Wellstream International Limited

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**Title:** FlexSteel™ Flexible Steel Pipe – Technical, Operating, and Maintenance Manual

**Report Abstract:**

This manual provides detailed engineering data on Wellstream FlexSteel pipes. These pipes are API 17J type pipes that have been specifically customized to target onshore use. The capabilities have been optimized for cost competitiveness, while retaining the key features of traditional flexible steel pipes. FlexSteel pipe can be deployed by stringing lengths and either leaving it exposed or burying below grade. In addition, FlexSteel pipe is suited to pull-in applications, either to support directional boring type installations or to pull through long lengths of existing pipelines for rehabilitation purposes.

This manual presents an engineering description of the FlexSteel pipe including detailed 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, 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.

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Onshore steel flexible pipes, FlexSteel, Product N, handling, packaging, flanges

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1 EXECUTIVE SUMMARY

This manual provides detailed engineering data on Wellstream 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 standards using well understood design methodologies. Wellstream has earned Lloyd’s type approval and the API 17J monogram on its offshore flexible steel pipes.
- FlexSteel non-bonded flexible pipe has capabilities optimized for onshore use. It combines features typical of flexible steel products with competitive installed cost. It largely complies with the requirements of the API documents, with minor variations. The compact swaged carbon or stainless steel end fittings are rapidly installed under factory or field conditions.
- Wellstream has conducted extensive testing 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 Wellstream 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

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1. FlexSteel, the layer names Flexbody, Flexbarrier, Flexlok, Flextensile, Flexshield, Flexpress, Flexwear, Flexgard, Flexinsul, Flexliner, Flextape, as well as PipeMaker, FlexPipe Stress, the Wellstream logo, logotype, and the expression “Flexible Pipe Technology” are trademarks of Wellstream.
with API requirements, and the variations from current API requirements are indicated. Stress and strain analysis results are presented for various load cases per API 17J requirements.

This report provides general pipe design information including pressurization/depressurization rates, operational temperature, environmental exposure, minimum bend radius, and handling. Specific data for each design is provided on the relevant Product Data Sheet (PDS). 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 Wellstream.

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 pipe datasheets, reports pipe properties and related definitions, summarizes the pipe layer materials and functions, and presents the end fitting designs.

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.

Wellstream developed a high capability onshore pipe design 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, described in more detail in Section 9.8, 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 application in locations ranging from tundra to desert to swamp and other shallow bodies of water.
Wellstream has also done significant research and development in the area of bonded reinforced thermoplastic pipes resulting in an aramid fiber (Kevlar) reinforced structure. Although this aramid fiber reinforced product has performed very well in general, 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) has led back to the traditional steel reinforced unbonded structure as 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.

Wellstream FlexSteel pipes are 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 of extreme UV exposure applications, an optional white UV resistant outer shield is provided that is designed for long term exposure to high intensity solar radiation. Details of typical installation scenarios are indicated in Section 9.

Wellstream FlexSteel pipe is often used in hydrocarbon production, such as oil and gas gathering lines, 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
3.2 Pipe Design Range

Current standard pipe designs are nominal 3-inch and 4-inch sizes with 5.15 MPa (750 psi), 6.89 MPa (1000 psi), 10.3 MPa (1500 psi) and (2250 psi) pressure ratings for each. Pipe datasheets for each design are available which report the calculated physical properties of the pipe structures in SI and US Customary units. The designs were prepared using Wellstream’s proprietary computer program PipeMaker™, which calculates the physical properties based on analytical formulae supported by comprehensive empirical test data. Designs for nominal 2-inch and 6-inch pipe sizes are currently under development.

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, Wellstream can make custom designs with pressure and diameter optimized for specific project requirements. Contact sales representatives 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, Reference [1], API 17K, Reference [2] and API RP 17B,
Reference [3]. API 17J is a specification for unbonded 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. Reference [4] is an ISO document based on API 17J using identical numbering for most sections. It was originally based on API 17J Revision 1, but most of the Revision 2 changes were adopted prior to issuance. It specifies Reference [5] in places where API 17J specifies API 17B, but this is considered an obsolete specification that has not been updated to reflect API 17B provisions. Wellstream is currently using the API documents as they are being actively updated and are driving the technology; longer term, the ISO documents are anticipated to eventually supersede the API documents.

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 Wellstream FlexSteel pipe conform to most requirements of API 17J. The most important area is that the Wellstream FlexSteel pipe complies with the design methodology and design factors demonstrated over decades of service on API 17J compliant products. In addition, the carbon steel strip and the PE material have been qualified to API 17J. The swaged end fittings used for Wellstream flexible steel pipes are 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 new product, there are some areas with minor deviations from the API 17J requirements. Some of these deviations result because the FlexSteel pipe is a new variant of unbonded flexible steel pipe, and the API 17 recommended practice and standards have not yet been updated to reflect certain characteristics of the new flexible steel pipe. Specifically, API 17B currently classifies non-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 unbonded smoothbore Product Family I and unbonded rough bore Product Family II, which has no pressure armor. The construction is analogous to the bonded smoothbore Product Family IV.

Some of the API 17J materials testing, design methodology, and Independent Verification Agent reviews have not been conducted for full API 17 compliance for these products. In addition, some of the API mandatory testing and other requirements is optional on the FlexSteel pipe. For example, the extensive ultrasonic, liquid dye penetrate and magnetic particle testing required on API 17J end fitting components are not standard on the swaged end fittings. Wellstream has representatives on the API 17 subcommittee, and has submitted detailed proposed changes to API 17B and 17J to reflect FlexSteel pipe requirements.

### 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 apply and specify compliance with Reference [6] for pipelines.
transporting most hydrocarbons and Reference [7] for pipelines distributing natural gas. In Canada, these types of pipelines are controlled by CSA Z662, Reference [8]. Regulators currently apply applicable Clause 13 (polymeric and composite) requirements to non-routine Permits to Construct using flexible steel pipe, and Clause 13 is being 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 Wellstream 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, \( \varepsilon \)** – The smooth extruded PE inner layer has a specific or absolute roughness of \( 1.5 \times 10^{-6} \text{m} \) (\( 5 \times 10^{-6} \text{ft} \)), 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 \( f \) 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 \( 23^\circ \text{C} \) (\( 73.4^\circ \text{F} \)), 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 (\( \mathcal{R} \)) can be determined from the bending moment (\( M \)) applied to the pipe:

\[
\mathcal{R} = \frac{EI}{M}
\]

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 temperature is roughly \( \frac{1}{2} \) that at nominal temperature. Cold weather installations are addressed in Section 9.8.

**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 hydrotest 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 1.5x the design pressure are common.

**Field Test Pressure** – Gauge pressure of water used to hydrotest the pipe after installation in the Field Acceptance Test, as noted in Section 10.3.2.
Installation Bend Radius, IBR — Minimum acceptable pipe radius during installation with low internal pressure, measured to the neutral axis 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 neutral axis 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. Wellstream reports the OHTC 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 Wellstream 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 15.6°C (60°F).

Short Term Collapse Pressure — External hydrostatic gauge pressure required to cause the flexible pipe structure to buckle essentially instantaneously at 23°C (73.4°F), with atmospheric pressure applied to the bore. Under external hydrostatic loading, the flexible steel 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 20°C (68°F). 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.

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.
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 23°C (73.4°F). 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 neutral axis of the pipe. The SBR is calculated in accordance with Section 5.3.1.6 of API 17J, Reference [1], which allows a maximum of 7.7% maximum 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 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 Flexliner Inner Sheath

The innermost layer of the FlexSteel pipe is a liner or sheath. For standard FlexSteel pipe, the liner is of pipe grade Polyethylene (PE). Wellstream has qualified a specific grade of PE 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 3-1. Wellstream normally provides liners with a natural color, however, the mechanical properties are not significantly altered by the pigments, thus, other colors are sometimes used for manufacturing convenience. Black
liner is not normally used, however, there have been rare reports of excessive buildup of static electricity in plastic pipes in dry gas service. While Wellstream has no direct experience with this issue on FlexSteel pipes, for this type of application a black liner with some conductivity can be supplied. The end fittings for this variant are electrically connected to the tensile wires as indicated in Section 7.

### Table 3-1 Liner Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Spec</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS Standard PE</td>
<td>WS-MTL-5205</td>
<td>Includes natural, yellow, static dissipative black</td>
</tr>
<tr>
<td>Food Grade PE</td>
<td>WS-MTL-5028</td>
<td>Approved for potable water</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 FlexLiner 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 FlexTensile Tensile Armor

The hoop and tensile structural strength of the FlexSteel pipe structure is provided by FlexTensile 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.

### Table 3-2 Steel Strip Material

<table>
<thead>
<tr>
<th>Application</th>
<th>Material Spec</th>
<th>UTS</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>WS-MTL-5233</td>
<td>690 MPa (100 ksi)</td>
<td>Cold Rolled/Stress Relieved</td>
</tr>
<tr>
<td>Sour Service</td>
<td>WS-MTL-DEV</td>
<td>690 MPa (100 ksi)</td>
<td>Meets NACE MR01-75</td>
</tr>
</tbody>
</table>

#### 3.5.3 FlexShield Outer Sheath

The FlexShield 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 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.

In addition to the standard yellow outer shield, optional black or white outer shields are available. The black PE shield contains 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, radiate heat at night, causing a significant cooling at night, especially when no clouds are present.

The optional white PE is specifically designed for 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 severe than expected service conditions because it uses a high intensity incident radiation and is accelerated by operating 24 hours per day.
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 a weld prep. The connector mates with other pipes or production facilities. The end fitting ID is typically only 3 mm (0.12-inch) 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 non-bonded flexible steel pipe offshore. These are bolted together from a number of components and filled with potting compound, and pressure resistant elements are required to be of ASTM A668 (forged carbon or alloy steel bar), ASTM A29 (carbon or alloy steel bar), or ASTM A182 Grade F51 (S31803 Duplex). 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. Wellstream qualifies the pipe and end fittings 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 presents the basic structure of the Wellstream end fitting design, a 4-inch end fitting ready for assembly onto the pipe, and assembled 3-inch and 4-inch end fittings. 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.

![End Fitting Design Diagram]

Figure 3-3 End Fitting Design

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) is used where additional corrosion resistance beyond that of carbon steel is required, such as produced fluids with water and ionics present. 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 by Wellstream. The ANSI flanges are typically connected using studs and nuts and normally sealed with a spiral wound metal gasket. Table 3-3 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 pair of mated mid-line end fittings.

<table>
<thead>
<tr>
<th>ANSI Class</th>
<th>3-inch End Fitting</th>
<th>4-inch End Fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[lb]</td>
<td>[kg]</td>
</tr>
<tr>
<td>300</td>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>400</td>
<td>Use CL 600</td>
<td>41</td>
</tr>
<tr>
<td>600</td>
<td>27</td>
<td>12</td>
</tr>
<tr>
<td>900</td>
<td>37</td>
<td>17</td>
</tr>
</tbody>
</table>

**Figure 3-4 Swaged End Fittings with ANSI Flanges**

A simple stub end can be supplied when bolted connections are to be eliminated. The field weld used to join these end fittings 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.

The forming of the end fitting is performed by a specialized hydraulic press referred to as a “swaging machine”. The swaging equipment includes the press itself, a hydraulic power unit (HPU), a control system, and tooling. Wellstream uses multiple variants of the equipment, with some commercially purchased, and others that have been developed in-house. A heavy duty general purpose swaging machine used at the factory is shown in Figure 3-5a; a lighter field version is shown in Figure 3-5b.

![Figure 3-5 End Fitting Swaging Equipment](image)

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, Wellstream recommends the use of our own technicians to perform all swaging operations on Wellstream pipe.

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.

Wellstream also provides a field training course 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 assu...
3.6.4 Installation End Fitting

An installation end fitting can be used for shipping, pull-in, and hydrotest. Unlike the standard end fitting with an ANSI lap flange, the installation end fitting has a short, low profile design well suited for pull-in operations. It is threaded to accept low profile pull heads as well as shipping and fill heads. The installation end fitting has a more restricted bore than standard end fittings, which can affect pigging operations. The installation end fitting is of carbon steel and designed for short term use and installation, and has not been tested and qualified for permanent use.

3.7 Marking

FlexSteel pipe marking includes manufacturer, structure number, nominal size, pressure rating, maximum temperature under optimum conditions, MBR and date of manufacture, and is printed in 25 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 factory acceptance tests (FAT). The hydrotest is the most important FAT. The pipes are typically fitted with end fittings on each end. End fittings can be applied to pipes and tested using the fixtures at the factory, at a Wellstream yard, or in the field.

3.8.1 Acceptance Tests

API 17J Section 9 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 9.1.2, 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 ashore, 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 then cut to length and end fitted in the field, the field hydrotest is the key acceptance test for segments cut in the field.

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 FlexLiner or FlexShield, so the field procedure is normally to verify flow at each end fitting separately, rather than both together.

4 PIPE CAPABILITIES

Wellstream FlexSteel pipes, like all piping components, are capable of withstanding certain 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

The maximum operating temperature for the FlexSteel pipe is shown on the respective pipe 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. Verify the temperature capability of the pipe in a given application with the factory 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.

4.2 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

As specified by API 17B 11.5.3.3 and 11.5.3.6, a typical maximum pressurization rate allowable for the hydrotest is 18 MPa/hr (3 bar/min; 45 psi/min) and a typical maximum depressurization rate is 108 MPa/hr (18 bar/min; 260 psi/min). Wellstream FlexSteel pipe is rated at up to 10 bar/min (145 psi/min) for pressurization and 20 bar/min (290 psi/min) for depressurization, based on extensive hydrotest 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 Reference [9]. 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 FlexShield outer sheath is not appreciably affected by fresh or salt water. Fluid compatibility for the outer sheath is similar to that for the inner sheath, as documented in Section 4.6. Before subjecting the FlexShield outer sheath to contact with any other chemicals, contact Wellstream to verify that the proposed exposure is acceptable.

UV resistance of the outer sheath is indicated in Section 3.5.3. The UV resistance of the yellow PE is somewhat limited, but either the black or white polymer systems are 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.

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 5x 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 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 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 Wellstream prior to subjecting the pipe to any fluid if there is any question regarding compatibility.

4.6.1 Hydrocarbon Compatibility

For Wellstream 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.

Certain other molecules can affect PE adversely, especially in high concentrations. As noted above, a
compatibility chart is presented in Appendix A.

### 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.

#### 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. Pitting can also
occur due to carbon dioxide or acid exposure, as indicated below.

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 0.0003
MPa or 0.3 kPa (0.05 psi) or greater are considered to constitute sour service. For example, a well at a
pressure of 6.9 MPa (1,000 psi) 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, H₂, 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 used by Wellstream
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 H₂S. 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 H₂S, embrittlement can occur quickly.

Wellstream typically uses plain carbon steels for flexible steel pipe reinforcements. For standard
offshore flexible steel pipes, Wellstream has qualified several plain carbon steels for sour service.
These steels have similar compositions and strengths to the steels being used for the FlexSteel pipe,
but have different processing.

Table 3-2 presents the steel used in FlexSteel pipes. The standard cold rolled/stress relieved steel
largely complies with NACE MR01-75, but does not meet the 5% maximum allowable cold work
requirement. Per API 17J, for conservatism, the H₂S 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
H₂S 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 0.1 bar (10 kPa) H₂S partial pressure, 0.9
bar (90 kPa) CO₂, however, some blistering from HIC was found. Thus, the standard steel is not
considered to be generally suitable for sour service with high H₂S concentrations.

Long term testing is ongoing for determining acceptable thresholds of H₂S 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 GM0177
requirements. Testing of this material in direct exposure to 1 bar (14.5 psi) H₂S has shown no
evidence of HIC or SSCC.

4.8 Flexible Steel Pipe Stress/Strain Analysis

API 17J Section 5 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 \( 0.67 \times 0.90 = 0.603 \)
- This load case is used to determine the pressure rating for the pipe, using the FPS software described in Section 12.5.1.2.

For extreme or abnormal operations, the maximum tensile armor stress factor \( 0.85 \times 0.9 = 0.765 \)

- For onshore fully static applications, the abnormal loads are generally the same as the recurrent operating loads indicated above. Since the load case allows 54% 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, Wellstream recommends 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 \( 0.91 \times 0.9 = 0.819 \)
- The factory hydrotest pressure is performed at \( 1.3 \times \text{Design Pressure} \) as required by API 17J for static flowlines. Maximum allowable hydrotest pressures are available for each specific design if customer operational standards require higher hydrotest 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.
• 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 FlexShield 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 Wellstream flexible steel pipes can be sealed to keep out oxygen, but this is not required. In addition, no preservation fluid inside the pipe is 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 hydrotested 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 FLOATATION AND ON-BOTTOM STABILITY

FlexSteel pipes are normally deployed onshore, however, with proper precautions they can also be successfully used in submerged applications. For submerged applications such as river crossings, the FlexSteel pipes are 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 pipe 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, Wellstream generally recommends using a heavier pipe 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 an inner sheath of extruded polymer. The PE inner sheath is nearly hermetic, but allows a small amount of gases to permeate through. CH₄, CO₂, H₂S, and H₂O comprise the major permeants. These permeants 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. Permeants 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 permeants 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, preventing excessive pressure build up. The end fitting contains a 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 gasses can be released to the atmosphere, conveyed to a disposal unit, or pressurized and re-injected into the conveyed fluid in the pipe bore. Wellstream can also supply in-line vent valves that will allow the gas to flow at pressures slightly above atmospheric while preventing the ingress of oxygen, water, or other environmental fluids. At midline end fittings, a tube is installed in both end fittings to connect the annuli of the two pipes together. The vent port at the wellhead end is typically blocked in using a threaded plug.

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.

Wellstream can conduct detailed gas permeation analyses using proven software tools for flexible pipes for specific applications, but these are rarely required. A typical permeation analysis was conducted for illustration purposes using an in-house computer program. The program is designed for use with flexible steel pipes. The analysis was conducted on a 102mm (4-inch) nominal bore pipe, using gas at 50 bar (725 psi) containing 0.15% CO₂ and 55.45 % CH₄, and assuming an ambient temperature of 25°C (77°F). The input values and results, including the calculated permeation coefficients and permeation rates, are presented in Table 6-1. For a pipeline of known length, the permeation rate, Q, in cm³/sec, would normally be presented. For this generic case, a rate per unit length or Q/L is presented. Typical permeation for this pipe is 70 std cm³/hr/100m pipe with the conveyed fluid at 25°C (10 std in³/hr/1000ft pipe at 77°F) and 6x more with the conveyed fluid at 60°C (140°F). The permeation coefficient for water is also presented, and is significantly less than the more mobile species.

Just as diffusion processes drive permeants from the pipe bore into the annulus, they also drive diffusion from the annulus to the external environment, and from the external environment to the annulus. However, due largely to the low pressure of the gasses in the annulus and the outside environment, the diffusion rate is extremely low, and as a practical matter can be neglected. This was verified in an Advantica (formerly British Gas) study, Reference [10]. The study measured the permeation rates of bonded and unbonded RTP’s, and verifies the gasses essentially all escape at the end fitting for both constructions. This contrasts with the venting system of spoolable composite pipes, which vent along the entire pipe length, rather than at the end fitting.
Table 6-1  Fluid Composition Data and Gas Permeation Calculation Results

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
<th>Results at 23°C</th>
<th>Results at 60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perm. Coeff.</td>
<td>Q/L</td>
<td>Perm. Coeff.</td>
</tr>
<tr>
<td></td>
<td>[cm²/s·bar]</td>
<td>[cm³/s·m]</td>
<td>[cm²/s·bar]</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.00 %</td>
<td>1.409E-07</td>
<td>0</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.15 %</td>
<td>7.567E-08</td>
<td>3.577E-06</td>
</tr>
<tr>
<td>CH₄</td>
<td>55.45 %</td>
<td>1.751E-08</td>
<td>3.691E-04</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.00 %</td>
<td>1.177E-06</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3.727E-04</td>
<td>0</td>
</tr>
</tbody>
</table>

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.

Wellstream FlexSteel pipes typically have electrical continuity between the tensile armor strips and the end fittings provided by continuity clips applied during end fitting installation. These can be omitted to ensure 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 ½Ω to 1Ω per kilometer of pipe, and the specific resistance for each pipe in milli-Ω/m (≡ Ω/km) is shown on the respective pipe datasheet. The end fitting and continuity clip resistance is in the µΩ range, and can be neglected.

8  PACKAGING AND ANCIILLARY EQUIPMENT

This section presents the packaging design and ancillary equipment information for Wellstream FlexSteel pipes. Wellstream packaging, such as reels, pallets, and slings and spreader bars used to lift reels are typically re-usable, and are generally rental units that are to be returned. Some ancillary equipment such as installation and pull heads can be either rented or, when specified by the contract, permanently supplied. Other ancillary equipment, such as fire resistant blankets or wrappings, bend limiters, and studs, nuts, rings, and gaskets for flanges are only supplied when required by the contract.

8.1  Packaging Design

Wellstream flexible steel pipes are typically supplied as full length reels. As delivered, each end of the pipe is usually terminated with a production end fitting. This section is necessarily general, as packaging varies by job requirements.
8.2 Pallets

While typically not supplied in this form, Wellstream flexibles in short lengths can be supplied on wood or steel pallets. Pallets are generally designed to be lifted only by fork truck, but can be designed with attachment points for overhead lifting if needed.

8.2.1 Reel Design

Wellstream flexible steel pipe is manufactured in essentially continuous lengths, limited only by manufacturing reel size and weight handling capabilities. Optimum shipping and installation reel size is a tradeoff between more easily handled small reels holding relatively shorter lengths of pipe that require more mid-line connections, and larger heavier reels with longer pipes with fewer mid-lines but increased handling difficulty and costs.

Wellstream FlexSteel pipes are normally shipped on steel reels that are Ø3.7m (Ø12 ft) x 2.6m (8.5 ft) wide. Wellstream has several similar styles of reels, with some variations in reel dimensions. The reels shown in Figure 8-1a and b are 2.6m (8.5-ft) wide, and the reel in Figure 8-1c is about 1.2m (4-ft) wide. The narrower reel is used to match some existing installation equipment. The reels are sized to fit on trucks for road transport, and approximate lengths per reel are shown in the most current product brochure. Reel handling procedures are indicated in Section 9.1.

Figure 8-1 FlexSteel Pipe Reels

In planning for transportation and handling, consider the equipment and methods used to offload the transportation vehicle, stage the reels for installation, and load the payoff equipment to assure adequate lift capacity is available as required.

8.3 Lifting Equipment

Spreader bars should be used to lift the reels, as the flanges are not designed for side loads resulting from a direct hook lift. Lifting should always be done from the central tube or a shaft through this central tube.

8.4 Payoff Equipment

Once the reel is in the field, payoff equipment is required to remove the pipe from the reel, as noted in Section 9.2. This can be as simple as a frame with a pipe fitted through the hubs of the reel to allow it
to turn, or as sophisticated as a powered A-frame or rim drive unit with a level winder/traversing beam/fairlead and tensioner for maximum control of the pipe during spooling and unspooling operations. Such equipment is normally provided by the installation contractors.

### 8.5 Shipping Heads

Shipping heads are assembled to pipes to prepare them for shipping. The shipping head is a light duty head designed to allow the pipe end to be tied off during shipping. Depending on the packaging method used, shipping heads can range from being a simple plywood or polymer cover to being a steel plate or blind flange. They can be tied to the packaging by running wire rope through holes in the head, connected to an eyebolt or swivel hoist, or occasionally, a padeye. Shipping heads are not pull tested or certified, and should not be used for overhead lifting. Safety precautions must be taken when the shipping heads are used to prevent injury or property damage should a rigging or pull head failure occur.

### 8.6 Pull Heads

To pull a pipe, the shipping head is removed and a pull head attached. The pull head has fixturing to attach a wire rope or other rigging. Standard pull heads do not necessarily make a fluid tight connection, but they can be designed to resist test pressures if needed. Such pull/test heads normally have a small fill port that can be used to pressurize the pipe.

While the pull heads are designed to take tensile loads, safety precautions must be taken during pulling or lifting operations to prevent injury or property damage should a rigging or pull head failure occur.

### 8.7 Fill Heads

Pipeline systems are normally filled with water to conduct a hydrotest during the commissioning process. Provisions are normally provided during the design phase of the system to water and dewater the system, including the flexibles. Occasionally flexibles are filled directly before tie-in to the system, especially for flexible steel pipes in pulled in applications. The fill ports in test/pressure heads are normally small, and for long flowlines, the flowrates needed to expeditiously fill the pipe are much larger than can be reasonably accommodated by the very small ports in most pressure heads. In these cases, fill heads are normally installed to provide a direct interface to fill hoses and pumps. Fill heads are fabricated by drilling and tapping a fill hole in a blind flange, or in a steel plate if the fill head is not required to withstand hydrotest pressures.

### 8.8 Rigging

The end fittings are typically fixed directly to the reel flange by nylon rope, lightweight wire rope or tie-down straps, and are not supplied with installation rigging. The supplied rigging, normally including the shipping head, is for shipping only, and is not intended to be subjected to installation loads. It must be replaced by certified rigging prior to installation. Do not use rigging for installation unless it is adequately rated, and verified to be in serviceable condition.
Most flexible steel pipes are shipped with unrated shipping heads and rigging. Do not use the rigging for lifting or installation operations. Wellstream can provide rated pull heads as required by the contract.

8.9 Mounting Hardware

Mounting hardware, such as clamps for hub type terminations or studs, nuts, and rings or gaskets for flange type terminations are typically supplied by the contractor, but can be supplied by Wellstream when specified in the contract. New hardware should be used when installing the pipes, and new seal rings or gaskets should be used whenever the flange seal is broken open, unless otherwise indicated by the flange manufacturers or pipeline engineer.

8.10 Riser Protection

Wellstream flexible steel pipe can be connected below grade to a steel riser, or more commonly, simply brought up to the surface. The surface connection is often horizontal, though a 45° elbow canted downward is helpful in routing the riser. Figure 8-2 shows some typical riser top end connections prior to final burial. Both of the illustrated installations have the flanges supported by a steel plate attached to a pile, which are just visible in the photos. In Canadian applications, CSA Z662 requires mechanical protection for risers in composite systems. This requirement probably reflects the relatively brittle nature of the rigid fiberglass pipe for which Clause 13 was originally written. FlexSteel is both tough and flexible, and has better impact resistance than both composite and steel pipe. Thus, no mechanical protection for FlexSteel risers is required in typical applications. Figure 8-2a and b show a riser flanged to a valve in a satellite facility. Figure 8-2c shows a riser to a manifold at the wellhead.

![Figure 8-2 Typical Riser Top End Details](image)

For applications that require additional protection, Wellstream can supply a short length of flexible outer sheathing of either extruded UV resistant polymer, or corrugated stainless steel. These are strapped to the end fitting to fix them in place. In addition, standard insulation and sheathing, as used on rigid steel pipe, can also be applied.
9 REEL HANDLING AND INSTALLATION PROCEDURES

Rapid installation is one of the major advantages of flexibles. Rapid installation results from the flexible nature of the pipe and the long continuous lengths of pipe that are stored and transported on each reel. Because of the size and weight of the reel, reel handling is one of the major considerations in preparing for an installation. This section presents guidelines for reel handling and surveys common installation procedures used for Wellstream flexible steel pipes. Installation contractors typically use their own procedures, equipment, and expertise. At all times during installation and handling, the limitations of Section 4 must be accommodated to assure the pipe is not damaged.

9.1 Reel Handling

Reels of flexible pipe can be transported and stored in either the flange vertical or flange horizontal position. Reels are normally handled in the flange vertical position, because overturning and uprighting the reels is more difficult and takes more equipment than the straight lifts used for flange vertical reels.

9.1.1 Reel Storage

Round reels that are stored vertically are placed on cradles or chocked to prevent rolling. Rolling a reel on the ground is not recommended, for structural and safety reasons. Fork lifts can be used on some reels. Stacking (horizontal flange) reels is not recommended. Outside storage is generally acceptable.

9.1.2 Horizontal Lifts

A horizontal lift of a reel is normally accomplished with a triple or quad leg sling. Shackles are often used to connect the lifting slings to the reel. Lift the reels only from appropriate lift points.

9.1.3 Vertical Lifts

Vertical lifts are generally accomplished by lifting the reel from an overhead hook. A spreader bars should be used to lift the reels, as the flanges are not designed for side loads resulting from a direct hook lift. Headroom on the crane using the planned load and rigging should be verified prior to conducting a lifting operation.

The reels can be lifted by a sufficiently large fork truck. The fork truck typically lifts the reel from a shaft through the center of the reel rather than standard forks. Reel weights are important in sizing the lifting equipment. For fork trucks, both the CG and the weight must be considered.

9.1.4 Uprighting and Overturning Reels

The reel flanges are not designed to take large side loads near the rim. Thus, when uprighting and overturning reels, take care to assure the flanges do not have a significant side load applied near the rim.
9.2 Unspooling Equipment

Two general types of drive systems are generally used to spool (or takeup) and unspool (or payoff) flexibles in the flange vertical position: rim drives and hub drives.

Rim drives, also referred to as “underrollers” and “dollys”, support the reel on driven wheels that rotate the reel. They are easily loaded by lowering the reel onto the rim drive. The driven wheels support the reel with essentially four points, and the reels must have sufficient strength in the flanges to withstand this type of loading.

Hub drives systems generally have a shaft or hubs that support the reel, and can be significantly more difficult to load than rim drives. They can be designed to lift reels off the ground themselves, thus can have more flexibility in loading. Hub drives positively restrain the reel and are thus better suited to mobile applications and can be capable of much higher speeds than rim drives. They also tend to have higher capital and maintenance costs than rim drives. Reels that are used only in hub drive systems can be lighter and lower cost than rim-drivable reels. Wellstream round reels are capable of being deployed in either type of drive system.

The simplest form of hub drive is a passive stand. A passive stand is acceptable for unspooling short lengths of pipe, however are not generally recommended for typical installations. Passive systems are usually not able to maintain any consistent level of back tension, and can free wheel enough to loosen the pipe on the reel. At a minimum, a system with brakes should be used to facilitate maintaining tension on the pipe. The best type of system is a powered system. A powered system not only gives fine control of the tension on the reel, but also allows the pipe to be respooled on the reel if necessary.

![Figure 9-1 Installation Using Passive Stands with Brakes](image)

For field use, several types of unspooling equipment are used. For an installation where the reel does not move along the installation route such as a pulled in rehabilitation project, any of the static machines such as stands, can be used. For mobile deployment, one relatively light duty type is a simple frame that attaches to a bucket loader and holds a reel. The pipe is paid out by driving the bucket loader along the length of the trench. Another type of mobile unspooling equipment is a
dedicated installation trailer. These range from very light trailers typically used in the utilities industry to custom designed machines that accommodate large reels.

![Installation Trailers](image)

**Figure 9-2 Installation Trailers**

### 9.3 Installation Procedure

The loads imposed on flexible pipe during installation must be less than the limits indicated in Section 4. To assure these loads are limited, a detailed procedure can be established taking into account such factors as the arrangement of the facilities, equipment capabilities, allowable pipe stress, and environmental conditions.

As noted in Section 4, flexibles can be damaged by imposing a localized concentrated load or sharp bend in the line causing it to kink or buckle. This type of damage is generally caused by mishandling such as choking the pipe with only one sling, or by pulling the pipe around an obstruction. It is important to maintain the largest bending radius possible during handling and installation of the pipe. Particular attention should be given to avoid excessive bending to the pipe, especially behind the end fittings during installation. Crushing and tension loads must also be controlled to prevent damage to flexible steel pipe.

### 9.4 Loading Reel into Equipment, Unloading Pipe from Reel

Before loading the reel into the unspooling equipment, first determine the direction in which to load the reel. To do this, determine which end fitting will be removed first, and the direction in which it is to be unspooled. Orient the reel so that the pipe unwinds from the bottom of the reel, not over the top. The reel may be placed on an A-frame, hub drive system, or stand using a sling and shackle arrangement, or the shaft may be pre-installed through the arbor hole, and the assembly lifted onto the A-frame.

To load a reel into a drive system, the reel is lifted vertically, then lowered into position. Turn the reel so the first-off end fitting is near the ground, as the end fitting could otherwise potentially spring back over the top of the reel and fall over the other side. The outer end fitting is fixed to the reel flange.
with lightweight rigging not intended for installation loads. For maximum control and safety, the installation rigging should be installed to the end fitting prior to disconnecting shipping rigging.

Whenever handling the pipe, assure the handling requirements of Section 9.1 are met. The pipe can be unspooled for installation by pulling it from the reel. As the last of the pipe is pulled from the reel, unreel it carefully to prevent damage to the pipe or loss of control as the inner end fitting is pulled from the reel.

The pipe can also be unreeled horizontally by suspending the pipe horizontally from a hook using a swivel. The shipping container must be carefully handled, as it is not designed to withstand significant dynamic loads.

9.5 Plowed and Trenched Installations

Most buried applications are installed using either plowing, trenching, or combination of the techniques. Flexible steel pipes are well suited to buried applications because of their negligible axial strain with pressure. When free, flexibles undergo thermal strains that are somewhat less than those of PE pipe. When buried, the soil typically fixes the flexible pipe so it does not move. One big advantage of flexibles over rigid steel pipe is the relatively narrow rights of way that are feasible with the flexibles.

Plowing in a pipe is generally the fastest installation method. It is widely used in open areas without pipe crossings, especially in areas with deep soil or sand. The plow essentially cuts a trench and lays the pipe simultaneously. Figure 9-3 shows a typical plowing operation. Plowing is better suited to open spaces than crowded areas, and some trenching during a plowed installation is common, especially near the ends of the pipe and at crossings.

![Figure 9-3 Plowing Operation](image)

Trenching in flexible steel pipe is accomplished by digging a trench, moving the pipe into the trench, then backfilling. Figure 9-4a shows a typical trenched installation. Like plastic pipes, the areas in contact with the pipe should be free of large, sharp rocks or protrusions. Crossings under roadways are typically pulled into a carrier pipe. The bottom of the trench should be prepared with a thin layer of soil or sand in rough or rocky conditions. Once the pipe is laid in the trench, the system is normally flanged up, filled with water, and hydrotested before filling the trench. If movement of the pipe is a concern, some fill can be placed in the trench as needed to restrain the pipe. In areas with large sharp rocks, the pipe should be covered with soil, sand, or fine gravel prior to using rough fill.
Flexibles are typically installed in trenched installations onshore by paying out the pipe from the reel as the reel is transported along the pipe route. The pipe can be laid directly in the trench, or beside the trench and the position can then be adjusted by moving or dragging the pipe into place as necessary. For swamps or other areas with difficult access, the reel can be fixed and the pipe pulled into position with a remote winch or tow vehicle. Figure 9-4b shows pipe being pulled off a reel into a ditch, illustrating that the flexible pipe easily accommodates bends in the trench. The trench should be as straight as possible to minimize the tension required to pull in the pipe. Because of the tensile strength of the pipe, lengths of well over 1km can be routinely installed using this method. Figure 9-4c shows that FlexSteel pipe is easily routed under existing pipes by digging out under the pipe and pulling the flexible in underneath. When pulling FlexSteel pipe where tensions may exceed 5000lbs, it is recommended that a dynamometer or tension monitoring device be used to assure the tension does not exceed the maximum load recommended on the data sheet or authorized by Wellstream engineering. Once strung, FlexSteel pipe can be covered or left exposed. Pipes are normally left exposed only in secure areas or areas with very low population densities, partly to prevent contact with the pipe by outside parties.

Figure 9-4  FlexSteel Pipeline Routing

9.6  Trenchless Installation

FlexSteel pipe is also used in trenchless applications, both to remediate existing pipelines, and in new installations using horizontal directional drilling techniques.

For pipe pull through applications, the first step is to prepare the existing pipeline for the installation of the flexible. This is accomplished by clearing the pipeline and cutting out any obstacles, generally with scraper pigs and gauging pigs. Bends typically have to be cut out to allow the pipe to move easily around the corner, and the pipe is normally installed through each such section separately, with end fittings joining the sections of flexibles where the bends were cut out. Pipes are typically cleared
by passing multiple pigs through the pipeline to clean out wax, followed by scraper and brush pigs to clean the pipe and then a gauge pig to verify the pipe is clear.

Once the pipeline is prepared, either a wire rope line is pulled through the pipeline with a pig, or a drill pipe or rod is assembled and passed through the pipeline. The end of this is attached to the flexible pipe. By pulling on the wire rope or drill string, the flexible pipe is drawn through the pipeline. The pipe can be attached to the fixturing with a breakaway link to limit tension. A liquid slurry, typically a bentonite, polymer, or bentonite/polymer mixture, is used to lubricate the pipe to ease its passage through the old pipeline.

Flexible steel pipe is also well suited for trenchless applications where there is no existing pipeline. These applications use a horizontal directional drilling technique to drill a pilot hole using a steerable drill head. The head is retrieved in a receiving pit at the end of the run and replaced by a reamer, to which the flexible pipe is attached. As the reamer is pulled back, it increases the diameter of the pilot hole to accommodate the pipe, which is pulled behind the reamer. The lubricant can be pumped through the drill pipe to the pulling head.

Wellstream FlexSteel pipe, being flexible, is not well suited for use in hydraulic mechanisms that directly push the pipe into the ground. This technique requires a rigid pipe, and is best suited to the cast iron pipe for which it was developed.

For modest tensions, the Wellstream FlexSteel pipes have very limited elongation. However, once a FlexSteel pipe has experienced significant tension for an extended period, it should be pressurized to the design pressure prior to backfill or physical constraint. This allows a pipe that has experienced axial strain to return to its design length. If a pipe is over-tensioned, the damage is normally limited to the area immediately adjacent to the end fitting. Cut off the old end fitting and install a new one to remove the damaged area. In rare cases where the excessive tension of the pipe results from friction build up away from the end fittings, longer lengths of pipe may need to be removed. In any tension damage situation, it is recommended that Wellstream be contacted so the product can be cleared by Wellstream engineering prior to placing in service.

9.7 Submerged Installation

Submerged installation procedures, in addition to the factors indicated above, should consider the water depth, sea bed conditions and profile, and any contingency plans for abandonment and retrieval. The installation procedure needs to consider all the pipe properties and handling concerns indicated in Section 4, including limitations on the tensile loads applied.

9.8 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 gets greater 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. To reduce the effects of the stiffness and the pre-set, the pipe can be pre-heated to soften the PE or respooled onto a large diameter reel to allow a larger radius pre-set to be formed. The pipe is normally applied with some degree of tension 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. 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, normally essentially straight in most sections.

The current Wellstream onshore flexible steel pipe design was developed from flexible steel pipes deployed onshore on the North Slope in Alaska. The first generation of onshore flexible steel pipe included 17 jumpers installed at Prudhoe Bay in 1996 and 1997 as documented in Reference [11]. Steel pipes in this application are installed above grade on vertical support members, with expansion loops. The flexible properties of the pipe allow installation without expansion loops, and the flexible steel pipe was provided with sufficient thermal insulation to allow the pipe to be laid directly on the tundra soil. The flexible pipe offered reduced installation cost and time from the rigid steel pipe equivalent, and facilitates removal when the infrastructure is removed and the land restored to its original condition.

This first generation pipe included a protective stainless steel layer both inside the pipe bore and outside the pipe OD. In addition, a relatively thick layer of insulation, integral heat trace, and two watertight layers outside the steel layers was used to meet the customer specification. The combination of extensive capability coupled with the standard offshore fabrication technology resulted in a product that was a technical success, but was not commercially feasible.

The major concern with the flexible steel pipe in cold weather was the handling of the pipe, specifically the properties of the PE pipe grade polymer used in the pipe structure. As indicated in Reference [11], extensive testing was conducted to verify the PE properties and pipe properties. This testing included determination of the glass transition temperature, Tg, to be -126°C (-194.8°F) based on a 1 Hz test using the inflection point on the Tan δ vs. temperature curve, a brittleness test at -90°C (-130°F) with no breaks, a freeze-thaw test, and tensile test, pipe bend test to MBR, impact testing, and a hydrotest, all at -40°C (-40°F). The conclusion of the paper is that the flexible pipe and the PE material had been demonstrated as fit for use and installation in cold weather down to at least -40°C (-40°F).

A second generation pipe developed to improve cost competitiveness was installed in 1999, as documented in Reference [12] and shown in Figure 3-1. Since qualification of the earlier pipe had demonstrated fitness for purpose, extensive cold weather testing was not required for this pipe. Like the first generation flexible steel pipes, these pipes are still in service and operating without incident since being installed.

In addition to the cold weather testing conducted on flexible steel pipes, Wellstream has conducted cold temperature testing on an RTP (Reinforced Thermoplastic Pipe) that uses PE for the inner and outer sheaths, as documented in Reference [13]. The pipe is of bonded construction and is reinforced with aramid (PPTA) fiber. A four point bend test conducted with the bore at -74°C (-101°F) and the outer shield at -50°C (-58°F) and a spooling test at -23°C (-9.4°F) showed no problems with the pipe. While the pipe construction is somewhat different from the flexible steel pipes, again the PE is shown to have good cold temperature properties.

Full scale reel-to-reel testing was conducted on a 4-inch 1000 psi FlexSteel sample at -29°C (-20.2°F) and -40°C (-40°F), on reels with a drum diameter of 2.13m. Cold temperature pipe handling was similar to that at 20°C (68°F), and while the pipe is somewhat stiffer at these cold temperatures, the
pipe itself is still safely handled without unusual effort. Thus, as detailed in Reference [14], the pipe is suited to cold weather installations.

9.9 Flexible Pipe Retrieval

Flexible steel pipes can generally be retrieved without damage using procedures similar to those used in its installation. Particular attention should be given to the retrieval of intermediate connection. Buried pipe is difficult to retrieve, because the tension required to pull up the pipe is excessive unless the pipe is dug out. Pipe should be retrieved in a manner that prevents kinking, abrasion, or other physical damage. As noted in Section 11.1, the pipe should be visually inspected for physical damage as it is retrieved.

9.10 Pipe Repackaging

If a FlexSteel pipe is respooled or retrieved and stored, it should be packaged on a reel with a drum at least as large as that on the shipping reel. Attach a shipping head to the first-on (inner, drum, or last-off end) end fitting (or a shipping end fitting and head), apply a protective wrap as needed, position it appropriately and fix it to the reel flange, preferably aligned on the reel to use the original attachment points. When large flanges are present on the pipe, care must be taken to avoid point loads on the pipe during the packaging process. Tension should be carefully controlled when spooling to near the minimum bend radius. Too little tension can allow the pipe to buckle; too much tends to flatten and ovalize the flexible steel pipe. Internal pressures of up to 90psi have been used successfully to provide additional stability during respooling and greatly reduce the tendency to flatten or kink. The trailing end fitting and final wrap of flowline should be snugly fixed to the reel flange in a manner similar to that used for the inner end fitting.

10 COMMISSIONING

A pipeline system is typically commissioned after completion by filling it with water and conducting a pressure test referred to as a field hydrotest or field acceptance test. Flexible steel pipe behavior when hydrotested is somewhat different from the behavior of rigid steel pipes, due to thermal expansion and creep of the polymer in the pipe. The pipe is held at pressure until the rate of creep slows, in a process known 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.

10.1 Filling the Pipeline

Prior to conducting a field hydrotest, the pipeline system is filled with water. Pipeline systems are normally designed with dedicated fixturing to facilitate this system hydrotest. To fill a long flexible steel pipe, a pig is normally installed at the fill end of the pipeline, and the pig driven through the pipe by filling the pipe with water. The use of a pig keeps the water segregated from the air in the empty pipe, allowing the pipe to be filled with a minimum of trapped air.

The hydrotest of an individual pipe may be accomplished prior to connecting the pipe into the pipeline system. To fill a pipe not connected to a system, a head is removed from one end and the
other end is vented. A pig is installed, a fill head installed and connected to a water supply, and the pipe filled. Particular care is to be exercised at the vent end of the pipe, as pressure can build up inside the pipe, and the resulting energy in the compressed gas can be hazardous. Once the pig reaches the other end of the pipe, the vent port is plugged and the pipe is ready to be pressurized. The pig can be removed from the pipe prior to the hydrotest, or can remain in the pipe during the hydrotest.

After the hydrotest is complete, the pipe is dewatered by driving a pig through the pipeline with compressed air, removing the majority of the entrapped water. Suitable pigs are detailed in Section 10.2.

### 10.2 Pigging Specification and Details

Elastomer or foam pigs can be used to pig smoothbore flexible pipelines. Pigs made of metal should not be used in the pipelines, as they can damage the PE interior of smoothbore pipes. Consult Wellstream before using any type of pigs other than the soft elastomer or foam pigs in the flexible pipes.

Elastomer pigs are generally urethane, but can be of other materials. They typically feature multiple disks connected together by an elastomer shaft. The elastomer shaft allows the pig to bend to follow curves in the pipe, while the disks have some radial compliance to accommodate variations in pipe diameter. The disks seal tightly in the smoothbore pipe interior, and provide a smooth squeegee action that makes elastomer pigs especially effective to fill and dewater flexibles. Some cup type elastomer pigs are optimized for travel in one direction; others are symmetrical to allow bidirectional use. The rigidity of the pig provides verification that any pipe the pig passes through is clear, though this type of pig is not as sensitive an indicator as is a gauge pig.

Foam pigs are general purpose pigs. Foam pigs seal even for extreme variations in pipe diameter, thus, do not provide any significant gauging of the pipe. They can be used for wax removal, as anything other than a complete wax plug will not normally block the travel of the pig. Foam pigs do not seal as tightly, or wear as well as the PU variety.

There are also composite pigs that have foam disks supported by molded PU reinforcements. Their performance is generally between that of the pure PU and foam pigs, suiting them well for use with Wellstream FlexSteel pipe.

### 10.3 Hydrotest

Pipeline systems are typically hydrotested 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, hydrotests are occasionally used to demonstrate pipeline integrity in service.

Wellstream flexibles are tested prior to installation by a factory hydrotest, and virtually all are tested after installation in commissioning the pipeline. A hydrotest 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.
10.3.1 Factory Hydrotest
The factory acceptance test or hydrotest is conducted per API 17J and 17B requirements. The test conditions are 1.3x design pressure and are held for a 24 hour period.

10.3.2 Field Hydrotest
A field hydrostatic test is conducted on a pipeline system to demonstrate that it is leak tight and, if a factory hydrotest 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, they can also be used to verify pipeline integrity.

Pipeline codes specify field hydrotest 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 hydrotested. Field strength tests of 1.25x the design pressure are also common. When no factory test is conducted, some codes specify a field hydrotest at up to 1.4x or 1.5x the design pressure. Contact Wellstream prior to conducting any hydrotests at pressures greater than the factory hydrotest detailed in Section 10.3.1.

The field hydrotest period is often 24 hours, though Wellstream considers a hold period of 4 hours to be sufficient, unless conditioning or excessive temperature changes are occurring.

10.3.3 Test Conditions
The hydrotest pressure and hold period is determined by the operator, as required by applicable codes. The minimum test pressure, \( P_{HT, \text{MIN}} \) is determined as noted in the previous section. The nominal hydrotest pressure, \( P_{HT, \text{NOM}} \) is normally 4% above the test pressure. The maximum allowable test pressure, \( P_{HT, \text{MAX}} \) 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.

10.4 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, 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 hydrotested once, it is relatively stable when hydrotested again at the same pressure. Wellstream FlexSteel pipe has a very tight structure that conditions quickly, with minimal pressure drop.

10.5 Conditioning Procedure

At no time during the conditioning is the pipe pressure allowed to exceed $P_{HT\_MAX}$. Pressurize the pipe up to or slightly below the hydrotest 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 hydrotest, 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 hydrotest 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 hydrotest. 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 hydrotest, and the pipe would be expected to pass hydrotest. Pipe conditioning in the FlexSteel pipe occurs relatively rapidly, and a period of several hours is typically sufficient to essentially complete the conditioning phase.

10.6 Hydrotest Procedure

Once the conditioning is complete, the hydrotest 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 least at 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 hydrotest 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.

Wellstream has traditionally used this API 17J procedure for hydrotest. However, the pressure of a blocked in pipe varies as a function of temperature. Wellstream is adopting an active hydrotest system that automatically injects or releases measured amounts of water to maintain hydrotest pressure precisely. This allows accurately comparing volume changes with temperature changes to verify pipe integrity.

### 10.7 Hydrotest Acceptance Criteria

The pressure test is acceptable if the internal pressure does not drop below $P_{LT,MIN}$ during the hold period. However, if the pressure does drop below $P_{LT,MIN}$ during the hydrotest, 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 hydrotest 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 hydrotest has otherwise passed. A leak small enough to allow the pipe to pass hydrotest is extremely rare, but is possible, especially if the pressurized system is sufficiently large.

### 11 FLEXSTEEL PIPE INSPECTION AND MAINTENANCE

Wellstream FlexSteel pipes are generally maintenance free, however, Wellstream recommends operators determine and document operating procedures for systems containing flexible steel pipes, including monitoring of fluid composition, pressures, and temperatures to which the flexible steel pipes are exposed. The operating conditions should be compared to the original design specifications to assure the conditions are within the design conditions.

#### 11.1 Inspection Program

Buried pipes are not inspected, except at the risers or exposed sections at the ends.

Exposed flexible pipes should normally be visually inspected periodically during operation. Monitor the external and internal environment regularly to reveal any deviation from the design environment. This includes the recording of accidental loads, composition of the product flow, and pressure and temperature monitoring. In some cases, for example in submerged applications, tracking of rough weather periods is also recommended.

In addition, the pipe should be inspected and evaluated when any of the following events occur:
Any abnormal or emergency operating condition occurs which may have resulted in the flexible pipe to be subjected to overpressure or otherwise exceeds the original design conditions.

Unintended movement or abnormal loading by environmental causes, changes in environmental loading conditions (free spans, increased localized overburden, etc.).

Third party encroachment on the pipeline corridor is reported, or in the event of any potential damage to the pipeline, such as contact with heavy moving objects. In the event of such impacts a full pipeline inspection should be performed including external condition, alignment survey and hydrostatic testing.

The pipe is recovered and stored to reinstall in an alternate location.

Visual inspections should include:

- Outer shield layer damage (severe gouges, crushes, abrasion)
- Any undue pipe length change, ovalization, buckles, kinks, or other pipe distortion
- Leakage of conveyed fluid
- Damage or external corrosion to end fittings, connectors, hardware, or ancillary equipment
- For unburied submerged conditions, divers or ROV’s (remote operated vehicles) can conduct the inspections

Buckles or kinks are considered major damage which may significantly affect the pressure retaining integrity of the pipe. Pipe exhibiting such conditions should be immediately removed from service for full inspection and replacement as necessary.

The use of color video or still photography for documentation purposes is recommended. Any changes from the as-installed conditions should be documented. Documentation should include a full description of the pipe condition such as type, size and location of defects or abnormal conditions as noted above.

Small amounts of gases may vent from the end fittings. The gasses are a result of normal operation of the flexible pipe venting system which allows permeated gasses to escape without damaging the flexible pipe outer sheath. For submerged end fittings, this is noted as gas bubbles in the vicinity of the end fitting. Large volumes of production liquids escaping the end fitting or along the pipe is indicative of a leak. If this occurs the system should be depressurized and repaired or replaced immediately.

11.2 Pipe Damage Assessment

Wellstream should be notified in the event inspection reveals damage to the flexible pipe or flexible pipe system. In addition, notification shall also be made when operating design parameters have been exceeded. Failure to do so may effect the terms of the warranty.

11.3 Routine Pipe Maintenance

If an end fitting connection leak occurs, replacing pressure seal rings/gaskets and/or tightening nuts and bolts would be expected to stop the leaks. If gas or liquid service fluid is leaking at a location other than the mechanical pipe connection, the pipeline should be removed from service and
Wellstream should be contacted for further inspection and possible repair or replacement of the end fitting.

Cleaning is normally not required, however, if undertaken, select cleaning devices that avoid damage to the FlexShield. Do not use wire brushes or other mechanical cleaning devices on the FlexShield without prior testing to ensure that the cleaning method does not damage the FlexShield. The FlexShield is highly resistant to most chemicals, however, certain highly concentrated fluids can remove markings or cause potential damage to the end fittings, seals, or shield. Section 4.6 indicates fluid compatibility for PE. If there is a question as to the suitability of a solution for use on the flexible pipes, contact Wellstream with details.

Repair of damage to the shield such as abrasions or cuts can be accomplished in accordance with Wellstream procedure WS-MFG-4106, “Weld Repair of HDPE FlexShield and FlexWear with Hand Held Extruder.” Shallow damage can be protected by covering with appropriate adhesive tape or shrink-wrap material. Damage that extends to the tensile steel elements or damage to the end fitting or end fitting connection area to the flexible should be referred to Wellstream for disposition. The damaged area or fitting would normally be cut out and new end fitting(s) installed.

12 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.

Non-bonded flexible pipes are typically custom designed for each individual application, with the pipe materials, number and type of layers, and strengths/thicknesses/cross sections of each layer determined during detailed design. Specialized layers, materials, and pipe designs have been developed to accommodate this wide range of conditions cost effectively, which in turn leads to issues of qualifying individual pipe designs. This custom approach to non-bonded flexible steel pipe design leads to the necessity to define qualification requirements for each new design.

The API documents developed specifically address qualification requirements for each new design as indicated in Section 3.3. Per API 17J 6.2.5, 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. The individual tests conducted are documented in Reference [15].

12.1 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 nonbonded flexible steel pipes 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\}

12.2 Offshore vs. Onshore Requirements

Non-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 3,000 meters (10,000 ft). Temperatures range from -40°C (-40°F) for external temperatures to fluid temperatures of 120°C (248°F) or more, combined with variations in fluid composition including sour service. Offshore developments typically have much higher pressures than onshore applications, with 20 to 35 MPa (3 000 to 5 000 psi) design pressures common for production lines, and some injection type applications with operating pressures of 103 MPa (15 000 psi) or more. Pipe sizes range from Ø50 mm (Ø2-inch) diameter to Ø508 mm (Ø20-inch) 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.

12.3 Requirements forPrototype 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.

Wellstream adopted this design methodology verification approach. The robustness of the Wellstream design process is documented by the Lloyds Type Approval, Reference [16]. 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 Reference [17].

Wellstream non-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 Wellstream 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 Wellstream qualification requirements, and assures a high level of confidence in Wellstream product reliability with a practical level of testing.

12.4 Prototype Tests Overview

API 17B specifies prototype tests to be used to measure or verify principal properties \{Table 19\}. 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 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, Wellstream is using the end fitting integrity test from the ISO TS for qualification purposes.

12.4.1 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.

12.4.2 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.

12.4.3 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.

12.4.4 Pipe Minimum Bending Radius
The pipe minimum bend radius calculation methodology meets the requirements specified by API 17J, including a maximum allowed strain for PE of 7.7%. This strain limit is conservative, as material testing indicates limits of 10% or more strain are acceptable in pipe grade PE.

12.4.5 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.

12.4.6 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, Wellstream has conducted elevated temperature tests per ISO TS 18226 Reference [18].

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 20°C (36°F) or 25°C (45°F). 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.

12.5 Design Methodology Qualification
An overview of the design process for non-bonded flexible pipes is summarized in API 17B {5.2}. The Wellstream design methodology is qualified based on a number of prototype tests conducted on different pipe designs from all of the API 17B non-bonded flexible pipe families. The Wellstream
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 Wellstream design methodology has been documented and verified as required in API 17J [6.2.5] by Lloyd’s as documented in Reference [19]. This also indicates the references that document the algorithms used for burst, collapse, and failure axial tension for the flexible steel pipes.

12.5.1 Software
Wellstream non-bonded flexible steel pipes are designed and analyzed using proprietary in-house software. The software applicable to static lines like the FlexSteel pipes includes PipeMaker and FPS (FlexPipe Stress). PipeMaker is used to design the pipes and determine basic pipe properties. FPS determines 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. PM Extensions contains utilities that assist Wellstream engineering to rapidly design FlexSteel pipe.

12.5.1.1 PipeMaker
PipeMaker is the software used at Wellstream to design pipes. It allows the user to select which layers to use in a given pipe design, and to specify the layer geometry, materials, and standard parts in each layer. Based on user input, PipeMaker 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. PipeMaker 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 Reference [20].

12.5.1.2 FlexPipe Stress
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. At Wellstream, the FlexPipe Stress (FPS) program is used for this analysis. FPS accepts pipe geometry and material properties data from PipeMaker; then calculates the stresses and strains in each layer of the pipe for each load case defined by the operator. It determines stresses and strains in each pipe layer under user-defined load conditions, which can include complex combined load cases.

FPS has three functional modules, the Straight Pipe Model (SPM), the Coaxial Bending Model (CBM), and the Installation Stress Check (ISC). In the SPM, 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 reports all models applicable for each load case. The CBM determines the stresses in the FlexTensile tensile armor wires, including general stress for static flexibles, and corner stresses for flexibles in dynamic service. The ISC determines the stresses in the hoop layers that are generated by the installation specific loads. Finally, FPS superposes the results from the three modules 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. The formulations used in FPS are documented in References [21] and [22].

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. Wellstream normally considers these values; however, uses customer specified material utilizations when required.

12.5.1.3 PM Extensions
PipeMaker and FPS were designed to conduct general design calculations for flexible steel pipes, customized for each application. PM Extensions is a program used on top of these programs to ease data entry and partly automate pipe optimization for flexible steel pipes. It allows rapid development of families of designs, has tools to largely automate optimization of the pipe designs, and generates specialized reports, such as datasheets, in a custom format better suited to the FlexSteel pipes. This is not considered to truly be design software, as the key design calculations are conducted by PM and FPS.

12.5.2 Design Algorithms
Many of the design algorithms used for the FlexSteel pipes are those developed and verified at Wellstream over years of flexible steel pipe experience. However, certain of the algorithms were not designed to consider the unique structure of FlexSteel pipe, and alternative techniques have been developed as indicated below.

12.5.2.1 Burst Pressure
FPS is used to determine the burst pressure for the flexible steel pipe designs, rather than the PipeMaker algorithm. The results are similar; however, the FPS results are better suited for use in optimizing the pipe design. Thus, for consistency, the FPS burst value is used, considering a 100% utilization of the tensile elements.

For most offshore flexible steel pipes, the calculated strength of the polymer layers in FPS is negligible compared to the thick steel layers. 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.

12.5.2.2 Collapse
The collapse test measures the capability of a given flexible pipe structure to resist hydrostatic pressure, an important load case for subsea pipes. The collapse capability of the flexible steel pipe is considered to result only from the polymer layers. The PipeMaker smoothbore collapse algorithm, though originally designed for carcass collapse, computes a reasonable value for the liner collapse.
The results correlate well with the collapse data at 20°C (68°F) in Annex A of API 15 LE, Reference [23], and have been verified by proprietary Wellstream tests on RTP samples as indicated in Reference [24]. This value is conservative, and the steel layers are expected to add to the collapse resistance. This design methodology has not been fully developed or reviewed by Lloyd’s. Therefore, the collapse resistance of all FlexSteel design configurations is being verified by tests.

12.5.2.3 Axial Tension
Axial tension calculations for FlexSteel pipes have not been confirmed to accurately predict axial tension predictions. This is due to the complex failure mode coupling the stability of the FlexLiner and local loading at the end fittings. Therefore, the tension capacity of all FlexSteel design configurations is being verified by tests and conservative installation loads recommended.

12.5.3 End Fitting Analysis
Classical flexible steel pipe end fittings are designed and analyzed using proprietary Wellstream software. This software is not considered applicable to analyze and design swaged end fittings, as the operating principle of the swaged end fitting is different from that of the classic Wellstream end fitting used on traditional flexible steel pipe. Instead, thin and thick walled cylinder calculations coupled with testing are used to assure the pressure capability of the end fittings is adequate.

12.6 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, Wellstream conducts MBR tests and an end fitting integrity test. 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 Wellstream encapsulated end fittings, Wellstream is also conducting an accelerated life test to demonstrate the end fittings function for the planned design life, referred to as an end fitting integrity test.

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

13 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. Wellstream has earned Lloyd’s type approval and qualification from API to use the API 17J monogram on its standard flexible steel pipes.

• Wellstream has developed a version of the non-bonded flexible pipes with capabilities optimized for onshore use, 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.

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

Conveyed Product Compatibility with PE
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(CH₂)ₙH, where n is the number of carbon atoms, and CH₂ 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.

```
  H H H H H H
  |      |      |      |     |      |
H – C – C – C – C – C – C – H
  |      |      |      |     |      |
  H H H H H H
```

Figure A - 1 Schematic of Aliphatic C₆ Hydrocarbon (Hexane)

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 C₁₀₀₀₀ or more. While definitions vary, Low Density PE is considered to have molecular weights of 20kg/mole to 40kg/mole (C₁₅₀₀ to C₃₀₀₀), and high density PE is considered to have molecular weights of 28 kg/mole to 700 kg/mole (C₂₀₀₀ to C₅₀₀₀). The variation is 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.
A.3 PE Chemistry

Polyethylene (PE) is formed of long chain polymer molecules consisting of a large number of CH$_2$ 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 D 3550 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 D 3550 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 2406 and 3408.

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 60°C (140°F). Most PE-80’s have a unimodal 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

Table A-1 Hydrocarbon Groups

<table>
<thead>
<tr>
<th>Bottle Gasses</th>
<th>Petroleum Ethers(solvents)</th>
<th>Gasoline</th>
<th>Other Hydrocarbons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$ Methane</td>
<td>i-C$_4$; n-C$_5$</td>
<td>Pentane</td>
<td>Heptane</td>
</tr>
<tr>
<td>$C_2$ Ethane</td>
<td>$C_6$</td>
<td>Hexane, cyclohexane</td>
<td>$C_8$ Octane</td>
</tr>
<tr>
<td>$C_3$ Propane</td>
<td></td>
<td>$C_9-C_{12}$ Various</td>
<td></td>
</tr>
<tr>
<td>i-C$_4$; n-C$_4$</td>
<td>Butane</td>
<td></td>
<td>$C_{30}-C_{40}$ Paraffin wax</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\geq C_{60}$ Asphalt</td>
</tr>
</tbody>
</table>

Aromatics contain a highly symmetric planar ring with 6 carbon atoms sharing delocalized or floating $\sigma$ and $\pi$ 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.
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 80°C (176°F). 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 an 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 80°C (176°F) and PEX up to 90°C (194°F), 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_{16} range or above are large enough to cause major disruptions in the PE matrix, but have such slow diffusion 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, Reference [25]. A more detailed compatibility chart is presented by the Plastics Pipe Institute (PPI) in Reference [26].

### Table A-2 Summary of PE Compatibility with Various Fluids

<table>
<thead>
<tr>
<th>Fluids</th>
<th>20°C (68°F)</th>
<th>60°C (140°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, octane and methanol</td>
<td>No effect</td>
<td>No effect</td>
</tr>
<tr>
<td>Ethanol, gasoline, heavier hydrocarbons</td>
<td>Satisfactory</td>
<td>Limited</td>
</tr>
<tr>
<td>Benzene</td>
<td>Limited</td>
<td>Limited</td>
</tr>
<tr>
<td>Heptane</td>
<td>Satisfactory</td>
<td>Not Satisfactory</td>
</tr>
<tr>
<td>Hexane, ethylbenzene, toluene, xylene</td>
<td>Limited</td>
<td>Not Satisfactory</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>Not Satisfactory</td>
<td>Not Satisfactory</td>
</tr>
</tbody>
</table>

Hexane (C₆), cyclohexane (C₆), heptane (C₇), 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 (C₆), heptane (C₇), 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 190°C and 230°C. 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 60°C. 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 10°C of increased temperature, the diffusion rate at 60°C would be expected to be roughly 16 times the rate at 20°C. 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 60°C 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.

CO₂ diffuses rapidly into the PE matrix. The amount of diffused CO₂ increases with temperature, CO₂ partial pressure, and the degree of plasticization of the PE matrix. N₂ also diffuses into the PE matrix, but typically has no significant effect on blistering because it has lower solubility than CO₂ and is essentially inert. If the pressure in the pipe bore is rapidly reduced when the PE matrix has a large concentration of diffused CO₂, the gas expands and may cause microvoids. This process is driven by the high vapor pressure of the CO₂. 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 CO₂ is small.
- Pressures are low.
- The number of rapid decompressions is limited.
## A.8 PE Compatibility Table, 3 Months Exposure

<table>
<thead>
<tr>
<th>CHEMICAL</th>
<th>TEMPERATURE</th>
<th>TENSILE STRENGTH</th>
<th>ELONGATION</th>
<th>% WEIGHT CHANGE</th>
</tr>
</thead>
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<td></td>
<td>°F</td>
<td>°C</td>
<td>psi</td>
<td>MPa</td>
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<td>Battery Acid (36%)</td>
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<td></td>
<td>120</td>
<td>49</td>
<td>4360</td>
<td>30.0</td>
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<tr>
<td></td>
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<td>4670</td>
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<td></td>
<td>120</td>
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<td>4490</td>
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<td></td>
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<td>66</td>
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Additional information regarding the chemical resistance of Walker polyethylene is presented in other Plastic Technical Center publications. This data is provided for use only as guidelines in preliminary determination of package suitability 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.
APPENDIX B

Constant Pressure Rupture Tests
B.1 Spoolable Reinforced Plastic Line Pipes

SRPLP’s undergo a pressure test to determine long term pressure capability. This section provides some details of the regression testing typically conducted on SRPLP’s. These tests are not applicable to Wellstream FlexSteel pipes, as the steel reinforcements used do not exhibit the weakening that occurs with spoolable composite products.

B.2 SCP Pressure Rating Determination

To determine the pressure rating of a polymer or composite pipe, long term constant pressure rupture (burst or sometimes “static fatigue”) tests are conducted under lab conditions at the design temperature, using short straight samples and water as the test fluid. The results of the constant pressure burst tests are statistically analyzed to determine the mean regression line and a lower confidence limit of the pressure. From these ultimate strengths of the pipe, various de-rating factors are applied to determine the pressure rating of the pipe.

Two major methods have been used in codes for determining pressure ratings of polymer and composite materials. The North American codes typically determine the mean pressure or stress value from the mean regression line for failure at a design life, for example 11.4 or 50 years, then derate the pressure capability by applying design factors of 2, 3 or 4, depending on the code and the pipe material. The mean pressure or stress value from the mean regression line is termed the Long Term Hydrostatic Stress or Pressure (LTHS or LTHP). The LTHP is usually rounded down to the nearest Hydrostatic Design Basis standard value. Plastic pipes often also have a maximum allowable pressure specified, independent of stress calculations. The European methods statistically determine a lower bound for the burst pressure at the design life of often 20 to 50 years, above which 97.5% of the failures are anticipated to occur, then derate from this value. The North American method applies a sufficiently conservative design factor to consider scatter in the data, while the European method penalizes scatter to varying degrees, depending on the statistical method used, and normally applies a more aggressive overall design factor.

B.3 Data Collection

To determine the pressure capability of an SCP, a series of pressure tests are conducted. Pipe samples are filled with water or an alternate fluid and subjected to a constant internal pressure at a design temperature until they burst. The time required to burst each sample is recorded. The most common design temperature is 60°C (140°F). Virtually all polymer or composite piping specifications require a minimum of 18 tests distributed over time, with at least one test that survives over 10 000 hrs. Typical test points are shown in a generic graph in Figure B-1 as hollow dots. As shown in the figure, polymer practice, unlike standard engineering practice, is to place the dependent variable time on the abscissa or x axis, and the independent variable pressure on the ordinate axis.
B.4 Statistical Methodology

Statistical analysis is used to determine the relation between pressure and time at a given temperature from the results of constant pressure rupture tests. This is typically conducted per the methods specified in ASTM D2837, ASTM D2992, or ISO/DIS 14692-2. The algorithms used in each of these methods fit a mean regression line to the data, then a lower bound burst pressure at the design life is determined. The lower bound pressure is determined by calculating the nominal burst pressure at the design life from the mean regression line, then derating this pressure to assure 97.5% of the failures occur above this lower bound value. The ISO/TR 9080 document is also commonly used. It has two methods. Method 1 is more general, is intended for determining the characteristics of new materials, and requires data at 3 or more temperatures. Method 2 is a simplified method intended for variants of existing materials that have already been characterized using method 1. Further simplifying the ISO/TR 9080 algorithm for only one temperature results in the method of ASTM D2837, including the LCL calculation.

B.5 Mean Regression Line

In conducting the statistical calculations, first the mean regression line is determined. This is a straight line that best fits the data, and represents the average time for straight new pipe filled with water at constant pressure at the design temperature to burst under laboratory conditions. To fit the mean regression line to the data, all these methods consider the mean (arithmetic average) of the x data and y data to be one point on the line, then use a least squared fit algorithm to fit a line to the data.
points. Three least squared algorithms are used: minimizing the $\Delta X^2$, the $\Delta Y^2$, and the $\Delta X \Delta Y$, where Time is considered the X (independent variable) and Pressure or Stress is considered the Y (dependent) variable. The $\Delta X^2$ method has traditionally been used. Minimizing the $\Delta X^2$ and the $\Delta Y^2$ are identical methods, except that the variables are switched. This is the method used by ASTM D2837. The composite pipe methods, ASTM D2992 and (proposed) ISO/DIS 14692-2 use a method that minimizes the $\Delta X \Delta Y$ to determine the mean regression line. The ASTM D2992 method is computationally more difficult than the ASTM D2837 method, as it cannot be determined directly using common summation functions standard in most software.

B.6 Lower Confidence Limit and Lower Predicted Limit

The calculated lower bound values for the burst pressure at the design life are the Lower Confidence Limit and the Lower Prediction Limit. The LCL and the LPL are determined at a design life by reducing the mean regression value by the confidence interval and prediction intervals respectively. Both the LCL and LPL of the pressure are curves, not straight lines. The LCL {LPL} pressure is determined by extrapolating the mean regression line to the design life, then reducing this value to the desired confidence {prediction} level. The three methods used (ASTM D2837, ASTM D2992, and ISO/DIS 14692-2) have different algorithms to determine the LCL and LPL, resulting in slight variations in the calculated values. In all three methods, the 95% confidence {prediction} level is used with the two-sided 0.05 level of significance to determine the time and pressure combinations above which an average of 97.5% of the conducted tests {new individual tests} are expected to lie. In this application, using only the lower tail of the probability curve, the LCL is slightly higher than the LPL. The methods are listed in order of increasing computational difficulty, but all of them can be readily computed with modern spreadsheets and computers for any reasonable number of samples.

B.7 Pressure Rating

The pressure rating of an SCP is determined by the responsible engineer during the design process. This is accomplished by de-rating an ultimate pressure, usually a mean or LCL pressure at the design life, or at 11.4, 20, or 50 years. The de-rating is accomplished by multiplying the selected ultimate pressure by design factors. The planned temperature-pressure-durations are used in a Minor’s rule cumulative damage calculation to verify the pipe has sufficient life with appropriate design factors to withstand these planned load cases. There are no industry accepted standards for RTP ratings, though work is in progress. An RTP JIP worked for some time, with Wellstream as a participant, and resulted in the ISO TS, Reference [18]. Standards for rigid fiberglass pipes are specified in codes, however, agreement is not universal that the same design factors are appropriate for the spoolable products.

B.8 SRPLP Pressure Rating

The JIP developed a draft methodology for determining pressure ratings, as indicated in References [18] and. In this methodology, multiplying the LCL pressure by the Product Variability Factor yields the Manufacturer's Nominal Pressure Rating (MNPR). The Product Variability Factor is a de-rating factor of roughly 1.27, derived statistically using the DnV method documented in Reference [27] to consider the probability of failure of a long pipeline by adding the probability of failure of independent events (failures of short segments of pipe). The MNPR is multiplied by the Application Specific Service Factors for temperature, fluids, and fatigue to yield the Maximum Service Pressure.
(MSP). Per the JIP method, this is considered equivalent to a design pressure or MAOP, except that the JIP allows operating pressures to exceed the MSP, and specifies further safety factors to determine the SMSP. The design life is typically 20 years (175 200 hours), or sometimes 50 years (438 000 hours) but the period is not rigidly defined by the JIP qualification document. Finally, the JIP draft methodology includes further de-rating factors for the effects of safety zones, bending and tension which are applied to the MSP to determine the specific maximum service pressure (SMSP).

An API spoolable products working group is working on somewhat similar technique.
References

16. Lloyd’s Register Type Approval Certificate 92/00147(E2).
17. Lloyd’s Register Design Appraisal Document TSO 9905100/001.