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1 EXECUTIVE SUMMARY

This manual provides detailed engineering data for FlexSteel flexible steel pipe. This is an API 17J type pipe that has been specifically customized to target onshore use in applications ranging from tundra to desert to swamp or other bodies of shallow water. The pipe design has been optimized for cost competitiveness, while retaining the key features of traditional flexible steel pipe. These features include the ease of installation typical of long length spoolable flexible products, long life, high reliability, and internal and external corrosion resistance. FlexSteel pipes can be deployed by stringing lengths of pipe and either leaving them exposed or burying them below grade. In addition, they are suited to pull-in applications, installed either with directional boring or pulled through long lengths of existing pipeline for rehabilitation purposes.

This manual presents an engineering description of the FlexSteel pipe including general design information, related standards and codes, pipe capabilities including chemical compatibility, acceptance testing, pipe stress and strain analysis, on-bottom stability, cathodic protection, packaging and ancillary equipment data, reel handling and installation considerations including cold weather, pipe commissioning and maintenance, and pipe qualification. Operating instructions and limitations provided in Section 4, Pipe Capabilities, are mandatory to prevent damage to the pipe and maintain warrantee coverage.

Conclusions include:

- Flexible pipes are a proven product with extensive field experience, built to widely accepted API and ASTM standards using well understood design methodologies. Prime Flexible Products has earned the API 17J monogram on its flexible steel pipes.
- FlexSteel un-bonded flexible pipe has capabilities optimized for onshore use. It combines features typical of flexible steel products with competitive installed cost. The compact swaged carbon or stainless steel end fittings are rapidly installed under factory or field conditions.
- Extensive testing has been conducted to verify and characterize the performance of the FlexSteel pipes and end fittings, and to qualify them for service.

2 INTRODUCTION

This manual provides engineering data on FlexSteel flexible steel pipes. It presents background information and the design and range of pipe sizes and pressure ratings in this product line. FlexSteel pipe has been developed to bring the advantages of flexible steel pipe to the onshore pipeline market. The pipe and end fitting designs are presented in depth, relevant standards and codes are reviewed, and pipe properties and definitions are detailed. The FlexSteel pipe largely complies with API requirements, and the variations from current API requirements are indicated.

This report provides general pipe design information including pressurization/depressurization rates, operational temperature, environmental exposure, minimum bend radius, and handling recommendations. Specific data for each design is provided on the relevant Customer Data Sheet (CDS). Compatibilities of both PE and steel with conveyed fluids and permeated components are detailed. Brief sections provide on-bottom stability, gas permeation, and cathodic protection information.
Operating and maintenance considerations are documented, such as pipe commissioning, packaging and ancillary equipment, reel handling, and pipe installation including cold weather handling.

A qualification section details the applicable API definitions, has a general discussion of similarities and differences between the new product and previously qualified pipes, indicates the API 17 qualification testing required, reviews the tests used in qualification, defines the design methodology used, and lists the key qualification testing planned.

The handling and use of the pipe must be limited to the design conditions and considerations specified in this manual to avoid possible damage to the thermoplastic and metallic layers of the pipe, and to the end fittings. The instructions and recommendations contained herein are to be used as a general guide to aid the operator in developing detailed written procedures for conducting normal, abnormal and emergency operations and maintenance activities. Nothing written or implied in this manual is intended to supersede the contractual requirements or the use of sound engineering judgment or good operational practice. Warranty provisions as specified in the contract will apply as appropriate. Questions pertaining to product operational limitations should be directed to Prime Flexible Products.

3 FLEXSTEEL PIPE DESCRIPTION

This section documents the general issues driving the development of the FlexSteel pipe, indicates the range of pipes currently offered, references the customer datasheets, reports pipe properties and related definitions, summarizes the pipe layer materials and functions, and presents the end fitting designs. FlexSteel pipe

3.1 Background

Flexible steel pipes have extensive offshore experience, with many thousands of kilometers of installed pipes demonstrating exceptional reliability over decades of use in very demanding service. Applications range from static flowlines, with some buried and some lying exposed on the sea bottom, to deepwater dynamic risers that connect constantly moving floating vessels to fixed seabed facilities.

A high capability onshore pipe was developed in 1995 using mostly standard offshore oriented technology. A 2nd generation onshore design was shipped in 1999, featuring further refined and simplified pipe and end fitting designs, but still using mostly standard offshore technology. These insulated pipes were both targeted for tundra applications and functioned well, but had difficulty competing with steel pipes on an installed cost basis.

The FlexSteel pipe is a 3rd generation design optimized to combine key flexible pipe features with cost competitiveness with rigid steel pipe, and targeting onshore applications in locations ranging from tundra to desert to swamp and other shallow bodies of water.

The former owners of FlexSteel, Wellstream International Limited, conducted significant research and development in the area of bonded reinforced thermoplastic pipes resulting in an aramid (Kevlar®) fiber reinforced structure. Because of the issues associated with stress rupture behavior of aramid and fiberglass reinforced polymer structures and degradation of glass fibers when exposed to some environments (especially salt water), it was concluded that a steel-reinforced, un-bonded structure is the most reliable and economically viable spoolable product for both onshore and offshore applications.
3.1.1 Flexible Steel Pipe Features and Applications

Flexible pipe has a number of features that result in better performance and lower cost than steel pipe. Chief among these is the ease of installation and recovery typical of spoolable flexible products. The long pipe lengths minimize the number of welds or connections, aiding in maximizing reliability. FlexSteel pipe has internal and external corrosion resistance for long life, generally eliminating the corrosion inhibitors, cathodic protection systems, and periodic inspections required for steel pipes. The thermoplastic layers provide FlexSteel pipe with thermal insulating properties far superior to steel pipe. Its superior flow characteristics result from the low internal flow friction factor inherent in the smoothbore design, augmented by the thermal insulating properties that retain heat, minimizing viscosity of the conveyed fluid. In addition to the low installation costs, FlexSteel pipe has low operating costs because of its high reliability, long life, and low maintenance. FlexSteel pipe has the lowest installed and operating cost per pressure capability of any spoolable product.

FlexSteel pipe is easily installed below grade using traditional trenched technology or plowing. It is also ideal for trenchless installations, such as directional drilling applications, or for rehabilitation applications in which the pipe is pulled through deteriorated conventional steel lines. FlexSteel pipe is particularly attractive for rehabilitation because it has its own inherent pressure retaining capability, and does not depend on the structural integrity of the pipelines through which it is pulled. Trenchless applications minimize environmental impact by reducing encroachment on property for installation.

FlexSteel pipe can also be installed above ground. With additional insulation, it is ideal for environmentally sensitive applications, such as the tundra, where exposed lines can be installed with minimal infrastructure such as supports, and in many cases, can be installed without roads. For desert applications, an optional white UV resistant outer shield is available that is designed for long term exposure to high intensity solar radiation.

FlexSteel pipe is often used for oil and gas production flowlines, water or gas injection lines, and civil or military water and fuel transfer lines. Related uses include utility applications such as gas transmission lines, water distribution lines, pumped sewage lines where more than a few bar of pressure capability is required, and mining and agricultural applications.
Figure 3-1 Typical Above Ground Flexible Pipe Applications

Figure 3-1 shows flexible pipe in a marsh application and a flexible pipe in a desert application. These above ground applications contrast the ease of routing flexible pipe which are simply strung into position with typical installations for steel pipes that require multiple supports and elbows.

3.2 Pipe Design Range

Current standard pipe designs are listed in Table 3-1. FlexSteel Customer datasheets for each design are available which report the calculated physical properties of the pipe structures in SI and US Customary units. The designs are prepared using proprietary software which calculates the physical properties based on analytical formulae supported by comprehensive empirical test data.

Table 3-1 Summary of Current Pipe Designs

<table>
<thead>
<tr>
<th>Pipe Size</th>
<th>750 psi (5,150 kPa)</th>
<th>1,000 psi (6,890 kPa)</th>
<th>1,500 psi (10,300 kPa)</th>
<th>2,250 psi (15,500 kPa)</th>
<th>3,000 psi (20,600 kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-inch</td>
<td></td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>3-inch</td>
<td>•</td>
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<td>•</td>
<td>•</td>
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<tr>
<td>4-inch</td>
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<td>•</td>
</tr>
<tr>
<td>6-inch</td>
<td>•</td>
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</table>

The standard FlexSteel pipe bores approximately match those of schedule 80 steel pipe. The pressure ratings match ANSI classes for compatibility with other components, such as valves and flanges. In addition to the standard product line, custom designs with pressure and diameter optimized for specific project requirements are possible. Contact a FlexSteel sales representative to determine pricing and delivery for custom builds.
3.3 Flexible Steel Pipe Standards

Two types of standards are common for flexible steel pipes: design and manufacturing standards, and national codes.

3.3.1 Flexible Steel Pipe Design and Manufacturing Standards

Recognized industry norms for flexible steel pipes have been developed by the American Petroleum Institute (API). These include API 17J [1], API 17K [2], and API RP 17B, [3]. API 17J is a specification for un-bonded flexible steel pipe. API 17K is a bonded steel flexible pipe specification that is, other than end fitting requirements and some bonded pipe requirements, nearly identical to API 17J. API RP 17B is a recommended practice for testing and qualification of flexible steel pipe bought to either API 17J or 17K. ISO 13628-2 [4] is an ISO document based on API 17J using identical numbering for most sections. The companion recommend practice document is ISO 13628-11 [5] used in the same manner that API 17J references API 17B.

The development of these documents has historically been driven primarily by the offshore market, but they are also applicable to topside and onshore applications. These specifications and recommended test methods have been developed with customer, supplier, and oil company input, have been successfully used for many years, and are widely accepted by a variety of suppliers and purchasers.

3.3.1.1 FlexSteel Pipe Conformance to API Documents

The pipe design and materials for FlexSteel pipe conform to most requirements of API 17J. The most important area is that the FlexSteel pipe complies with the design methodology and design factors demonstrated over decades of service on API 17J compliant products. The carbon steel strip material has been qualified to API 17J and the bi-modal HDPE resin in accordance with ASTM D3350 [6] has been commonly specified for oil and gas pipelines for many years. The swaged end fittings used for FlexSteel pipes are designed similar to the simpler and smaller API 17K type end fitting, rather than the large and complex API 17J type end fittings, as noted in Section 3.6.

Because the FlexSteel pipe is a relatively new product, there are some deviations from the API 17J requirements. Some of these deviations result because the FlexSteel pipe is a new variant of un-bonded flexible steel pipe, and the API 17 recommended practice and standards have not yet been updated to reflect certain characteristics of the new FlexSteel pipe. Specifically, API 17B currently classifies un-bonded and bonded flexible steel pipes into five types, referred to as “product families” (4.3.4.1 Table 1 and 4.3.4.2 Table 2). FlexSteel pipe combines features of the un-bonded smoothbore Product Family I and un-bonded rough bore Product Family II, which has no pressure armor. The construction is analogous to the bonded smoothbore Product Family IV.

FlexSteel is not a bespoke product like traditional flexible pipes utilized in the offshore oil and gas industry. It is intended to be a “off the shelf” type product and as such some of the routine API 17J materials and nondestructive testing, design methodology, and Independent Verification Agent reviews are not typically performed. For example, the extensive ultrasonic, liquid dye penetrant and magnetic particle testing required on API 17J end fitting components are not standard on the swaged end fittings.

A new standard, ASTM F2805 [7], has been developed for flexible steel pipe that maintains the API 17J design criteria but is better suited for an off the shelf product intended for onshore and shallow water applications.
3.3.2 Onshore Flexible Steel Pipe National Codes

Most countries have codes to which new pipeline installations are required to comply. In the United States, certain sections of US Code of Federal Regulations apply and specify compliance with ASME B31.4 [8] for pipelines transporting most hydrocarbons and ASME B31.8 [9] for pipelines distributing natural gas. In Canada, these types of pipelines are controlled by CSA Z662 [10]. Clause 13 of this specification has been updated to specifically include flexible steel pipes to allow the use of routine Permits to Construct.

These codes generally accommodate older materials like PE pipes and rigid fiberglass reinforced pipes. Installations with modern pipe designs and materials, such as the flexible steel pipe, are generally approved when supported by technical documentation.

3.4 Flexible Steel Pipe Properties and Definitions

This section presents properties and related definitions that are applicable to FlexSteel pipes.

**Absolute or Specific Roughness, ε** – The smooth extruded PE inner layer has a specific or absolute roughness of $5 \times 10^{-6}$ ft ($1.5 \times 10^{-6}$ m), and a Hazen-Williams roughness C = 150. Relative roughness, $\varepsilon/D$, is the absolute roughness divided by the pipe ID, and varies with pipe size. The relative roughness is often used with a Moody chart or the Colebrook equation to determine the friction factor $\tau$ to use in the Darcy (or Weisbach) equation in determining pressure drop in pipes.

**Bending Stiffness** – Equivalent short term EI or bending stiffness of the unpressurized pipe structure at 73.4°F (23°C), where $E$ is the Young’s Modulus, and $I$ is the area moment of inertia. The radius of curvature to the neutral axis of a pipe (ρ) can be determined from the bending moment (M) applied to the pipe:

$$\rho = \frac{EI}{M}$$

Most of the bending stiffness is due to the effect of the polymer layers. Since PE properties are temperature and time dependent, $EI$ increases as temperature drops, and decreases with dwell time. $EI$ at very cold temperatures is roughly 3x larger than nominal, and at high temp is roughly ½ that at nominal temperature.

**Burst Pressure** – Gauge pressure required to burst the pipe at ambient temperature, with no other loads applied. This is an ultimate failure value under nominal test conditions and the pipe cannot be reliably operated under these conditions.

**Collapse Pressure** – See Short Term Collapse Pressure

**Effective Thermal Conductivity, $k_e$** – Equivalent wall conductivity considering the pipe wall to be a monolithic member, and neglecting surface heat transfer coefficients. This is commonly required for thermo-hydraulic computer program input.

**Factory Test Pressure** – Gauge pressure of water that would normally be used to hydro test the pipe at the factory in the Factory Acceptance Test, if the optional FAT test is conducted. Customer defined pressures can also be accommodated. Pressures of 1.3x the design pressure are common.

**Field Test Pressure** – Gauge pressure of water used to hydro test the pipe after installation in the Field Acceptance Test, as noted in Section 8.1.2.
Installation Bend Radius, IBR – Minimum acceptable pipe radius during installation with low internal pressure, measured to the inside radius of the pipe. To assure safe installation, the installation bend radius is specified to be equal to the minimum operating bend radius subsequent to payoff from the storage reel.

Maximum Design Temperature – Maximum conveyed fluid or external temperature to which the flexible pipe may be subjected at any time during the service life. The pipe temperature rating depends on the conveyed fluid composition and operating conditions, as noted in Section 4.1.

Operating Bend Radius – Minimum acceptable pipe radius while pipe is pressurized, measured to the inside radius of the pipe.

OHTC – Overall Heat Transfer Coefficient, or thermal conduction per unit area of the pipe wall based on a specified diameter or circumference. OHTC is often required as an input value for computer programs that conduct thermo-hydraulic flow calculations. The OHTC is reported at the pipe inner diameter, the most commonly requested value. Users should verify the characteristic diameter selected for use in the OHTC calculation is consistent with the diameter assumed by the program. If the OHTC at any other diameter is required, it can be computed by dividing the C/L value on the datasheet by the appropriate circumference. Accuracy of the unit conversions can be verified by checking hand calculation results against the reported value for OHTC at the pipe ID. The calculations of OHTC do not consider surface heat transfer coefficients, as these have a negligible effect compared to pipe thermal resistance.

Short Term Collapse Depth – Depth of water corresponding to the short-term collapse pressure, assuming a fresh water specific gravity of 0.999 at 60°F (15.6°C).

Short Term Collapse Pressure – External hydrostatic gauge pressure required to cause the flexible pipe structure to buckle essentially instantaneously at 73.4°F (23°C), with atmospheric pressure applied to the bore. Under external hydrostatic loading, the FlexSteel pipe can be conservatively considered to act as two concentric PE pipes. In addition, the steel provides some collapse capability. The capability of the pipe to withstand collapse depends on a number of factors, principally the pipe diameter and thickness, ovality, and especially the modulus of the PE. The modulus of the PE varies with temperature, time, and degree of plasticization in the presence of certain hydrocarbons. Once these factors are considered, a safety factor is applied to determine the collapse rating. Other factors, like pipe curvature, are not expected to dramatically affect the collapse pressure. API 15LE Appendix A indicates the decline of collapse pressure of HDPE pipes with time at 68°F (20°C). It reports that factors of [the inverse of] 2 - 2.3x are commonly applied to the ultimate collapse to determine the collapse rating of PE pipes. The short term collapse is an ultimate failure value for the pipe under nominal test conditions and the pipe cannot be reliably operated under these conditions. FlexSteel collapse values as published on customer datasheets are equal to ½ the minimum test value achieved at approximately 73.4°F (23°C) from three samples with pressure being applied directly to the internal liner.

Working Tension – Rating for short term tension applied to the pipe with no internal pressure, at ambient temperature. When tension is applied to a FlexSteel pipe, the pipe structure increases slightly in length and decreases slightly in diameter. With an applied load over time, the pipe continues to elongate, though at a steadily decreasing rate, displaying a typical polymer creep/stress relaxation behavior. Some internal pressure during tension is allowed per Section 4.8 if necessary for installation purposes. FlexSteel working or installation tension values as published on customer
datasheets are equal to ½ the minimum ultimate failure tension value achieved at approximately 73.4°F (23°C) from two pipe samples.

**SG empty in air** – The specific gravity of the empty pipe, including the effect of the empty pipe bore. See Section 5. The SG of the pipe wall alone is also reported.

**Spooling tension** – Tension required to bend the pipe to its minimum storage bend radius at 73.4°F (23°C). Spooling tension can be used when sizing spooling or de-spooling equipment.

**Storage Bend Radius, SBR** – Minimum acceptable pipe radius for storage on a reel, measured to the inside radius of the pipe. The SBR is calculated in accordance with Section C.2.9 of Appendix C in API 15LE, which allows a maximum of 5.5% strain in the polymer.

**Thermal Conductivity/Pipe Length, (C/L)** – Specific thermal conductivity of the pipe. This is the most meaningful pipe property for use in calculating heat loss. Neglecting all surface heat transfer coefficients, the heat loss from a pipe (q) can be calculated from the temperature difference between the conveyed fluid and the outside environment (ΔT) and the pipe length (L):

\[
q = (C/L) \cdot \Delta T \cdot L
\]

**Weight** – The customer datasheet reports specific weights of the pipe in the gravimetric units of kgf/m and lbf/ft. Gravimetric units are used so that the conversion coefficient between weight and mass is unity. Thus, a weight of 20 kgf/m is exactly equivalent to a mass of 20 kg/m, and a weight of 15 lbf is exactly equivalent to a mass of 15 lbm, both at sea level. The weight units on the datasheet are “kg” rather than the more correct “kgf” units to encourage SI users unfamiliar with gravimetric units to interpret the specific weights to be specific masses. Thus, the specific masses (i.e. mass/unit length) can be taken directly from the datasheet weights in SI units. In US customary units, users are accustomed to use of the gravimetric units for weight, and confusion is less likely. The pipe specific weights are commonly used to determine shipping weights or installation tensions, both of which commonly use tons (US short ton = 2000 lb) or metric tonnes (tonne = 1000kg ≡ 2204.6 lb). To determine weight in the SI force units such as N or kN, or for mass in slugs in US customary units, a numerical conversion is required.

### 3.5 Pipe Layer and Materials

FlexSteel pipes have concentric extruded polymer and helically wrapped reinforcing steel layers, as shown in Figure 3-2. A detailed discussion of the functional characteristics and structures for each of the pipe layers and materials follows.

#### 3.5.1 Liner

The innermost layer of the FlexSteel pipe is a liner or sheath. For standard FlexSteel pipe, the liner is of pipe grade Polyethylene (PE). A specific grade of PE has been qualified per API 17J. Other pipe grades of PE are considered qualified based on their similar composition and properties. For example, the food grade PE is similar. The liner materials are listed in Table 3-2. FlexSteel normally uses liners with a black color, however, the mechanical properties are not significantly altered by the pigments and other colors (or no color additives) are sometimes used for manufacturing convenience.
There have been rare reports of excessive buildup of static electricity in plastic pipes in dry gas service. While there has been no direct experience with this issue on FlexSteel pipes, for this type of application a black liner with some conductivity may help prevent static electricity buildup. The end fittings for this variant are electrically connected to the tensile wires as indicated in Section 7.

Table 3-2 Liner Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Spec</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard PE</td>
<td>MTL-P-5205 or MTL-P-5700</td>
<td>Includes black, natural, white, or yellow</td>
</tr>
<tr>
<td>Potable Water Grade PE</td>
<td>MTL-P-5028 or MTL-P-5700</td>
<td>Approved for potable water per National Sanitation Foundation.</td>
</tr>
</tbody>
</table>

Pipe grades of PE provide strength while providing excellent Environmental Stress Crack Resistance (ESCR). Pipe grade PEs typically retain high toughness (high strain at break values) even when aged by chemical attack at temperature over the design life. The considerations for the selection of material for a liner application are long term compatibility with the chemical to which it is exposed at the service temperature and mechanical properties. Chemical compatibility of PE with the conveyed fluids is discussed in Section 4.6.

3.5.2 Tensile Armor

The hoop and tensile structural strength of the FlexSteel pipe structure is provided by tensile armor layers. The tensile layers consist of contra-wound sets of steel strips applied over the liner at roughly a 55° lay angle. The considerations for the selection of material for the tensile layers are strength, toughness, and resistance to the chemicals in the annulus environment. The tensile layers are not exposed to the bore fluid; instead they are in the considerably milder annulus environment. The annulus environment results from the permeants from the bore fluid as noted in Section 6.
Considerations regarding compatibility with the steel are documented in Section 4.7. The tensile materials are listed in Table 3-3.

<table>
<thead>
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<th>Application</th>
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<th>Comments</th>
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</thead>
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<td>Standard</td>
<td>MTL-P-5233</td>
<td>690 MPa (100 ksi)</td>
<td>Cold Rolled/Stress Relieved</td>
</tr>
<tr>
<td>Sour Service</td>
<td>MTL-P-5237</td>
<td>690 MPa (100 ksi)</td>
<td>Meets NACE MR0175</td>
</tr>
</tbody>
</table>

### 3.5.3 Shield

The shield (or outer sheath) is an extruded external polymer barrier applied to resist mechanical damage and to provide the underlying layers of the pipe protection from the environment. The shield is made of a pipe grade PE. The long term considerations for the shield are fluid compatibility, temperature, and occasionally, resistance to sunlight. PE is generally not affected by water and salts, or the low concentrations of hydrocarbons that permeate into the annulus. As long as the internal and external temperatures are limited to the design temperature, the shield temperature is within the design limits. Incident UV can break the polymer chains in a PE matrix, embrittling the material. This is controlled by specifying optional shield formulations when needed.

The standard shield material is a PE formulated with carbon black. The outermost molecules of carbon black in the shield absorb incident light, blocking the UV and protecting the underlying PE. Thus, black PE is considered to withstand UV indefinitely. The black PE has a high emissivity. This means black pipes absorb incident light heating the pipe during daylight hours and radiating that heat at night, causing a significant cooling at night, especially when no clouds are present.

The optional white PE shield is specifically designed for surface applications with long term high intensity exposure. It contains a high concentration of TiO₂ (titanium dioxide) pigment and an enhanced package of antioxidants and stabilizers. The TiO₂ filler couples low emissivity with opacity. It reflects most incident radiation to minimize temperature gain during the day and loss at night, and blocks any incident UV radiation that is not reflected. The stabilizers and antioxidants are compounded in high concentrations to provide at least a 20 year life in exposed desert applications. The effect of UV on the PE is determined with accelerated indoor tests and weathering tests in Florida and Arizona. The indoor ‘weatherometer’ test regime is more extreme than expected service conditions because it uses a high intensity incident radiation and is accelerated by operating 24 hours per day.

An optional shield material is a yellow PE formulated with a package of colorants, stabilizers and antioxidants. The colorants define the pipe color and emissivity. Stabilizers minimize damage to the polymer chains from heat and UV irradiation. The antioxidants trap radicals formed when chain scission occurs, limiting the catalytic reaction of the radicals with diffused oxygen to cause additional chain scissions. The standard yellow material is considered suitable to resist direct sunlight in temperate areas for up to 3 years, and up to 18 months in tropical or desert applications.

### 3.6 End Fitting Design

The end fitting terminates the end of the pipe, maintaining the integrity of the pipe structure, sealing to the inner and outer extruded layers, and providing a fixture to transmit tension and pressure loads to the pipe structure. It interfaces between the pipe and a connector, such as a
flange or stub end with weld prep. The connector mates with other pipes or production facilities. The end fitting ID is typically only 0.12-inch (3 mm) smaller than the ID of the pipe.

A special type of end fitting is the midline connection. This fitting is used to connect two lengths of FlexSteel pipe together without having an intermediate flanged or welded joint. Beyond this, the primary difference between these two fitting types is that the midline is only swaged externally and therefore requires a thicker stem. This thicker stem results in a slightly larger reduction in the bore, typically about 0.59 to 0.79-inch (15 to 20 mm) smaller than the ID of the pipe.

The current revision of 17J specifies heavy and complex assembled end fittings of the type traditionally used with un-bonded flexible steel pipe offshore. These are bolted together from a number of components and filled with potting compound. Instead, the FlexSteel pipe is terminated with simple and light swaged end fittings of the API 17K type, like those proven through many years of experience on hoses. The pipe and end fittings are qualified per API RP 17B, as required by both API 17J and API 17K. The design methodology and factors are the same for both specifications. FlexSteel pipe conformance to API documents is indicated in Section 3.3.1.1.

Figure 3-3 illustrates the three basic types of end connections; a lap flange fitting, a weld-neck fitting and a midline. The end fitting body is a steel tube that fits inside the pipe bore. The jacket is a concentric steel tube that fits outside the pipe. The body and jacket are welded together and the end connector attached prior to assembly on the pipe.

Figure 3-3 Connection Types
(from left to right: Midline Connection, Lapped Flange End-Fitting, and Weld-neck End-Fitting)
3.6.1 End Fitting Material

The end fitting material is typically selected based on fluid compatibility and corrosion issues. Carbon steel is generally used where corrosion is not a key issue, such as for test and installation end fittings, or for dry gas production. 316L stainless (S31603) or carbon steel with electroless nickel (EN) plating is used where additional corrosion resistance beyond that of carbon steel is required, such as produced fluids with water and brine. 316L stainless steel is the standard material for end fittings and midline couplings. Electroless nickel coated carbon steel is a price-sensitive optional material for midline couplings. The midline coupling is coated with electroless nickel on all surfaces. The swaging process may damage the electroless nickel coating on the exterior of the midline coupling. Additional corrosion preventive measures such as heat shrinkable wraps are recommended.

Electroless nickel is well suited for oilfield applications containing CO₂, H₂S, and chlorides. EN coatings do not provide sacrificial protection if there is a coating holiday. For fluids streams containing sand or other potentially erosive particulates, the 316L stainless steel is recommended over the electroless nickel coated carbon steel.

End fittings of other materials suitable to various extreme chemical environments are developed on a case-by-case basis utilizing existing in-house technology applied to specialized offshore products.

3.6.2 Available Connectors

The standard end connector is an ANSI raised face flange that consists of a carbon steel lapped flange ring and a stainless stub end, which act as a swivel flange. The stub end is factory welded to the end fitting. The same end fitting and stub end are suitable for use with Class 300, 400, 600, and 900 flanges. Welding the stub end to the end fitting permanently attaches the ring to the end fitting. Since different ANSI classes require rings with different dimensions, the flange class must be known before the end fitting/connector fabrication is assembled. The ANSI flanges are typically connected using studs and nuts and normally sealed with a spiral wound metal gasket. Table 3-4 indicates the approximate weights of the various end fittings, including flanges. Figure 3-4 shows end fittings with ANSI flanges attached to a valve and a tee.

FlexSteel has designed, developed and tested a midline pipe connection. The midline connection is a fitting that joins two reels of FlexSteel with no flanges involved. The approximate weights of the midline coupling are listed in Table 3-4.

The midline fitting also allows for easier installation in plowed pipeline projects as in most cases it will run right through the plow chute eliminating the need to dig bell holes to join two reels of pipe.

<table>
<thead>
<tr>
<th>ANSI Class</th>
<th>2-inch End Fitting</th>
<th>3-inch End Fitting</th>
<th>4-inch End Fitting</th>
<th>6-inch End Fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[lb] [kg]</td>
<td>[lb] [kg]</td>
<td>[lb] [kg]</td>
<td>[lb] [kg]</td>
</tr>
<tr>
<td>300</td>
<td>N/A N/A</td>
<td>25 12</td>
<td>40 18</td>
<td>68 31</td>
</tr>
<tr>
<td>400</td>
<td>Use CL600</td>
<td>Use CL600</td>
<td>Use CL600</td>
<td>Use CL600</td>
</tr>
<tr>
<td>600</td>
<td>14 6</td>
<td>27 12</td>
<td>49 22</td>
<td>95 43</td>
</tr>
<tr>
<td>900</td>
<td>N/A N/A</td>
<td>37 17</td>
<td>59 27</td>
<td>122 56</td>
</tr>
<tr>
<td>Midline</td>
<td>25 12</td>
<td>34 16</td>
<td>73 33</td>
<td></td>
</tr>
</tbody>
</table>
A simple weld-neck fitting can be supplied when welded connections are preferred in lieu of bolted connections. Welding of end fittings to mating piping should be fabricated by a welder certified for the appropriate carbon steel or stainless alloy, and appropriate non-destructive tests conducted.

Contact sales representatives to determine pricing and delivery for custom flanges or hubs.

### 3.6.3 Swaging Operation

The end fittings are installed in several sequential steps. First, the pipe is cut off square, the swaging tooling is set up, and the end fitting is positioned on the pipe end. Then, swaging operations are conducted to form the steel walls of the end fitting permanently onto the pipe wall. Swaging provides a uniform tight compression on the pipe wall by the end fitting, on both the inner and outer surfaces of the pipe wall. Midline couplings feature swaging of the outer surface only.

The forming of the end fitting is performed by a specialized hydraulic press or swaging unit. The swaging equipment includes the press itself, a hydraulic power unit (HPU), a control system, and tooling. Multiple variants of the equipment are used, with some commercially purchased, and others that have been developed in-house. A typical unit for swaging end fittings and midline connections is shown in Figure 3-5.
The swaging operation is well suited for use in the factory or in the field. It is simple and quick, and is not sensitive to ambient temperature or cleanliness. Despite these strengths, some degree of operator skill is required to assure consistent results. To provide this, the use of our own FlexSteel technicians is required to perform all swaging operations on FlexSteel pipe.

A field training course is available that can be performed on site or in our factory. This course covers the installation of the end fittings as well as general installation and handling guidelines with an emphasis on safety and proper documentation. Completion of this course is evidenced by a non-transferable certificate of completion that indicates the course was successfully completed, but does not assure ongoing competency or give any authorization to act on behalf of Prime Flexible Products or train others. Installation of end fittings by these outside trained technicians is not monitored by Prime Flexible Products and proper records must be kept to maintain the warranty on the end condition.

Once the swaging operation has been completed, a dimensional check is conducted. This check demonstrates the integrity of the end fitting connection by directly verifying the end fitting is applying the correct amount of compression to the pipe wall.

### 3.7 Marking

FlexSteel pipe marking includes manufacturer, structure number, production serial number, nominal size, pressure rating, maximum temperature under optimum conditions, MBR and graduated pipe length in 1 meter increments. The information is printed in 0.59-inch (15 mm) high characters along the full length of the pipe.

### 3.8 Factory Processing

FlexSteel pipe is typically manufactured to stock, unlike classic flexible steel pipe which is custom designed and built for each project. Some stock is maintained at the factory, pipe is also stored at local yards in large markets. As orders are received, pipe is taken from stock and shipped to customers. For very large and custom orders, a factory build must be scheduled. Contact sales representatives to determine pricing and delivery for custom builds.

As each reel of pipe is finished, it undergoes a structural pressure integrity test. This test is typically performed without end fittings being installed on the pipe and is intended to prove the absence of structural defects to the pressure carrying tensile layers.
3.8.1 Acceptance Tests

API 17J Section 10 requires that acceptance tests be conducted on each fully compliant pipe. These tests include gauge, hydrostatic pressure, electrical continuity (for pipes with cathodic protection or other continuity requirements), electrical resistance, and the gas venting system test. Per API 17J Section 10.1.2, the gauging and electrical resistance tests do not apply to smoothbore pipe, such as the FlexSteel pipe, and the electrical continuity test is for pipes that require continuity, such as those that are cathodically protected.

API 17J requires the factory acceptance tests be completed on all pipes after end fitting assembly to test the pipe and end fitting integrity. The sequence is based on the traditional offshore business model, where the pipe is assembled and tested onshore, possession accepted by the customer, the pipe is sent offshore and installed, and a final field acceptance test is conducted. Commercially, the FAT’s demonstrate the offshore pipe is functional before it changes possession as it leaves the factory. Since the Factory Acceptance Tests are conducted after the final end fittings are applied, and FlexSteel pipe is typically supplied in full reels without fittings installed then cut to length and end fitted in the field, the field hydro test is the key acceptance test. A factory strength test as described in section 8.1.1 is performed on all FlexSteel pipe.

API 17J requirements for the factory acceptance tests are typically somewhat modified when they are conducted in field. In particular, the gas vent system test procedure normally involves pressuring the entire pipe annulus by introducing compressed air from one end fitting, and verifying flow from the other end fitting. This can entail a considerable wait time, and must be carefully monitored to avoid damage to the liner or shield, so the field procedure is normally to verify flow at each end fitting separately, rather than both together.

4 PIPE CAPABILITIES

FlexSteel pipes, like all piping components, are capable of withstanding operating conditions, such as pressures, temperatures, water depths, tensions, bending moment, and fluid compositions. During the design process, the capability of the structure is compared to the operating conditions to verify its suitability for use in a given application, and to demonstrate the pipe life meets the specified design life. In particular, some of the ratings, for example temperature, are reduced by certain operating conditions such as fluid composition. Whenever load conditions change over time from the original design conditions, the new design conditions must be checked to verify they are within the pipe capability.

4.1 Pipe Temperature Rating

4.1.1 Elevated Temperature Service

The maximum operating temperature for the FlexSteel pipe is shown on the respective customer datasheet. Depending on the pressure and fluid components, the maximum temperature rating of the pipe may be adjusted accordingly. This adjustment is primarily based on the chemical compatibility of the inner liner, as the properties of the steel layers are not significantly affected by temperatures within this range. Contact your FlexSteel representative to verify the temperature capability of the pipe in a given application before installing and using a pipe, or changing the service of an existing pipe.
Thermoplastic is not self-repairing after overheating. Therefore, it is important to avoid external heat sources such as open flames, welding, or placing the pipe in contact with other elevated temperature piping, heaters, etc. To conduct any high temperature operations near the pipe, such as welding, protective shields are applied with temperature sensors such as thermocouples in contact with the pipe or end fitting to verify the temperature is within acceptable limits.

4.1.2 Cold Weather Installation and Use

Handling flexible steel pipe in cold weather is similar to handling at ambient. The PE used for the liner and shield layers retains toughness, even down to very cold winter temperatures. However, the pipe stiffness increases as the temperature decreases, as noted in Section 3.4. Flexible steel pipe tends to take a semi-permanent pre-set to the curvature at which it is stored. This effect is more apparent at lower temperatures. Because of the additional stiffness, heating the pipe is recommended when the temperature of the pipe is below -13°F (-25°C) when measured by infrared pyrometer or other suitable means. A tension load is commonly applied to the pipe to straighten it out until it is flanged up. Mechanically straightening the pipe immediately prior to laying the pipe can help, but the pipe “memory” tends to quickly cause it to curl at the ends of the pipe. The pre-set is neither harmful nor permanent, and after the pipe has been laid out for a period, stress relaxation in the polymer layers causes the pipe to take a semi-permanent set in the new shape, essentially straight in most sections.

Full scale reel-to-reel testing was conducted on a 4-inch 1000 psi and 6-inch 1500 psi FlexSteel pipe at -40°F (-40°C), on reels with a drum diameter of 7 ft (2.13 m). Cold temperature pipe handling was similar to that at 68°F (20°C), and while the pipe is stiffer at these cold temperatures, the pipe itself is still safely handled. Thus, as detailed in Report R092E011 [11], the pipe is suited to cold weather installations.

4.2 Pipe Internal Pressure

As with any piping or pipeline component, the operator must assure that the maximum operating pressure, including static head and transient surges, does not exceed the design pressure at any point in the FlexSteel pipe system. The operator is responsible for assuring the system is equipped with pressure regulating devices of adequate capacity and design to meet the pressure, load, and other service conditions under which the system will operate or to which it may be subjected.

4.3 Pressurization and Depressurization Rates

API 17B 11.5.3.3 and 11.5.3.6 recommends a typical maximum pressurization rate for the hydro test of 45 psi/min (3 bar/min); and a typical maximum depressurization rate of 260 psi/min (18 bar/min). FlexSteel pipe is rated at up to 145 psi/min (10 bar/min) for pressurization and 290 psi/min (20 bar/min) for depressurization, based on extensive hydro test experience in-house. Some testing conducted using water as the test fluid on high pressure flexible steel pipe indicated that very high rates of pressurization and depressurization cause no structural damage, as reported in OTC 7727 [12]. For temperatures above ambient, especially those including CO₂, depressurizations under operating conditions are best limited as noted in Section 4.6.2.

4.4 Environmental Exposure

The PE shield is not appreciably affected by fresh or salt water. Fluid compatibility for the shield is similar to that for the liner, as documented in Section 4.6. Before subjecting the shield to contact
with any other chemicals, contact your FlexSteel representative to verify that the proposed exposure is acceptable.

UV resistance of the shield is indicated in Section 3.5.3. The UV resistance of the yellow PE is somewhat limited, but either the black or white outer shield is designed to withstand UV exposure for at least 20 years.

4.5 Minimum Bend Radius

Care during handling is required to assure the pipe does not exceed the MBR listed on the applicable Customer Datasheet.

Applying a moment to a flexible steel pipe causes it to deflect to a radius defined by the applied load and the pipe stiffness (EI). Most of the bending stiffness of the pipe is caused by the polymer layers as noted in Section 3.4, and over time the pipe bending stiffness decreases as the polymer relaxes and creeps. Under a constant moment, the pipe deflection tends to increase somewhat with time.

At the end fittings, avoid overbending the pipe. Instead, arrange the pipe so it is straight in the vicinity of the end fittings (at least 5 times the pipe OD) to assure the bending moment is negligible. The steel tensile members are fixed in the end fitting and free to move in the pipe, resulting in large stresses in the tensile members at the pipe-end fitting interface if the pipe has significant local curvature. This effect also tends to make the pipe stiff near the end fitting.

4.6 Conveyed Product Compatibility with PE

The ability of the PE material in a flexible steel pipe to resist the effects of the conveyed fluid over the design life is a primary concern in verifying the suitability for a specified application. Pipe grade PE’s are considered by PE manufacturers to be usable to a maximum of 140°F (60°C) in oil and gas service. This compatibility limitation is imposed for use in unreinforced plastic pipes to control the loss of structural properties that accompanies the swelling of the PE resulting from plasticization. In reinforced flexible pipe service, the structural properties of the PE are secondary because the steel layers resist the internal pressure.

Fluid compatibility details are indicated in Appendix A, including detailed compatibility charts. Consult your FlexSteel representative prior to subjecting the pipe to any fluid if there is any question regarding compatibility.

4.6.1 Hydrocarbon Compatibility

For flexible steel pipes, the major issues with fluid compatibility are swelling and blistering of the liner. Swelling is caused by chemical similarity between the solvent and the PE. Blistering is caused by the plasticization effects of the solvents and the reduction in modulus caused by increased temperature coupled with the action of dissolved gases in the matrix during rapid depressurization cycles. The PE temperature capability is reduced by:

- High fractions of gas condensates and light crude, specifically concentrations of hexane, cyclohexane, heptane, and the benzene, toluene, ethyl benzene, and xylene aromatics. These components couple high solubility in PE with molecule sizes small enough to diffuse easily into the polymer and large enough to affect the properties. Thus, they plasticize the PE, reducing the resistance to blistering.

- High partial pressure of CO₂ in the bore, and large numbers of rapid decompression cycles.
4.6.2 Fluids Other Than Hydrocarbons

PE has non-polar long chain molecules. Thus, polar molecules such as those with [OH] radicals including water, alcohols, and bases typically have little or no effect on PE. It is also highly resistant to most biocides, dyes, corrosion inhibitors, and oxygen scavengers in concentrations typical of hydrocarbon, water and gas injection service.

PE is attacked by very strong acids, and the damage is more severe at higher temperatures. The low concentrations and durations of acid exposure typical of oil production are not detrimental to PE, but long term exposure to highly concentrated acids are to be avoided.

Carbon dioxide, CO₂, does not chemically affect PE, however, the molecules are relatively mobile in PE and readily migrate throughout the liner. When the pressure in the bore rapidly depressurizes, blistering can occur from repeated cycles as noted in Appendix A. Par. 7.2.3.2 of API 17J specifies requirements for blister resistance testing. Tests have been conducted per the 17J requirements on polyethylene samples heated to 60°C and pressurized using CO₂ to 2250 psi (155 bar). After the development of steady state conditions, the test cell is depressurized at a rate of 1015 psi/min (70 bar/min). The test cell is then re-pressurized for the next cycle, and so on for 20 cycles total. Samples were inspected following the first, tenth and twentieth pressure cycle at 20x magnification for evidence of micro-voids and blistering. No blistering was observed.

A fluid compatibility chart is presented in Appendix A for other molecules that may affect the HDPE.

All materials used in the flexible pipe construction are reviewed to determine that they are compatible permeated gases and liquids at design temperatures. Decomposition of these materials does not create by-products harmful to thermoplastic layers of the pipe. All lubricants and corrosion protection coatings used in the manufacture of the pipe are compatible with the thermoplastic pressure-sealing materials in the pipe.

4.7 Conveyed Product Compatibility with Steel

The steel tensile strips in the pipe annulus are protected from the bore fluids by the inner liner. As indicated in Section 6, small quantities of certain molecules can migrate through the PE inner liner into the pipe annulus. The light hydrocarbons do not adversely affect the steel in the pipe annulus, but H₂O, H₂S, and CO₂ permeants can cause issues with typical carbon steels.

Corrosion may be defined as the destruction of metal through electrochemical and mechanical action between the metal and its environment. Corrosion can be accelerated by physical stresses that change the crystalline structure of steel and by the chemical composition of the environment. This section discusses three types of corrosion: general weight loss, hydrogen attack or sulfide stress cracking, and carbonic acid corrosion.

All materials used in the flexible pipe construction are reviewed to determine that they are compatible permeated gases and liquids at design temperatures. Decomposition of these materials does not create by-products harmful to steel layers of the pipe. All lubricants and corrosion protection coatings used in the manufacture of the pipe are compatible with all other structural materials in the pipe.
4.7.1 Water

Water in the annulus by itself does not cause a corrosion problem. Many years of offshore experience with flexible steel pipe indicates that water in the annulus, even in the presence of ionics, does not result in serious corrosion. Dry gas, or dead crude which has been processed through a separator/dryer facility can be considered to be dry, and will not result in permeated water in the annulus. Produced fluids are considered to contain water, as even small amounts of water in the conveyed fluid will permeate into the annulus.

4.7.2 Pitting Corrosion

Pitting is a loss of cross-sectional area and weight of the steel reinforcements, and is generally considered to be the most common type of steel corrosion. Pitting typically occurs as iron or steel forms rust, Fe₂O₃, in the presence of oxygen. This iron oxide has poor physical integrity, and does not effectively protect the underlying base material. As a result, pitting continues as long as oxygen is present and uncorroded iron or steel remains. In the FlexSteel pipe annulus, essentially no oxygen is available, thus, flexible steel pipes are extremely resistant this type of corrosion.

4.7.3 CO₂ Service

Carbon dioxide, CO₂, is a common constituent of natural gases and is present in most types of formation fluids. CO₂ is relatively mobile in PE and readily migrates into the annulus where the steel tensile elements are located. In the presence of water, carbon dioxide dissolves and forms carbonic acid, H₂CO₃. Carbonic acid reacts to form a thin oxidant film on the surface of the steel. This film partially protects the underlying metal, slowing the rate of corrosion. When the steel is in contact with flowing fluid, such as in a typical steel pipe, this film is continuously removed, exposing fresh metal to attack. Since the annulus environment is relatively protective, this film remains intact. In addition, the carbon dioxide ultimately causes scale production as the carbonic acid reacts with iron in the steel to form a white/gray corrosion product, FeCO₃. This iron carbonate scale acts to protect the steel from further corrosion. Between the film and the scale, the corrosion of the steel layers in the annulus resulting from CO₂ is minimal.

4.7.4 Sour Service

Hydrogen sulfide is a toxic and corrosive gas that occurs naturally in some produced fluids. It is formed primarily by the decomposition of organic matter that contained sulfur. In sufficient concentrations, hydrogen sulfide can have a significant corrosive effect on steel. Per NACE MR01-75, sour service is defined by the partial pressure of H₂S. This partial pressure can be calculated as the concentration of H₂S in ppm multiplied by the fluid total pressure. H₂S partial pressures of (0.05 psi) (0.3 kPa) or greater are considered to constitute sour service. For example, a well at a pressure of 1,000 psi (6,900 kPa) is considered sour if the H₂S concentration is only 50 ppm.

MR01-75 considers steels to be suitable for sour service with a hardness of less than 22 HRC and a permanent outer fiber deformation from cold working of less than 5%. Steels that do not meet these criteria are not assured to be resistant to sour service, and must be tested to verify suitability.

H₂S service is an issue for flexible steel pipes because of its potential effect on the steel reinforcements. H₂S in the pipe bore diffuses into the annulus as indicted in Section 6. Once in the annulus, H₂S in contact with steel in presence of water undergoes a corrosion process that results in the formation of FeS. The reaction releases atomic hydrogen (H⁺ ions) at the surface of the steel. Some of this enters the steel at a rate that seems to be enhanced by the presence of the H₂S. Once
in the steel, the atomic hydrogen readily diffuses throughout the steel. These hydrogen ions tend to
gather at imperfections in the steel structure such as grain boundaries, dislocations, inclusions, and
voids. Two mechanisms for hydrogen damage are hydrogen blistering and hydrogen embrittlement.

Hydrogen blistering is caused by the recombination of diffused atomic hydrogen into molecular
hydrogen, \( \text{H}_2 \), in voids. Since molecular hydrogen essentially cannot diffuse through steel, the
concentration and pressure of hydrogen gas within the imperfection increases. The equilibrium
pressure of molecular hydrogen in contact with atomic hydrogen is several hundred thousand
atmospheres. The pressure buildup in the void results in local deformation of the steel, a
mechanism referred to as Hydrogen Induced Cracking (HIC), and because of the characteristic
appearance of the steel surface, the process is known as hydrogen blistering. The cold worked steels
have a fine granular structure with few voids, thus have limited susceptibility to hydrogen blistering.

For the steels used in the FlexSteel pipe, hydrogen embrittlement is a concern in sour service.
Sulfide Stress (Corrosion) Cracking (SSC or SSCC) is considered a type of hydrogen embrittlement
where the hydrogen ion source is \( \text{H}_2\text{S} \). Most of the mechanisms which have been proposed for
hydrogen embrittlement are based on slip interference by dissolved hydrogen accumulating at
defects in the structure, such as at grain boundaries, near dislocation sites, at microvoids or at crack
tips. Crack formation and growth appear to be related to interactions between the atomic hydrogen
and the steel at these sites. Accumulated hydrogen ions along the grain boundaries can reduce the
cohesion between grains. Cracks and other damage occur more rapidly with higher concentrations
of hydrogen, at higher stress levels, and in higher strength steels. Steels with greater toughness and
fewer dislocations, such as ultra-low sulfur steels, have greater resistance to hydrogen
embrittlement. With high concentrations of \( \text{H}_2\text{S} \), embrittlement can occur quickly.

Plain carbon steels are commonly used for flexible steel pipe reinforcements. Steels for sour service
have similar compositions and strengths to the steels being used for the standard FlexSteel pipe, but
use different processing methods.

Table 3-3 presents the steel used in FlexSteel pipes. The standard cold rolled/stress relieved steel
largely complies with NACE MR0175, but does not meet the 5% maximum allowable cold work
requirement. Per API 17J, for conservatism, the \( \text{H}_2\text{S} \) partial pressure in the bore is considered to act
directly on the steel. Thus, the standard steel is considered acceptable for up to 0.05 psi (0.34 kPa)
of \( \text{H}_2\text{S} \) in the bore. In practice, since the annulus is limited to approximately atmospheric pressure,
somewhat higher partial pressures in the bore can be allowed. The cold rolled/stress relieved steel
passed Sulfide Stress Corrosion Cracking (SSCC) testing at 1.45 psi (10 kPa) \( \text{H}_2\text{S} \) partial pressure,
13.05 psi (90 kPa) \( \text{CO}_2 \), however, some blistering from HIC was found. Thus, the standard steel is not
considered to be generally suitable for sour service with high \( \text{H}_2\text{S} \) concentrations.

Long term testing is ongoing for determining acceptable thresholds of \( \text{H}_2\text{S} \) in FlexSteel pipes
constructed of the standard cold rolled/stress relieved steel. To date this testing supports partial
pressures in the bore of up to 0.8 psi (800 ppm @ 1000 psi) with no evidence of material
degradation. This laboratory testing is supported by ongoing field monitoring programs where
samples are removed from service after specified periods of time and dissected.

The sour service steel indicated in the table is a low alloy steel meeting NACE TM0177 requirements.
Testing of this material in direct exposure to 14.5 psi (100 kPa) \( \text{H}_2\text{S} \) has shown no evidence of HIC or
SSCC.
4.8 Flexible Steel Pipe Stress/Strain Analysis

API 17J Section 6 requires that for a given application, appropriate combined load cases be selected, the maximum applied loads be determined, and the stress and strain in each layer of the pipe be determined. The loads are verified as being acceptable by comparing the resulting calculated stresses and strains to the maximum allowable utilizations specified in API 17J.

In general, the pipes share essentially a single design, and similar design factors. Thus, a single analysis suffices to meet API 17J analysis requirements for all of the FlexSteel pipes.

Strip steels typically have a specified minimum ultimate tensile strength (UTS), the strength at which the steel breaks. For design purposes, a yield strength is needed. The 0.2% offset strength is a common yield strength, but has some variability. Instead, API 17J uses a more conservative structural strength $\sigma_s$ that is similar to the yield strength, but is not necessarily determined using the same test method. API 17J indicates the typical factor between the steel UTS and the structural strength is 0.90. This factor is appropriate for the extensively cold worked steel and the low alloy steel used in standard FlexSteel pipes.

API 17J specifies the maximum allowable material utilization, essentially the reciprocal of a design factor. The maximum stress fraction is the maximum allowed ratio between the actual stress and the UTS. FlexSteel pipe is rarely used with the combined load cases typical of subsea installation and operation; thus individual loads can be considered separately.

Load Cases

The major operating load case is recurrent operation with internal pressure:

API 17J revision 2, allows up to $0.67 \times \sigma_s$

This load case is used to determine the pressure rating for the pipe, using the design software described in Section 9.5.1.2.

For extreme or abnormal operations, the maximum tensile armor stress factor is $0.85 \times \sigma_s$

For onshore fully static applications, the abnormal loads are generally the same as the recurrent operating loads indicated above. Since the load case allows 21% higher stresses than the recurrent load case, this load case is not limiting.

The major installation load case is applied tension.

The maximum tension is determined experimentally, and the resulting general stresses are low compared to the API allowables. For FlexSteel pipe, internal pressure increases the load capability of the pipe. Using the API utilization criteria for installation, full design pressure would be allowed, however, it is recommended that not more than 20% of design pressure be applied during pull-in.

Hydrostatic pressure test case:

API 17J allows a maximum tensile armor stress factor of $0.91 \sigma_s$

For static flowlines, the API 17J minimum required hydro test pressure is $1.3 \times$ Design Pressure. The pipe is designed to handle a $1.5 \times$ Design Pressure as this is often required by design codes such as ASME B31.8. Maximum allowable hydro test pressures are available for each specific design if customer operational standards require higher hydro test factors.
4.9 Flexible Steel Pipe Storage

Flexible pipe should be stored under environmental conditions which do not affect its performance characteristics as indicated below:

- The storage temperature is to be within the acceptable design limits specified in Section 4.1.
- Where applicable, protect the end fitting connections to prevent damage to the seal area, threads, and other areas susceptible to damage.
- Allowable UV exposure of the pipe depends on the shield color, as noted in Section 3.5.3. The liner generally has good chemical resistance, and does not require preservation fluid inside the pipe. The flexible steel pipes can be sealed to keep out oxygen, but this is not required. The stainless steel end fittings do not require any special consideration, but carbon steel end fittings require standard protective measure for steel – keep painted and dry or lubricated.
- The reels are best kept under cover for long term storage, as they are fabricated from carbon steel, and are subject to corrosion with extensive weathering. For short term storage, the reels can be left outside without protection. Pipes from the factory have typically been tested with essentially potable water, and may contain small amounts of water. Pipes with small amounts of water can be exposed to unlimited freeze/thaw cycles without problems.

5 FLOTATION AND ON-BOTTOM STABILITY

FlexSteel pipe is normally deployed onshore, however, with proper precautions the pipe can also be successfully used in submerged applications. For submerged applications such as river crossings, the FlexSteel pipe is sometimes enclosed in a carrier pipe. In this case, the floatation and on-bottom stability of the pipe is unimportant.

As detailed in the relevant customer datasheets, all FlexSteel pipes have wall specific gravities or equivalent wall densities greater than 1.0 and will all therefore sink when filled with water. Pipes with lower pressure class ratings will, however, float when filled with air or gas. The net buoyancy is progressively less when filled with crude, fresh water, or seawater.

For stability in submerged applications, the pipes must sink. This can be accomplished by adding weights or anchors to the lighter pipes, but these solutions add considerable complexity and cost to the installation operations. Thus, a heavier pipe is generally recommended in this situation. An on-bottom stability analysis can be conducted on submerged flowlines in open waters to verify pipe stability. Stability calculations determine if the pipe weight is sufficient to assure the pipe does not move under the applied environmental loads. Since flexible pipes are more forgiving of bending stresses and spanning issues than rigid pipes, absolute stability of a flexible flowline is not necessarily required. Thus, some criteria would be to require stability under, for example, 1 year storm conditions, while allowing some movement under 10 year or 100 year storm conditions. Flexible steel pipes can also be restrained with mattresses or buried to assure the pipes do not move.

6 GAS PERMEATION ANALYSIS

In flexible steel pipes, the conveyed fluid is sealed within the pipe bore by the liner. The polyethylene liner is nearly hermetic, but small amount of gases may permeate through. CH₄, CO₂,
H$_2$S, and H$_2$O comprise the major permeated gases. These permeated gases accumulate in the flexible pipe annulus. Flexible steel pipes have a venting system that conveys the gasses to the end fitting and out of the pipe.

6.1 Flexible Pipe Annulus and Venting

Flexible pipes have reinforcements in layers located between the inner and outer sheaths. This area is referred to as the flexible pipe annulus. Steel layers in the annulus typically have about 90% steel and 10% gap. Permeated gases gather in this gap volume. Since the tensile armor strips are spirally wrapped around the pipe from one end to the other, the gaps allow the permeated gases to travel easily throughout the annulus. A slight overpressure above atmospheric develops in the pipe annulus driving the gases to the end fittings where they are vented as illustrated in Figure 6-1, preventing excessive pressure build up. The end fitting contains a 1/8" NPT threaded hole for venting purposes. The vent system can be connected to an exhaust manifold at the satellite or battery end of the flowline. From the manifold, the gases can be released to the atmosphere, conveyed to a disposal unit, or pressurized and re-injected into the conveyed fluid in the pipe bore. In-line vent valves can be supplied that will allow the gas to flow at pressures slightly above atmospheric while preventing the ingress of oxygen, water, or other environmental fluids. In midline connections, a vent path is integrated inside the fitting itself allowing permeated gases to continue downstream.

![Figure 6-1 Illustration of Permeated Gas Venting](image)

The environment in the annulus is normally much milder than that in the pipe bore, and the annulus is generally a favorable environment for plain carbon steels. When hydrocarbons are present in the bore, the annulus will normally contain a reducing atmosphere. The permeation rate is a function of the pipe geometry and material properties, internal and external temperatures, and the bore partial pressures.

Detailed gas permeation analyses using proven software tools can be conducted for specific applications, but these are rarely required. Typical permeation rates range from 1 - 2 std ft$^3$/day/mile (75 - 135 std cm$^3$/hr/100m).

7 CATHODIC PROTECTION

Cathodic protection is applied to many flexible steel pipes in subsea service. This prevents corrosion on the low alloy steel end fittings which are in contact with the seawater, and any internal structural elements exposed by damage to the external polymer shield. However, on land applications with stainless end fittings, cathodic protection systems are not typically required.
FlexSteel pipes typically have electrical continuity between the tensile armor strips and the end fittings provided by continuity clips applied during end fitting installation as illustrated in Figure 7-1. These can be omitted to assure electrical isolation. The continuous electrical path normally provided allows the injection of a signal to facilitate accurate location of the pipe. In some cases, it may be useful to pass CP current through the pipe. For this, the electrical resistance of the pipe is needed to conduct CP calculations. Electrical resistance of the pipes is roughly \( \frac{1}{4}\Omega \) to \( \frac{1}{2}\Omega \) per kilometer of pipe. If specific values are needed, contact FlexSteel Engineering. The end fitting and continuity clip resistance is in the \( \mu\Omega \) range, and can be neglected.

![Figure 7-1 Illustration of Continuity Clips Installed](image)

8 COMMISSIONING

A pipeline system is typically commissioned after completion by filling it with water and conducting a pressure test referred to as a field hydro test or field acceptance test. Flexible steel pipe behavior when hydro tested is somewhat different from the behavior of rigid steel pipes. The layers are un-bonded and upon initial pressurization undergo a stabilization process referred to as conditioning. After conditioning, the pipe is held at the test pressure for a period of time. The test is considered successful if the pressure does not drop below the minimum allowable value over the hold period. Upon successful completion of the test, the pipe is depressurized and ready to be put into service.

8.1 Hydro test

Pipeline systems are typically hydro tested prior to being placed in service. The purpose of the hydrostatic test is to demonstrate that the pipe is leak tight and to verify the strength of the pipe by subjecting it to loads more severe than any it will encounter in service. In addition, hydro tests are occasionally used to demonstrate pipeline integrity in service.

Every Reel of FlexSteel is tested prior to installation by a factory strength test, and virtually all are hydro tested after installation in commissioning the pipeline. A hydro test at 1.25x to 1.5x the design pressure to verify the structural integrity of the pipe is often referred to as a strength test, and later tests at 1.0x to 1.25x the design pressure to verify the connections is often referred to as a leak test.
8.1.1 Factory Strength Test
The factory strength test is conducted at 1.3x design pressure for an 8-hour period. A rapid drop in pressure will indicate that the pipe has a structural defect.

8.1.2 Field Hydro Test
A field hydrostatic test is conducted on a pipeline system to demonstrate that it is leak tight and, if a factory test has not been conducted, to verify the strength of the pipe by subjecting it to loads more severe than any it will encounter in service. As noted previously, the test can also be used to verify pipeline integrity.

Pipeline codes specify field hydro test conditions and acceptance criteria. Field leak tests are commonly conducted at 1.1x or 1.0x the design pressure on pipe components that have been factory hydro tested. Field strength tests of 1.25x the design pressure are also common. When no factory test is conducted, some codes specify a field hydro test at up to 1.4x or 1.5x the design pressure. Contact your FlexSteel representative prior to conducting any hydro tests at pressures greater than the factory hydro test detailed in Section 8.1.1.

The field hydro test period is often 24 hours, though a hold period of 4 hours is often sufficient, unless conditioning or excessive temperature changes are occurring.

8.1.3 Test Conditions
The hydro test pressure and hold period is determined by the operator, as required by applicable codes. The minimum test pressure, \( P_{HT,MIN} \) is determined as noted in the previous section. The nominal hydro test pressure, \( P_{HT,NOM} \) is normally 4% above the test pressure. The maximum allowable test pressure, \( P_{HT,MAX} \) is limited by the stresses in the pipe as noted in Section 4.8. The test period is also determined by the pipeline operator, as required by applicable codes. Allowable pressurization and depressurization rates are indicated in Section 4.3.

8.2 Pipe Conditioning
Flexible pipe performance under internal pressure is different from that of rigid steel pipelines, especially the first time the flexible is pressurized.

As a rigid steel pipeline is pressurized, it increases slightly in internal volume, and then holds a constant internal volume while resisting the pressure. For welded steel pipes, any pressure drop is indicative of plastic failure due to deformation of the structural layer, temperature changes or leaks. Leaks can be easily distinguished from the other causes of pressure changes simply by noting the constant rate of the pressure drop.

When a flexible steel pipe is initially pressurized and blocked in, it likewise immediately increases in internal volume from strain in the steel tensile elements. As the polymer liner creeps to bed into the tensile elements, the flexible pipe internal volume increases and the pressure drops. This effect, referred to as conditioning, does not occur at a constant rate. Instead, the volume initially increases relatively quickly, and then gradually slows with essentially a logarithmic curve. Pressure drops from leaks can be distinguished by their consistency, as pressure drops from leaks do not slow with time.

Once conditioning has occurred to a certain degree, it does not reoccur if the pipe is retested at a later time. Thus, if a pipe is hydro tested once, it is relatively stable when hydro tested again at the
same pressure. FlexSteel pipe has a very tight structure that conditions quickly, with minimal pressure drop.

8.3 Conditioning Procedure

At no time during the conditioning is the pipe pressure allowed to exceed the hydro test maximum pressure, \( P_{HT, MAX} \). Pressurize the pipe up to or slightly below the hydro test nominal pressure, \( P_{HT, NOM} \), at or below the maximum allowed pressurization rate. Shut in the pipe and monitor the pressure drop every 15 minutes for at least one hour; then, re-pressurize to near \( P_{HT, NOM} \) and block the pipe in again. Monitor the pressure drop for one hour and compare the findings to the readings of the previous hour. If the pressure drop is less than that of the previous hour, the pipe is expanding rather than leaking.

If the rate of pressure drop does not taper off, there is a possibility that a small leak exists in the pressure boundary system. Generally, these types of leaks are in the test fixturing or flange connections rather than the pipe. If this occurs, testing should continue for two additional cycles to verify that the pressure drop is not an isolated incident. Should the rate of pressure drop remain constant, or increase, the test fittings and flange connections should be checked for leakage. Following this, if there is still no decline in the rate of pressure drop, a leak in the pipe is indicated. A leak in the pipe is quite rare, and if it occurs, it could result from a faulty end fitting or end fitting installation. Thus, the end fittings should be carefully inspected and/or replaced to determine if the leak occurred at an end fitting.

After the pipe has been cycled to near \( P_{HT, NOM} \) several times (each cycle for one hour as described above) and the results have shown diminishing pressure drops for each cycle, the hold period of the pressure test can begin. To determine if the pipe will likely pass the hydro test, compare the 1 hour pressure drop for the test period to the allowable pressure drop. For example, for a 75 bar \( P_{HT, MIN} \) and 78 bar \( P_{HT, NOM} \), the difference is 3 bar. If the pipe dropped 0.5 bar in the most recent hour, during a 24 hour hydro test it would be expected to drop a maximum of 0.5 bar * 24 hr = 12 bar. This pipe should be further conditioned before initiating the hydro test. When the pipe pressure has dropped 0.05 bar in the most recent hour, it would be expected to drop a maximum of 1.2 bar over a 24 hour hydro test, and the pipe would be expected to pass hydro test. Pipe conditioning in the FlexSteel pipe occurs relatively rapidly, and a period of several hours is typically sufficient to essentially complete the conditioning phase.

8.4 Hydro Test Procedure

Once the conditioning is complete, the hydro test begins by pressurizing the pipe near or to \( P_{HT, NOM} \) and blocking it in for a specified hold period. Record pressure ratings continuously if possible, or at a minimum of 15 minute intervals. A slight pressure drop may be noticed throughout the testing period, and if so, the rate of pressure drop should diminish over the period of the test. Pressure changes as a result of temperature changes must be considered separately. The pipe is not to be pressurized above \( P_{HT, MAX} \), even temporarily. If the pressure increases above \( P_{HT, NOM} \) and risks exceeding \( P_{HT, MAX} \), allow a small amount of water to bleed out to limit the pressure.

Occasionally, large temperature changes during the hydro test affect the pressure significantly, and therefore the temperature should be recorded at the same frequency as the pressure. More specifically, the internal pressure of the pipe increases or decreases as the temperature increases or
decreases respectively. For conditioned pipes, the water volume changes are typically greater than the pipe volume changes with respect to temperature.

After the pipe has completed the hold period, if the pipe meets the acceptance criteria, the pipe is depressurized and normally dewatered. If the pipe fails the criteria, it can be repressurized to near $P_{HT,NOM}$ and the hold period repeated.

This API 17J procedure has been traditionally used for hydro test. However, the pressure of a blocked in pipe varies as a function of temperature and as a result the strength test described in section 8.1.1 has been adopted.

## 8.5 Hydro Test Acceptance Criteria

The pressure test is acceptable if the internal pressure does not drop below $P_{HT, MIN}$ during the hold period. However, if the pressure does drops below $P_{HT, MIN}$ during the hydro test, and a decrease in pipe and water temperature accounts for a substantial portion of the pressure drop, the integrity of the pipe has been demonstrated. Under these conditions, an operator may determine the hydro test has been successfully concluded. In addition, if feasible, the end fittings should be inspected for leaks. Small amounts of water are not normally a cause for concern, however, if the water continues to seep or leak out during the test hold period, the test is considered to have failed, even if the hydro test has otherwise passed. A leak small enough to allow the pipe to pass hydro test is extremely rare, but is possible, especially if the pressurized system is sufficiently large.

## 9 FLEXSTEEL PIPE QUALIFICATION

Pipe qualification is a more complex issue for flexible steel pipes than it is for simpler pipe structures such as rigid steel or rigid fiberglass reinforced epoxy pipe.

For rigid pipes, design stress calculations can be conducted with simple classical equations to verify the suitability of a pipeline design for a given application. Codes typically specify suitable design factors that have been historically demonstrated to provide high confidence in the pipe design. Thus, whole catalogs of pipe diameters and wall thicknesses are considered approved for use based on the well known design methodology and the use of approved standard materials, such as the API 5L line pipes.

Flexible pipes have complicated interactions between the layers, and historically have been used in very demanding offshore and subsea applications. Accurately predicting the properties of such a structure is complex, and requires more sophisticated computations than are feasible with simple hand calculations.

The API documents developed specifically address qualification requirements for each new design as indicated in Section 3.3. Per API 17J 6.2.1, the design methodology is to be formally verified, and pipes outside the envelope of those previously verified are to be tested per API 17B. API 17B indicates the methods used to determine which tests are required to verify pipe performance for a particular application, and specifies various standard tests to be conducted. Initially, tests are conducted on each pipe. However, as the manufacturer gains experience, the ultimate qualification goal of API 17J/B is to develop a design methodology calibrated with sufficient testing over the range of product sizes and applications to reliably determine the properties and limitations of a new design without having to conduct dedicated tests demonstrating pipe suitability for each project.
This section presents definitions of some of the terms used in the API documents, compares requirements for offshore and onshore pipes, indicates the API requirements for qualification testing, summarizes the tests used, reviews the design methodology qualification, and indicates the qualification to be conducted for the FlexSteel pipe.

9.1 Definitions

API 17B sections are denoted throughout this section in braces as an abbreviation. Several API definitions of interest are indicated here.

**New Design** – substantive modification to any of: a) pipe manufacturing process of structural layers, internal pressure sheath, or end fitting, b) pipe structure, or c) pipe application. \{9.3.2.1\}

**Product Family** – one of three types of un-bonded flexible steel pipe designs or two types of bonded flexible steel pipe. \{4.3.4\}

**Objective Evidence** – documented field experience, test data, technical publications, finite element analysis (FEA), or calculations that verify the performance requirements. \{9.1.1.2\}

**Prototype Test** – test conducted to establish or verify a principal performance characteristic for a particular [new or existing] pipe design \{9.1.1.1\}, with the objectives of validating an unproven pipe design and to [further] validate the design methodology. \{9.1.2.2\}

9.2 Offshore vs. Onshore Requirements

Offshore un-bonded flexible steel pipes are typically custom designed for each individual application because the service conditions for offshore use are often very demanding and the requirements for each application are unique. While the interactions are complex, in general, several structural layers of robust construction are typically required to provide sufficient pressure, collapse, and tension capability. As the pipe structure gets larger and heavier, loads on the pipe due to self-weight increase, which often requires even more structural steel to resist the additional loads.

Flexible steel pipe offshore applications vary widely, from topside applications to dynamic and static risers to buried and unburied flowlines. Water depths range from topside applications to over 10,000 ft (3,000 m). Temperatures range from -40°F (-40°C) for external temperatures to fluid temperatures of 248°F (120°C) or more, combined with variations in fluid composition including sour service. Offshore developments typically have much higher pressures than onshore applications, with 3,000 to 5,000 psi (20 to 35 MPa) design pressures common for production lines, and some injection type applications with operating pressures of 15,000 psi (103 MPa) or more. Pipe sizes range from 2-inch (50 mm) diameter to 20-inch (508 mm) diameter or more, and service can be static or dynamic. Pipe tensions are small under operating conditions for static flowlines, but can be a thousand tons or more for deepwater dynamic risers. Installation loads, especially for deepwater applications, are large, even for flowlines. Thus, to meet the varied requirements of offshore service while containing costs, customized pipes with widely varying designs are used.

For onshore use, the pressures are usually much lower than offshore, the collapse requirements are minimal, and only a modest tension capability is typically required. This allows the use of a simplified structure for onshore use, with only the inner and outer sheaths for corrosion protection and the tensile armor layer for structural strength.
9.3 Requirements for Prototype Qualification Testing

API 17B indicates four alternative methods for qualification testing. The method often applied in the short term on a new pipe design is to build the pipe and conduct appropriate prototype tests (9.1.2.1). Mid-term solutions are to extend the application marginally of an established design based on objective evidence (9.1.1.2), or to scale the results of previous tests on a product family. This scaling is limited to the same criteria (utilization) as the original qualification for equal or lower pressure or P x ID over a range of ±50 mm (2-inch) ID, using the same temperature and test fluid (9.3.4.1). The last alternative, the preferred API 17J alternative and essentially the ultimate goal of API 17B, is to conduct sufficient prototype testing to verify the design methodology over the range of pipe families and properties, such that further prototype tests are not necessary (9.1.2.2, 9.1.2.3). This is similar to the “Type Approval” philosophy adopted by Lloyd’s and others.

This design methodology verification approach has been adopted by FlexSteel as a continuation of the Wellstream design process that is documented by the Lloyd’s Type Approval, [13]. As part of the API 17J approval process, Lloyd’s reviewed and approved the Wellstream design methodology as meeting API 17J requirements, as documented in the Lloyd’s Design Appraisal Document [14]. FlexSteel continues to use the same design methodology now that it is separate from Wellstream. Lloyd’s Register will be reviewing the methodology to confirm the continuity of the practice.

FlexSteel un-bonded flexible steel pipes and end fittings are qualified for use over defined envelopes. The qualification envelopes are defined based on engineering factors such as internal pressure, water depth, and stress levels in the structural layers. The tests have been used to improve and verify the design methodology, and have also demonstrated the suitability of particular pipes and end fittings for specific applications. The adoption of this standardized envelope qualification method assures uniformity in FlexSteel qualification requirements, and assures a high level of confidence in product reliability with a practical level of testing.

9.4 Prototype Tests Overview

Table 19 of API 17B specifies prototype tests to be used to measure or verify principal properties. The most common of these, referred to as Type I or Standard Prototype tests, include burst, axial tension, and collapse tests. Type II tests, or Special Prototype tests, determine pipe capability to withstand certain loads, such as dynamic fatigue test, sour service test, and installation crush tests. Type III tests, called Characterization and Other Prototype tests, are used to determine general or specialized pipe properties. The characterization tests include pipe stiffness, thermal characteristics, and structural damping characteristics. The tests of specialized properties include abrasion resistance, temperature tests, and weathering tests. In addition, the end fitting integrity test from the ISO TS 18226 is used for qualification purposes.

9.4.1 Burst Pressure

The pipe burst test verifies pipe and end fitting strength. Typical burst values are roughly 2x the design pressure. This is not a rigid rule, as the steel tensile elements plastically deform prior to failure, which causes non-linearities in the pipe performance near burst pressure. API 17J uses material utilizations rather than a burst pressure ratio to determine acceptable stresses in the pipe under design conditions.
9.4.2 Collapse Test
The hydrostatic collapse tests verify the structural capacity of the pipe cross section to withstand external hydrostatic pressure. The response of the pipe structure to external hydrostatic pressure is indicated in Section 3.4.

9.4.3 Axial Tension
The axial tension test determines the maximum tensile capability of the flexible pipe, normally in the unpressurized condition. The response of the pipe structure to axial tension is indicated in Section 3.4.

9.4.4 Pipe Minimum Bending Radius
The pipe minimum bend radius calculations are based on a 5.5% maximum allowable strain for the polyethylene layers and a locking bend radius for the armor layers.

9.4.5 Installation Load Tests
The installation load tests (combined bending with tension and combined radial compression with tension) verify the structural capacity of pipe layers under the loads experienced. These are typically customer dependent tests designed to reflect the requirements of specific projects.

9.4.6 End Fitting Integrity Test
API 17B considers the burst and axial tension tests to qualify the pipe design for API 17J and 17K. In addition to these API tests, elevated temperature tests are conducted per ISO TS 18226 [15].

The ISO TS elevated temperature test verifies the integrity of the end fitting. The failure mode is leakage resulting from long term loss of interlayer pressure in the portion of the pipe wall that is compressed by the end fitting. This pressure loss is caused by creep and stress relaxation of the polymers. The test was originally designed as an accelerated life test to simulate the behavior of the polymer over the design life. Thus, the test is conducted at a ΔT above the design temperature, typically 36°F (20°C) or 45°F (25°C). From the Arrhenius relationship for PE, a test duration is calculated that has equivalent creep to that which would be encountered by the pipe at the design temperature during its design life. The test pressure is equal to the design pressure or higher. After the pipe is held at the test temperature and pressure for the calculated duration, it is depressurized, cooled, and a low pressure leak test conducted. To pass the test, no leakage is allowable. This is an extremely conservative test, because the slope of the regression curve used in the design is much steeper than those for the pipe grade PE’s typically used.

9.5 Design Methodology Qualification
An overview of the design process for un-bonded flexible pipes is summarized in API 17B {5.2}. The design methodology is qualified based on a number of prototype tests conducted on different pipe designs from all of the API 17B un-bonded flexible pipe families. The design methodology is encoded in software used to design pipes, determine pipe properties, and verify pipe capability to withstand design loads for individual projects. The design methodology has been documented and will be verified as required in API 17J {6.2} by Lloyd’s.

9.5.1 Software
Un-bonded flexible steel pipes are designed and analyzed using proprietary in-house software. The software applicable to FlexSteel pipe is the FlexSteel Master Design Spreadsheet. This software is
used to design the pipes and determine basic pipe properties and to determine the acceptability of combined load cases by computing the stresses and strains in a pipe resulting from the application of specified loads and comparing these to the maximum allowable stresses and strains.

9.5.1.1 Pipe Design

The FlexSteel Master Design Spreadsheet is used to design pipes by allowing the user to specify the layer geometry, materials, and standard parts in each layer. Based on user input, the software retrieves material and section properties for each layer from standard listings, generates reports detailing the pipe designs with materials and pipe properties, and uses database type functions to store and retrieve pipe designs. The algorithms consider relatively simple load cases to determine pipe properties such as diameters, weight, pipe failure tension, minimum bend radius (MBR), and burst pressure. The algorithms used are documented in 410E002T [16].

9.5.1.2 Pipe Stress Analysis

To verify a flexible steel pipe is suitable for a potential application, a series of worst case load cases are defined and analyzed to verify the load cases do not exceed the maximum allowable utilization of the pipe structural members. The FlexSteel Master Design Spreadsheet is used for this analysis. It accepts pipe geometry and material properties data from the proposed Pipe Design; then calculates the stresses and strains in each layer of the pipe for each load case defined by the user. It determines stresses and strains in each pipe layer under user-defined load conditions, which can include complex combined load cases.

The FlexSteel Master Design Spreadsheet uses a Straight Pipe Model (SPM) in which a matrix of simultaneous force equilibrium equations are derived from the free body diagrams of each layer, using linear elastic behavior, the generalized Hooke’s Law, and considering geometric compatibility. These equations are numerically solved for a number of models, where each model has a specified type of loading. Checks in the software verify that the initial assumptions for each load case are valid and report all models applicable for each load case. The FlexSteel Master Design Spreadsheet superposes the results for each combined load case, outputs these in a tabular format, and compares the resulting stresses and strains to the maximum allowable values. Some properties of interest, such as axial stiffness and pressure elongation are also reported.

API 17J requires that the stresses on the metallic layers and strains on the polymer layers be limited to specified values for all of the various loading encountered with flexible steel pipe.

9.5.2 Burst Pressure

The SPM module is used to determine the burst pressure for the FlexSteel pipe designs considering a 100% utilization of the tensile elements.

For low pressure pipes, the calculated polymer contribution can be as much as 30% of the burst pressure. This is accurate for short durations and low temperatures, but for longer durations, the effects of modulus variation with temperature, creep, and stress relaxation decrease the contribution from the polymer layers. For conservatism, the strength contribution of the polymer layers is neglected in the FlexSteel stress calculations, and the tensile armor elements are considered to be the only structural members that resist the loads resulting from internal pressure in the pipe bore.
9.5.3  Collapse
The collapse test measures the capability of a given flexible pipe structure to resist hydrostatic pressure, an important load case for pipes in submerged applications. The collapse capability of the FlexSteel pipe is considered to result primarily from the liner and shield although the steel layers can provide some additional collapse resistance. Therefore, the collapse resistance of FlexSteel design configurations is established by test and conservative depth ratings recommended.

9.5.4  Axial Tension
The tension capacity of FlexSteel pipe is established empirically and recommended installation loads are conservatively derived from these test results.

9.5.5  End Fitting Analysis
Thin and thick walled cylinder calculations coupled with testing are used to assure the pressure capability of the end fittings is adequate. The failure mode for any load case encountered by the pipe and end fitting system is always located away from the end fitting.

9.6  Pipe Qualification Tests
All three of the API 17B Type I tests are conducted on the FlexSteel pipes for qualification. These are sufficient to qualify the pipe per API 17B.

In addition to the required tests, MBR tests and an end fitting integrity test are conducted. API 17J and 17K consider the end fittings to be qualified by the destructive burst and tension tests. Since the swaged end fittings have a failure mode in long term creep/stress relation that does not occur in standard encapsulated end fittings, an accelerated life test is conducted to demonstrate the end fittings function for the planned design life, referred to as an end fitting integrity test.

Regression testing is not required, as flexible steel pipes do not display the creep rupture phenomena typical of polymer or composite products.

10  CONCLUSIONS

- Flexible pipes are proven products with decades of use and many thousands of kilometers of installed pipe. They have demonstrated high reliability over long design lives. Widely accepted API documents control the design and qualification of flexible steel pipes. The design of flexible steel pipes is well understood as a result of extensive testing conducted to verify and calibrate the design methodology. FlexSteel has earned qualification from API to use the API 17J monogram on its flexible steel pipes.

- A version of the un-bonded flexible pipes with capabilities optimized for onshore use has been developed, which is less demanding than offshore service. This onshore pipe has a simplified design that combines competitive installed cost with the features typical of flexible steel products. These include the speed and ease of installation typical of spoolable products, long life, internal and external corrosion resistance, low operating and maintenance costs, and high reliability/low risk due to the steel reinforcements.

- The compact, low cost swaged end fittings used are optimized for long life, corrosion resistance, and rapid installation under factory or field conditions.
The design of FlexSteel pipes is largely covered by API documents, though some design variations from the classic products around which the API documents were developed do exist. The API documents are widely accepted and used, but have yet to be incorporated into many national standards. The ASTM F2805 standard has been developed to establish requirements for flexible steel pipe for onshore and shallow water applications.

Ongoing extensive test and qualification programs verify the performance of the FlexSteel pipes and characterize pipe performance as new configurations are introduced and operational envelopes expanded.
APPENDIX A

FlexSteel Pipe
A.1 Conveyed Product Compatibility with PE

The ability of the PE material in a flexible steel pipe inner liner to resist the effects of the conveyed fluid over the design life is a primary concern in verifying the suitability of a structure for a specified application. This section documents the effects of the conveyed fluid on the PE. These fluids, especially hydrocarbons, have several effects on PE. This section reviews hydrocarbon and PE chemistry, and indicates the effect of fluids on PE including chemical compatibility, aging, solvation, and blistering. Pipe grade PEs are considered by PE manufacturers to be usable to a maximum of 60ºC in oil and gas service. This compatibility limitation is imposed for use in unreinforced plastic pipes, to control the loss of structural properties that accompanies the swelling and weakening of the PE that results from plasticization. This limitation is based on testing that includes measurement of swelling, tensile testing and the determination of the material stiffness after exposure.

In reinforced flexible pipe service, the structural properties of the PE are secondary because the steel layers resist the internal pressure. With the lesser requirements on the PE in reinforced pipes, and the general lack of problems with solvation, blistering is the major concern. Consult Wellstream prior to subjecting the pipe to any fluid if there is any question regarding fluid compatibility.

A.2 Hydrocarbon Chemistry

The chemical formula for hydrocarbons is H[CH$_2$]$_n$H, where n is the number of carbon atoms, and CH$_2$ is the typical “building block” or mer. The carbon atom has 4 vacancies in the outer orbitals, thus has a tendency to form 4 covalent bonds. The hydrocarbon mer consists of a carbon tied to 2 hydrogen atoms, which can be visualized as sticking out the sides. This leaves 2 bonds, which can be visualized as being at each end. These form covalent bonds with adjacent mers. Thus, hydrocarbons are typically long chains of mers. A typical HC chain is shown in Figure A-1.

![Figure A-1 Schematic of Aliphatic C$_6$ Hydrocarbon (Hexane)](image_handle)

Aliphatic molecules are hydrocarbon molecules with an exclusively long chain configuration, often with side branches. Hydrocarbons can be listed by increasing molecular weight, and separated into groups. One such grouping is presented in Table A-1. Because the weights are ranges, there is some overlap in the number of carbon atoms between groups, and sources have some variance in the hydrocarbons considered to be in each group. Polyethylene is essentially a long chain hydrocarbon with C$_{3000}$ or more. While definitions vary, Low Density PE is considered to have molecular weights of 20kg/mole to 40kg/mole (C$_{1500}$ to C$_{3000}$), and high density PE is considered to have molecular weights of 28 kg/mole to 700 kg/mole (C$_{2000}$ to C$_{50000}$). The variation in density is largely due to the chain length and structure. For LDPE, chains tend to have extensive side branches. These tend to prevent adjacent molecules from packing closely together, which reduces material density and properties. HDPE is essentially aliphatic, and tends to form a crystalline structure because the long chains with few and short side branches nest together, increasing density and strength.
Table A-1 Hydrocarbon Groups

<table>
<thead>
<tr>
<th>Bottle Gasses</th>
<th>Petroleum Ethers(solvents)</th>
<th>Gasoline</th>
<th>Other Hydrocarbons</th>
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</thead>
<tbody>
<tr>
<td>C₁ Methane</td>
<td>i-C₅; n-C₅ Pentane</td>
<td>C₇ Heptane</td>
<td>C₁₂ – C₁₆ Kerosene, jet fuel</td>
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<tr>
<td>C₂ Ethane</td>
<td>C₆ Hexane, cyclohexane</td>
<td>C₈ Octane</td>
<td>C₁₆ – C₂₀ Lubricating (mineral) oils</td>
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<tr>
<td>C₃ Propane</td>
<td>C₉ – C₁₂ Various</td>
<td></td>
<td>C₂₀ – C₃₀ Greases</td>
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<tr>
<td>i-C₄; n-C₄ Butane</td>
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<td></td>
<td>C₃₀ – C₄₀ Paraffin wax</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ C₆₀ Asphalt</td>
</tr>
</tbody>
</table>

Aromatics contain a highly symmetric planar ring with 6 carbon atoms sharing delocalized or floating σ and π bonds, sometimes referred to as a “benzene ring”. Aromatic hydrocarbons include benzene, toluene, ethylbenzene, and xylene, referred to herein as BTEX. Because they contain this ring structure, aromatic hydrocarbons are not considered aliphatic.

A.3 PE Chemistry

Polyethylene (PE) is formed of long chain polymer molecules consisting of a large number of CH₂ units, i.e. a long chain hydrocarbon. PE molecules have a range of length with a distribution that is roughly bell shaped. Longer chains have a higher average molecular weight and generally better properties, also resulting in a PE with higher density. Properties of various PE’s correlate well with density. Chains also have branching when a smaller branch joins to the main chain. Side branches increase the creep and stress relaxation resistance of the polymer by providing chain entanglement that limits the ability of the molecules to slide past each other easily and gives the polymer a rubber-like ability to recover.

PE is a semi-crystalline polymer, as crystalline areas form when unbranched chains nest together within the otherwise random, amorphous polymer matrix. Pipe grades of PE are a compromise between high molecular weight and low crystallinity to achieve a material that will not encounter stress cracking and is still very processable.

Pipe grades of PE have traditionally been specified in a cell rating system per ASTM D3550 in North America. It defines some basic material requirements such as thermal stability, specifies the test methodology for each property, and classifies PE piping materials according to a classification system. Each cell represents a property or characteristic of PE that is significant to processing and/or performance. These include density, melt index, flexural modulus, yield strength, slow crack growth resistance, and Hydrostatic Design Basis. The Plastics Pipe Institute designation is derived from the ASTM D3550 grade (first two cells, density and MI) by adding the Hydrostatic Design Stress (0.5 * the HDB, in rounded/truncated psi units). Typical grades of PE are 2708 and 4710.

Pipe grades of PE are increasingly being specified to meet ISO TR/9080 MRS requirements. This provides a measure of the long term strength of the PE material in MPa at the design temperature, typically 140°F (60°C). Most PE-80’s have a mono-modal molecular weight distribution, similar to a “bell shaped curve”. This is a second generation or “standard” pipe grade PE. Recently, a third generation of pipe grade PE, PE-100 has become available. It has a bimodal molecular weight distribution, combining a tougher, lower grade of PE thoroughly mixed with a stiffer, higher grade of PE. The combination achieves better toughness and higher strength than PE-80.

PEX is a modified PE with bonds introduced chemically or physically between the long polymer chains to create a three dimensional network, and referred to as cross linked PE or XLPE, which is often
abbreviated as PE-X or PEX. The resulting material retains many characteristics of the original polymer, but some physical properties are changed. The primary reason for introducing the cross linking is to improve the thermal stability of the material under load, especially environmental stress crack resistance and resistance to slow crack growth. These properties are critical for cold temperature performance of unreinforced pipe; for reinforced pipe, the PE layers have little stress, and are thus are not subjected to cracks. Three types of cross linking is commonly used in pipe grades of PEX. PEX-A is hot cross linked under pressure inside a die, forming C-C bonds initiated by peroxide. PEX-B has C-Si-O-Si-C (siloxane) bonds that begin forming during extrusion, but mostly form in the solid state in the presence of water. Curing requires months at ambient temperature and humidity, or hours when subjected to hot water or low temperature steam, typically at 176°F (80°C). PEX-C forms its cross links when PE is subjected to beta particle (electron) radiation. All three, when properly processed, are generally considered to have equivalent chemical resistance and strength.

As PE density increases, the temperature capability also increases slightly. Thus, PE-80 performance is similar to that of PE-100 at a slightly higher temperature. Similarly, PEX offers similar performance at a temperature slightly higher than that for PE-100. For all three materials, the fluid compatibility essentially the same, with a slight temperature shift. Thus, the higher grades of material achieve a equivalent strength and swelling level to the PE-80 at a somewhat higher temperature. While HDPE is used in unreinforced pipes in water service up to 176°F (80°C) and PEX up to 194°F (90°C), in hydrocarbon service the temperature ratings are much lower due to chemical compatibility.

When diffusion of hydrocarbon molecules into a PE matrix occurs, the polymer properties are changed, primarily due to plasticization. Plasticization occurs when penetrant molecules spread the polymer matrix apart and create more free volume within the matrix. This allows the long polymer chains to more easily rotate about the bonds and slip past themselves under stress. This results in a reduction of the ultimate and yield tensile strengths and a corresponding increase in elongation to break. Creep resistance is reduced, but impact resistance is increased.

A.4 Chemical Compatibility

Hydrocarbons have a similar composition to PE, and because of their chemical similarity, tend to diffuse into the PE matrix and affect the matrix properties. Hydrocarbon gasses are very small molecules compared to the PE molecules, and easily enter or leave the structure of the polymer matrix. Their size is too small to cause significant expansion of the PE matrix, and any changes in properties are generally limited to a slight swelling of the PE. Molecules in the C\textsubscript{16} range or above are large enough to cause major disruptions in the PE matrix, but have such slow diffusions rates into the PE that they also cause minimal problems. The issue with PE in oil and gas service is the presence of the middle elements – gas condensates and the lower molecular weight elements in gasoline. These molecules are small enough to diffuse quickly into and out of the PE matrix, and yet are large enough to significantly affect the PE properties.

Chemical compatibility is determined by measuring the weight gain of the material PE when exposed to the test fluid for a period of time, until the PE is saturated with the chemical. Table A-3 summarizes the compatibility of PE with various fluids. This includes a compatibility table from Chevron Phillips Chemical Company literature [17]. A more detailed compatibility chart is presented by the Plastics Pipe Institute (PPI) in TR-19 [18].
Hexane (C<sub>6</sub>), cyclohexane (C<sub>6</sub>), heptane (C<sub>7</sub>), and BTEX (benzene, toluene, ethylbenzene, and xylene group of aromatics) are among the worst elements acting on PE. They are small enough to diffuse easily into the polymer, and are large enough to severely affect the properties.

### A.5 Aging

Aging in polymer systems occurs when the polymer bonds are broken by some mechanism resulting in a loss of properties due to the decrease of molecular weight, or the polymer crosslinks and becomes too brittle for its intended purpose. In the case of PE, unless the molecular weight of the parent distribution is decreasing, crosslinking is not considered to be detrimental. Thus, the primary concern with aging of PE is the loss of molecular weight due to chain scission. Chain scission is enhanced by the presence of hexane (C<sub>6</sub>), heptane (C<sub>7</sub>), and BTEX elements which partially solvate and plasticize the polymer, allowing elements that would normally only attack the polymer surface access deeper into the matrix.

The lifetime of the PE is considered to be determined by its thermo-oxidative resistance, which is measured by the Oxidative Inductance Time (OIT) test. During the OIT test, the sample is heated and held at a set temperature, usually between 190ºC and 230ºC. The sample is exposed to a flow of pure oxygen and the onset of degradation is characterized by a distinctive exothermal reaction. The Arrhenius relationship exhibited between the log of the induction time and the reciprocal of the temperature can be used to determine the lifetime of the PE at certain temperatures. This method has shown PE-80 to be good for better than 50 years at 60ºC. In hydrocarbon pipeline applications, there is very little oxygen available for reaction, thus making these predictions very conservative.

### A.6 Solvation

Solvation is the dissolution of polymer matrix into the conveyed fluid at the interface between the fluid and the PE. Each component of the conveyed fluid diffuses into the matrix until its concentration reaches saturation. Solvation of the matrix is inhibited until the PE is saturated. For the mid-range hydrocarbons for which solvation is a concern, saturation of the PE is almost guaranteed within the working life of the polymer.

Temperature affects the solvation rates, as does the amount of penetrant molecules at saturation. Using the approximation that typical chemical reaction rates double for every 10ºC of increased temperature, the diffusion rate at 60ºC would be expected to be roughly 16 times the rate at 20ºC. This also means that solvation occurs at a much higher rate. In addition, the lighter elements in the oil as well as aromatic solvents interact more with PE as the temperature increases.
In most cases, the more aggressive elements such as hexane, heptane and aromatics are relatively dilute. This limits the already very small rate of solvation. Field experience has shown that solvation of the PE is not a concern in typical service conditions with the temperatures limited to 60ºC and dilute concentrations of the mid-range hydrocarbons.

A.7 Blistering

The phenomenon of blistering is the most serious issue to be addressed with regard to the use of polyethylene at higher temperatures. Blistering is caused by the effects of dissolved gases in the matrix during rapid depressurization cycles.

CO$_2$ diffuses rapidly into the PE matrix. The amount of diffused CO$_2$ increases with temperature, CO$_2$ partial pressure, and the degree of plasticization of the PE matrix. N$_2$ also diffuses into the PE matrix, but typically has no significant effect on blistering because it has lower solubility than CO$_2$ and is essentially inert. If the pressure in the pipe bore is rapidly reduced when the PE matrix has a large concentration of diffused CO$_2$, the gas expands and may cause microvoids. This process is driven by the high vapor pressure of the CO$_2$. Repeated depressurization cycles gradually enlarge the microvoids. In the early stages of failure, the volume of the matrix increases, stressing the polymer bonds. In the later stages of failure, the bonds eventually rupture, causing the microvoids to form blisters. PE resists blistering for at least some time, and blistering resistance is improved when:

- The fraction of gas condensates and light crude is low, specifically when the hexane, heptane, cyclohexane, and aromatic hydrocarbons (BTEX) concentrations are low.
- The percentage of CO$_2$ is small.
- Pressures are low.
- The number of rapid decompressions is limited.
### A.8 PE Compatibility Table, 3 Months Exposure

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<th>CHEMICAL</th>
<th>TEMP. °F</th>
<th>TEMP. °C</th>
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<th>ELONGATION % CHANGE</th>
<th>% WEIGHT CHANGE</th>
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</thead>
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Additional information regarding the chemical resistance of Market polyethylene is presented in other Plastic Technical Center publications. This data is provided for use only as guidelines in preliminary determination of packagability because chemical compatibility is highly dependent on storage and use conditions. Furthermore, many products are combinations of chemicals so the ultimate compatibility with the packaging material involves testing the combination of the product material and its proposed container.
2. API 17K, Specification for Bonded Flexible Pipe.
3. API RP 17B, Recommended Practice for Flexible Pipe.
7. ASTM F2805, Standard Specification for Multilayer Thermoplastic And Flexible Steel Pipe And Connections
10. Canadian Standards Association Z662, Oil and Gas Pipeline Systems.
13. Lloyd’s Register Type Approval Certificate 92/00147(E2).
17. TSM-243, Engineering Properties of Marlex® Resins, 1994
18. TR-19, Thermoplastic Piping for Transport of Chemicals, Plastics Pipe Institute Inc.