaller, 2900-3B covers >16" diameter.	2900
TESTING		
*Test Type	Each batch of joint adhesive requires testing and reporting of data on Form RTRP-2/ Joint leak tests require no leakage when held for 10 minutes at system operating pressure / prior to initial operation testing per ND-6113 is required. ND-6221 hydro test is 1.25 times lowest design pressure. / Appendix II gives HDB test requirement	2310 / 5330 / 6111 / Appendix II
*Leakage Criteria	Assemblies pressurized to 4 times pressure rating, and no leakage or joint separation is permitted.	4220
INSPECTION		
*Specific Training for FRP	Joiners must be qualified/ NDE personnel require qualification	4211 / 5400
MISCELLANEOUS		
*	Definitions per Appendix IV or ASTM D883	1110
	Auxilliary materials classification includes joining or support of pipe of fittings including adhesives, overlay, gaskets, O-rings, lube, and pipe support materials.	2111.3
	washers are mandatory in bolted joints	2330
	Marking required to maintain control during manufacture and construction	2800
	Design per Section III, Division 1, Class 3 requirements of ND-3100 except as modified by Code case.	3000, 3100
	Buried pipe limited to <5% diametrical deflection (may be determined using Bureau of Reclamation Standard No. REC-ERC-77-1)	3133.9
	Service limits A-D permit allowable stress adjustment	3611.2c
	Liner thickness may be considered for corrosion evaluation or allowance	3613

	Wall thickness design based on circumferential and Longitudinal wall stress calculations where the manufacturing tolerance on wall thickness is considered.	3641.1
	Very detailed marking and material tracking required including as-built drawings with material tracability.	4122

ASME B31.1

TOPIC	**DISCUSSION**	**Section**
SCOPE		
*Anything Industry Specific	Coverage per Appendix III limited to pipe in water, non flammable liquid, buried flammable and combustible liquid service, and joints must be adhesively bonded.	105.3
*Above Ground/ Underground/surrounding media	Restricted to underground for flammable and combustible liquid service with flammable liquid temp less than 140F and pressure limit of 150psi. Other non flammable liquid may be above ground. Not permitted for installation in confined spaces where gas build-up due to temperature or flame exposure may occur.	105.3B 122.7.2
DESIGN CONDITION		
*Pressure	150 psi max	105.3, 122.7.2
*Temperature	140F max	105.3, 122.7.2
MATERIALS		
*Type of Fiber		
*Type of Resin		
*Liners		
DESIGN MARGIN		
*Factor on Pressure		
*How Qualified-Analysis or Performance test		
*Hydrostatic Design Basis (Cold Creep)		
FABRICATION		
*Construction Type continuous or chopped fiber		
*Bend Radius		
*Joint Types		
EXAMINATION		
*Anything special for FRP		
*Base material qualification		
*Joint exam		

TESTING		
*Test Type		
*Leakage Criteria		
INSPECTION		
*Specific Training for FRP	Code Compliance Verified by Code Authorized Inspector	136.1.2
MISCELLANEOUS		
*Hydrogen Service	Only acceptable materials are seamless steel with welded joints , seamless copper or brass with brazed, threaded or compression fitting joints.	122.7.3
*Nonmandatory Rules	Nonmetallic pipe design procedure	Appendix III
Standards	AWWA C950 listed as applicable.	Table III-4.1.1

ASME B31.3

TOPIC	DISCUSSION	Section
SCOPE		
*Anything Industry Specific	Scope is piping typically found in petroleum refineries; chemical, pharmaceutical, textile, paper, semiconductor, and cryogenic plants; and related processing plants and terminals.	300.1
*Above Ground/ Underground/surrounding media	Reinforced Thermosetting Resins (RTR) piping shall be safeguarded when used in toxic or flammable fluid services. Table A323.4.2C gives the recommended temperature limits for reinforced thermosetting resins.	A323.4.2
DESIGN CONDITION		
*Pressure	Same as metallic pipe design in Paragraph 301.2 except that references to paras. A302.2.4 and A304 replace references to paras. 302.2.4 and 304, respectively / For non-mettallic piping, allowances for variations of pressure or temperature, or both, above design conditions are not permitted. The most severe conditions of coincident pressure and temperature shall be used to determine the design conditions for a piping system. Variation allowances are permitted for lined pipe with performance data.	A301.2 / A302.2.4
*Temperature	Same as metallic pipe per Paragraph 301.3.1 applies; but see para. A323.2.2, rather than para. 323.2.2. A301.3.2, and for Uninsulated Components.The component design temperature shall be the fluid temperature, unless a higher temperature will result from solar radiation or other external heat sources. / maximum recommended temperature in Table A323.4.2C for RTR materials / material low temperature limits based on testing and listed values	A301.3 / A323.2.1 / A323.2.2

MATERIALS		
*Type of Fiber	Listed materials with design guidance include thermoplastics, RTR laminated, RTR-Filament Wound and RPM-Centrifigally Cast / Listed materials include glass and Carbon	/ Table A323.2.2
*Type of Resin	Listed materials include Epoxy, Phenolic, Furan,	Table A323.2.2
*Liners	May be any material that, in the judgment of the user, is suitable for the intended service and for the method of manufacture and assembly of the piping. Fluid service requirements in para. A323.4.2 do not apply to materials used as linings.	A323.4.3
DESIGN MARGIN		
*Factor on Pressure	When using the cyclic HDBS, the service (design) factor F shall not exceed 1.0. When using the static HDBS, the service (design) factor F shall not exceed 0.5.	A302.3.2
*How Qualified-Analysis or Performance test	Analysis results can be qualified with performance testing or demonstrated successful experience data is permitted for qualification.	A304.7.2
*Hydrostatic Design Basis (Cold Creep)	Based on ASTM D 2992 including design factor	A302.3.2
FABRICATION		
*Construction Type continuous or chopped fiber	NA	
*Bend Radius	For bends with external pressure, minimum required thickness after bending must be same as straight pipe required thickness.	A304.1.3, 332
*Joint Types	For RTR: Adhesive, Butt-and-wrapped	A328.5.6 / A328.5.7
EXAMINATION		
*Anything special for FRP	NA	
*Base material qualification	Materials and components in accordance with code para. 341.4.1(a)(1).	A341.4.1
*Joint exam	Acceptance criteria per Table A341.3.2 / Normal fluid service examination requires additional visual inspection with %inspected based on the type of joint	A341.3.2 / A341.4.1
TESTING		
*Test Type	Hydrostatic leak required at no less than 1.5 times the design pressure, but not more than 1.5 the Max pressure of the lowest rated component. Pneumatic testing may be performed with Owner's approval. / Category D requires initial service leak test using the service fluid.	A345 / 345.7
*Leakage Criteria	Leak test shall be maintained for at least 10 min, and all joints and connections shall be examined for leaks.	345.2.2

INSPECTION		
*Specific Training for FRP	Inspector shall have not less than 10 y experience in the design, fabrication, or inspection of industrial pressure piping. Each 20% of satisfactorily completed work toward an engineering degree recognized by the Accreditation Board for Engineering and Technology (Three Park Avenue, New York, NY 10016) shall be considered equivalent to 1 y of experience, up to 5 y total. No specific requirements for FRP. Inspector is responsible for determining that a person to whom an inspection function is delegated is qualified to perform that function.	340.4
MISCELLANEOUS		
*Applicable code section	Covered in Chapter VII, and makes no provision for severe cyclic use.	Chapter VII
*Designer Considerations	Adequacy and manufacture of nonmetallic material must consider, at a minimum, (a) tensile, compressive, flexural, and shear strength, and modulus of elasticity, at design temperature (long term and short term) (b) creep rate at design conditions (c) design stress and its basis (d) ductility and plasticity (e) impact and thermal shock properties (f) temperature limits (g) transition temperature: melting and vaporization (h) porosity and permeability (i) testing methods (j) methods of making joints and their efficiency (k) possibility of deterioration in service	A302.1
*Exclusions	Code excludes the following:(a) piping systems designed for internal gage pressures at or above zero but less than 105 kPa (15 psi),provided the fluid handled is nonflammable, nontoxic, and not damaging to human tissues as defined in 300.2, and its design temperature is from −29°C (−20°F) through 186°C (366°F)(b) power boilers in accordance with BPV Code2 Section I and boiler external piping which is required to conform to B31.1(c) tubes, tube headers, crossovers, and manifolds offired heaters, which are internal to the heater enclosure (d) pressure vessels, heat exchangers, pumps, compressors, and other fluid handling or processing equipment, including internal piping and connections for external piping	300.1.3
*Unlisted Components	May be qualified using extensive successful service or performance testing.	A304.7.2

ASME B31.8

TOPIC	DISCUSSION	Section
SCOPE		
*Anything Industry Specific	Covers the design, fabrication, installation, inspection, and testing of pipeline facilities used for the transportation of gas. / Location class defines buildings and occupancy proximate to pipeline, and governs factors used in design. / Not to be used for offshore lines	802.1 / 805.111 / A814.1
*Above Ground/ Underground/surrounding media	May be used above ground, or buried per listed restrictions, some of which include locations, and adding a metal jacket pipe.	842.43

DESIGN CONDITION		
*Pressure	Limited to 100 psi or less for all location classes / Fitting design pressure shall be same as that for pipe of same diameter	842.33 / 842.34
*Temperature	For RTR, Temperature can't be higher than temp used to obtain long-term hydrostatic strength./ can't be used for operating temp less than -20F or greater than 150F	842.31 / 842.33
MATERIALS		
*Type of Fiber	Limited to pipe and fittings manufactured per ASTM D 2517	814.13
*Type of Resin	Limited to pipe and fittings manufactured per ASTM D 2517	814.13
*Liners	NA	
DESIGN MARGIN		
*Factor on Pressure	Pipe specification based on size (diameter and thickness) with a given strength of 11000 psi based on hydrostatic design basis pressure of 15KSI factored by 0.72.	840.41
*How Qualified-Analysis or Performance test	Qualified by leak test at <3 times Design Pressure for RTR	842.52
*Hydrostatic Design Basis (Cold Creep)	Defined as hoop stress in pounds per square inch in a plastic pipe wall that will cause failure of the pipe at an average of 100,000 hr when subjected to a constant hydrostatic pressure. / Long-Term Hydrostatic Strength for Reinforced Thermosetting Pipes Covered by ASTM D 2517 is 11,000 psi. The values apply only to materials and pipes meeting all the requirements of the basic materials and ASTM D 2517. They are based on engineering test data obtained in accordance with ASTM D 1599 and analyzed in accordance with ASTM D 2837.	805.133 / Appendix D
FABRICATION		
*Construction Type continuous or chopped fiber	per ASTM D 2517 is limited to Filament Winding	
*Bend Radius	Plastic pipe and tubing may be deflected to a radius not less than the minimum recommended by the manufacturer for the kind, type, grade, wall thickness, and diameter of the particular plastic used.	842.44
*Joint Types	No threaded joints, solvent cement, heat-fusion, mechanical, and adhesive are all permitted.	842.392
EXAMINATION		
*Anything special for FRP	No mention	
*Base material qualification	No mention	
*Joint exam	Visual field inspection described in general terms, but no ASTM reference or other requirements.	842.421

TESTING		
*Test Type	Installed system shall be leak tested, and while tie-in piping does not require testing, tie-in joints do / RTR piping shall not be tested at material temperatures above 150°F. The test pressure for reinforced thermosetting plastic piping shall not exceed 3.0 times the design pressure of the pipe. Gas, air, or water may be used as the test medium.	842.51 / 842.52
*Leakage Criteria	No leak.	842.51
INSPECTION		
*Specific Training for FRP	No mention	
MISCELLANEOUS		
	Pipe must be transported in accordance with API RP5L1 or API RP5LW. Where it is not possible to establish that pipe was loaded and transported in accordance per the APIs, the pipe shall be hydrostatically tested for at least 2 hr to at least 1.25 times the maximum allowable operating pressure if installed in a Class 1 location; or to at least 1.5 times the maximum allowable operating pressure if installed in a Class 2, 3, or 4 location.	816
	Used RTR pipe may be used if it meets the requirements of ASTM D 2513 for new thermoplastic pipe or tubing, or ASTM D 2517 for new thermosetting pipe (b) a careful inspection indicates that it is free of visible defects (c) it is installed and tested in accordance with the requirements of this Code for new pipe.	817.3
	Location classes 1-4, for design, defined	840.22
	Design of Plastic pipe material specific section	842.3
	Table 842.33(c) gives required diameter and wall thickness for RTR pipe	

ISO 14692

TOPIC	DISCUSSION	Section
SCOPE		
*Anything Industry Specific	Glass reinforced piping standard for oil and natural gas industries. Primarily intended for offshore applications, but may also be used for high criticality onshore chemical systems. / Limited to t/D=<0.1	(-1)5.1 / (-2) 5.5
*Above Ground/ Underground/surrounding media	Offshore and onshore. Not specifically intended for buried pipelines, but it is noted that it may be adapted for pipeline applications.	(-1)5.2
DESIGN CONDITION		
*Pressure	All components are assigned a "qualified pressure=Pq" which is based on a 20-year long term performance of pipe with unrestrained ends. The maximum design pressure, Pdmax, is then obtained by factoring Pq using a factor for installation conditions, failure consequences, operational sustained loads, and another factor for axial loading. / Full detailed design considerations, including all loads, and requirements in section 3 of code.	(-1) 8.0 / (-3)
*Temperature	Recommended Maximum temperature is based on resin type with a maximum of 150C for phenolic resin. Min recommended temp is -35C	(-1)'6.0
MATERIALS		
*Type of Fiber	Principal reinforcement material of the component wall shall be glass fibre, e.g. continuous and woven rovings, but other reinforcement permitted based on agreement by principal (prjoject technical lead). / Glass fibre is the preferred reinforcement material because there is little information available about the longterm pressure retention, impact and fire performance of pipes manufactured from other reinforcement materials such ascarbon or aramid fibre.	(-1)6.0 / (-2) 5.2
*Type of Resin	Limited to the manufacture of rigid components made from fibre-reinforced thermosetting resins. Typical resins are epoxy, polyester, vinyl ester and phenolic. Thermoplastic resins are excluded.	(-1) 6.0
*Liners	Code is not applicable to pipe systems that incorporate internal thermoplastic or elastomeric liners because such materials may introduce significant changes in performance characteristics of the GRP piping.	(-1) 6.0

DESIGN MARGIN		
*Factor on Pressure	Qualified pressure is factored to account for temperature and chemical conditions to obtain Pqf. System design pressure, Pd, is then calculated using the same factors used for the maximum design pressure, but with the qualified pressure (Pd=f1xf2xPqf).	(-1) 8.0
*How Qualified-Analysis or Performance test	Full test qualification procedure is supplied to obtain the qualified pressure experimentally, and then calculation used to get 20 year value. / Other design life values may be obtained by calculation	(-2) 6.2.3 / (-2) 6.2.7
*Hydrostatic Design Basis (Cold Creep)	Based on ASTM-D2992 and -D1598 testing to get the qualified pressure.	(-2) 6.2.2
FABRICATION		
*Construction Type continuous or chopped fiber		
*Bend Radius	The standard bend radius should be 1.5 times the nominal diameter, but other sizes are acceptable with agreement of the principal.	(-2) 7.2
*Joint Types	Principal joint types include, but are not limited to, a) adhesive/resin for bonded/laminated joints; and, b) mechanical joints.	(-2) 5.4.1
EXAMINATION		
*Anything special for FRP	NA code is for FRP only	
*Base material qualification	Degree of cure shall be determined in accordance with the procedures given in (-2) 6.8.2. Other measurements, if applicable include Residual styrene monomer content, and Barcol hardness.	(-2) 6.8.2
*Joint exam	Falls under entire pipe assembly qualification and examination. Visual Inspection details are provided	(-4) 5.7
TESTING		
*Test Type	Detailed hydrostatic test steps given for various conditions that include different test pressures used for QC at mill. / Flushing required for all systems that require pressure testing. The test hydrostatic test pressure is the lower of 1.5 Design pressure or 0.89 qualified pressure where pressure is increase to test pressure over a period of 30 minutes or longer.	(-2) 8.3.2 / (-4) 5.6
*Leakage Criteria	The system shall be considered to have passed the hydrotest if there is no leaking or weeping of water from the piping and there is no significant pressure loss that cannot be accounted for by usual engineering considerations, e.g. thermal expansion of pipe, or other factors previously agreed with the principal.	(-4) 5.6

INSPECTION		
*Specific Training for FRP	Pipe bonder and inspector certification for installation provided	(-4) 5.4.1
MISCELLANEOUS		
	Standard broken into four parts 14692-1 includes definitions and materials, -2 is Qualification & manufacture, -3 is design, -4 is fabrication/installation/operation	(-1)Intro
	Typical fluid applications provided, and include many hazardous fluids and gases.	(-1)5.1
	ISO 14692 covers all the main components that form part of a GRP pipeline and piping system (pipe, bends, reducers, tees, supports, flanged joints) with the exception of valves and instrumentation.	(-1)7.0
	Envelope of thickness to diameter ratio piping that fits within code envelope is provided in Figure 1.	(-1)'7.0
	Detailed QC inspection procedure provided	(2) 8.3
	Parts used for qualification testing shall not be used in the pipe system.	(-2) 6.1
	Addtional details provided for issues like maintenance and repair after the onset of operations are provided.	(-4) 6.0

ASTM Standards

ASTM	Coverage
C581	This practice is designed to evaluate, in an unstressed state, the chemical resistance of thermosetting resins used in the fabrication of reinforced thermosetting plastic (RTP) laminates. This practice provides for the determination of changes in the properties, described as follows, of the test specimens and test reagent after exposure of the specimens to the reagent: hardness of specimens, weight change thickness, appearance of specimens, appearance of immersion media, and flexural strength and modulus.
C582	Covers composition, thickness, fabricating procedures, and physical property requirements for glass fiber reinforced thermoset polyester, vinyl ester, or other qualified thermosetting resin laminates comprising the materials of construction for RTP corrosion-resistant tanks, piping, and equipment. This specification is limited to fabrication by contact molding.
D149	Covers procedures for the determination of dielectric strength of solid insulating materials at commercial power frequencies, under specified conditions.
D257	Cover direct-current procedures for the measurement of dc insulation resistance, volume resistance, and surface resistance. From such measurements and the geometric dimensions of specimen and electrodes, both volume and surface resistivity of electrical insulating materials can be calculated, as well as the corresponding conductances and conductivities.
D638	Covers the determination of the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens when tested under defined conditions of pretreatment, temperature, humidity, and testing machine speed. For thickness of 1-14mm
D695	Covers the determination of the mechanical properties of unreinforced and reinforced rigid plastics, including high-modulus composites, when loaded in compression at relatively low uniform rates of straining or loading.
D696	Covers determination of the coefficient of linear thermal expansion for plastic materials having coefficients of expansion greater than 1 3 10−6/°C by use of a vitreous silica dilatometer.
D790	Cover the determination of flexural properties of unreinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars molded directly or cut from sheets, plates, or molded shapes.
D792	These test methods describe the determination of the specific gravity (relative density) and density of solid plastics in forms such as sheets, rods, tubes, or molded items.
D1598	Covers the determination of the time-to-failure of both thermoplastic and reinforced thermosetting/resin pipe under constant internal pressure.
D1599	Covers the determination of the resistance of either thermoplastic or reinforced thermosetting resin pipe, tubing, or fittings to hydraulic presssure in a short time period. Procedure A is used to determine burst pressure of a specimen if the mode of failure is to be determined. Procedure B is used to determine that a specimen complies with a minimum burst requirement.
D2105	Covers the determination of the comparative longitudinal tensile properties of fiberglass pipe when tested under defined conditions of pretreatment, temperature, and testing machine speed. Both glass-fiber-reinforced thermosetting-resin pipe (RTRP) and glass-fiber-reinforced polymer mortar pipe (RPMP) are fiberglass pipes.
D2143	Covers the determination of the failure characteristics of reinforced plastic pipe when subjected to cyclic internal hydraulic pressure. It is limited to pipe in which the ratio of outside diameter to wall thickness is 10:1 or more.
D2310	Classification covers machine-made “fiberglass” (glass-fiber-reinforced thermosetting-resin) pressure pipe. Methods of classification, requirements, test methods and the method of marking are included.

ASTM	Coverage
D2412	Covers the determination of loaddeflection characteristics of plastic pipe under parallel-plate loading.
D2444	Covers the determination of the impact resistance of thermoplastic pipe and fittings under specified conditions of impact by means of a tup (falling weight). Three interchangeable striking noses are used on the tup, differing in geometrical configuration. Two specimen holders are described.
D2583	Covers the determination of indentation hardness of both reinforced and nonreinforced rigid plastics using a Barcol Impressor, Model No. 934-1 and Model No. 935.
D2584	Covers the determination of the ignition loss of cured reinforced resins. This ignition loss can be considered to be the resin content within specified limits.
D2924	Covers determination of the resistance of fiberglass pipe to external pressure. It classifies failures as buckling, compressive, and leaking.
D2925	Covers measurement of the deflection as a function of time of a specimen of fiberglass pipe supported on a flat non-arced support as a simple beam under full bore flow of water at elevated temperatures.
D2992	Establishes two procedures, Procedure A (cyclic) and Procedure B (static), for obtaining a hydrostatic design basis (HDB) or a pressure design basis (PDB) for fiberglass piping products, by evaluating strength-regression data derived from testing pipe or fittings, or both, of the same materials and construction, either separately or in assemblies.
D2996	Covers machine-made reinforced thermosetting resin pressure pipe (RTRP) manufactured by the filament winding process up to 24 in. nominal size. Included are a classification system and requirements for materials, mechanical properties, dimensions, performance, methods of test, and marking.
D2997	Covers machine-made glass-fiberreinforced thermosetting-resin pressure pipe manufactured by the centrifugal casting process. Included are a classification system and requirements for materials, mechanical properties, dimensions, performance, test methods, and marking.
D3262	Covers machine-made fiberglass pipe, 8 in. (200 mm) through 156 in. (4000 mm), intended for use in gravity-flow systems for conveying sanitary sewage, storm water, and some industrial wastes.
D3517	Covers machine-made fiberglass pipe, 8 in. (200 mm) through 156 in. (4000 mm), intended for use in water conveyance systems which operate at internal gage pressures of 450 psi (3103 kPa) or less. The standard is suited primarily for pipes to be installed in buried applications, although it may be used to the extent applicable for other installations such as, but not limited to, jacking, tunnel lining and slip-lining rehabilitation of existing pipelines.
D3567	Covers the determination of outside diameter, inside diameter, total wall thickness, reinforced wall thickness, liner thickness (where applicable), and length dimensions of “fiberglass” (glass-fiber-reinforced thermosetting resin) pipe. Included are procedures for measuring tapered dimensions and taper angles for pipe intended to be joined by tapered socket fittings, and procedures for gaging internal and external threads.
D3615	test method provides a means for measuring the resistance of press-molded thermoset molding materials to various chemical reagents for a specified period of time at both room temperature and elevated temperatures.
D3681	Covers the procedure for determining the chemical-resistant properties of fiberglass pipe in a deflected condition for diameters 4 in. (102 mm) and larger. Both glass–fiber–reinforced thermosetting resin pipe (RTRP)
D3754	Covers machine-made fiberglass pipe, 8 in. (200 mm) through 156 in. (4000 mm), for use in pressure systems for conveying sanitary sewage, storm water, and many industrial wastes, and corrosive fluids. Pipe covered by this specification is intended to operate at internal gage pressures of 450 psi (3103 kPa) or less.

ASTM	Coverage
D3840	Covers fiberglass pipe fittings intended for use in gravity flow systems for conveying sanitary sewage, storm water, and those industrial wastes for which the fittings are determined to be suitable. This specification is intended to cover only dimensions, material properties, and workmanship rather than the structural design of the fittings.
D4024	Covers reinforced-thermosetting resin flanges other than contact-molded flanges. Included are requirements for materials, workmanship, performance, and dimensions.
D4161	Covers axially unrestrained bell-andspigot gasket joints including couplings required for machinemade “fiberglass” (glass-fiber-reinforced thermosetting-resin) pipe systems, 8 in. (200 mm) through 144 in. (3700 mm), using flexible elastomeric seals to obtain soundness. The pipe systems may be pressure (typically up to 250 psi) or nonpressure systems for water or for chemicals or gases that are not deleterious to the materials specified in this specification. This specification covers materials, dimensions, test requirements, and methods of test.
D5365	Covers a procedure for determining the long-term ring-bending strain (Sb) of “fiberglass” pipe.
D5421	Covers circular contact-molded fiberglass reinforced-thermosetting-resin flanges for use in pipe systems and tank nozzles. Included are requirements for materials, workmanship, performance, and dimensions.
D5677	Covers a reinforced plastic pipe and fittings system made from epoxy resin and glass-fiber reinforcement, together with adhesive for joint assembly, intended for service up to 150°F (65.6°C) and 150-psig (1034-kPa) operating pressure and surges up to 275 psig (1896 kPa) in aviation jet turbine fuel lines installed below ground.
D5685	Covers “fiberglass” (glass-fiberreinforced thermosetting-resin) fittings for use with filament wound or centrifugally cast fiberglass pipe, or both, in sizes 1 in. through 24 in. for pipe manufactured to Specification D 2996 or D 2997, or both.
D6041	Covers pipe and fittings fabricated by contact molding, for pressures to 150 psi and made of a commercial-grade polyester resin. Included are requirements for materials, properties, design, construction, dimensions, tolerances, workmanship, and appearance.
E228	Covers the determination of the linear thermal expansion of rigid solid materials using push-rod dilatometers. This method is applicable over any practical temperature range where a device can be constructed to satisfy the performance requirements set forth in this standard.
F1173	Covers reinforced thermosetting resin pipe systems with nominal pipe sizes (NPS) 1 through 48 in. (25 through 1200 mm) which are to be used for all fluids approved by the authority having jurisdiction in marine piping systems.