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## EXTRA HIGH-PRESSURE HIGH-TEMPERATURE (XHPHT) FLOWLINES – DESIGN CONSIDERATIONS AND CHALLENGES

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### ABSTRACT

Development of deep water oil reservoirs in the Gulf of Mexico may encounter conditions where the flowline product temperatures approach 177°C (350°F), water depths range to 3000 m (10,000 ft), and tie-back distances up to 40 miles are presently being considered. These high flowline temperatures, water depths and distances, present real challenges to the design of flowlines. The objective of this paper is to present the design considerations and challenges of designing for extra high pressure high temperature (XHPHT) conditions. For such conditions, a pipe-in-pipe (PIP) flowline system with thermal expansion management, and a limit state-based design are viable solutions. This paper is split into three main parts and covers (i) design challenges and how they are overcome, (ii) finite element analysis design methods, and (iii) qualification testing of PIP components. The first section presents the main design issues, and challenges, of designing flowlines for deepwater and high-temperature conditions. The paper discusses aspects of controlling the large axial loads, such as thermal expansion management using buckle initiators and end constraints for flowlines, and presents current methods. The second section describes the use of advanced finite element analysis (FEA) tools for the design and simulation of PIP systems, and presents local and global FEA models, using ABAQUS, to investigate the limit state design of XHPHT flowlines. A 3-D helical response of the inner pipe subjected to high temperature, and the sequential reeling and lateral buckling of flowlines is also discussed. The final section of the paper describes the qualification testing to be undertaken on PIP components to ensure structural integrity and long-term thermal and structural performance. Qualification testing for PIP components for 177°C (350°F) service is discussed, and includes the testing of centralizers, waterstop seals, thermal insulation and loadshares. This paper is based on both theoretical and practical research work.

### INTRODUCTION

Pipe-in-pipe (PIP) flowline systems are frequently used in the Gulf of Mexico (GoM) for subsea tie-backs where there is a requirement for high thermal performance. As compared to wet-insulated single-pipe flowlines, PIP provides a lower overall heat transfer coefficient (OHTC), facilitates longer cool-down times, and

allows long distance tie-backs. Figure 1 shows a typical PIP system configuration.

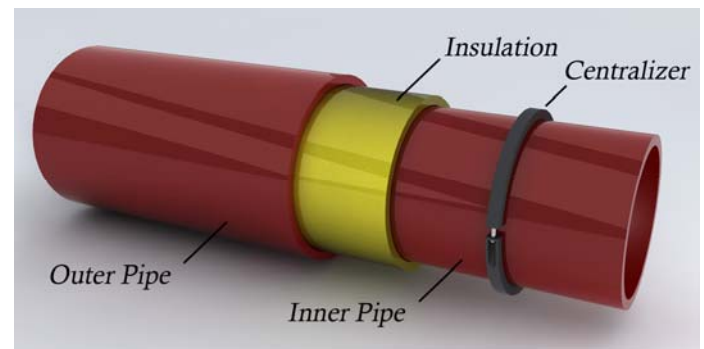


Figure 1: A Typical Pipe-in-Pipe Configuration

Recent project requirements of PIP systems, for GoM prospects, anticipate flowing product temperatures to 177°C (350°F), water depths to 3000 m (10,000 ft), maximum allowable operating pressures (MAOPs) of 6500 psi (44.8 MPa), and subsea tie-back distances up to 64 km (40 miles). These operating flowline temperatures present real design challenges, both in terms of the design and in the choice of appropriate materials for the PIP components (thermal insulation, centralizers, waterstop seals and loadshares). Failure modes have to be addressed (limit states), and high axial loads can lead to lateral buckling, and mitigation methods are necessary, such as thermal expansion management with the use of sleepers (8, 12), which are integrated into the design philosophy (21).

This paper covers the latest methods and status in the design of PIP systems for XHPHT conditions, and is split up into the following parts (i) design challenges, (ii) design solutions, (iii) finite element analysis design methods, and (iv) qualification testing of PIP components. The work presented in this paper is part of significant analysis works related to extra high-pressure and high-temperature PIP designs sponsored by a major operator (23, 24). For this study, the PIP

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nominal dimensional size of 8 x 12 inch has been selected as the base case, although results are applicable for other PIP sizes.

## Keywords

Aerogel, Annulus, Centralizer, Deep Water, Extra High-Pressure High-Temperature (XHPHT), Flowlines, Loadshare, Overall Heat Transfer Coefficient (OHTC), Pipe-in-Pipe (PIP), Pipelines, Spacers, Thermal Insulation, Waterstop.

## 1. DESIGN CHALLENGES

There are a number of challenges for the design of XHPHT pipelines (16). It should be noted that some of the key engineering challenges are interrelated, and should not be considered in complete isolation. The main engineering issues that have been identified are briefly summarized as follows:

### High Pressure/High Temperature (HP/HT)

HP/HT with shut-in pressures in the order of 700 bar (10,000 psi) or more, and temperatures to 160°C (320°F) are possible. For a major operator here in the GoM, temperatures to 177°C (350°F) are presently being considered. Stress-based design codes are no longer applicable at these high temperatures, and the solution is to design such pipelines using a limit state methodology.

### Thermal Management

High temperature pipelines create very large axial loads that lead to unwanted lateral or upheaval buckling within the pipeline. Uncontrolled lateral buckling can cause excessive plastic deformation of the pipeline, possibly leading to localized buckling collapse or cyclic fatigue failure during operation due to continuous heat-up and cool-down cycles. This problem is overcome by the adoption of a thermal expansion management philosophy that incorporates sleepers, or buoyancy.

### Thermal Performance

Thermal flow assurance issues are also important, and the main requirement is to insure the internal contents of the pipeline remain above the temperatures where wax and hydrates form and potentially block the pipeline. There are thermal and water depth limitations with wet insulation limiting their use for these XHPHT conditions. PIP systems are viable solutions.

### Inner Pipe Locked Compressive Load

PIP pipelay installation, by either S-lay or J-lay methods, employing a sliding or uncoupled inner and outer pipes has a problem in that the dead weight load of the inner pipe during pipelay is effectively locked into the inner pipe as a compressive load as the pipe is laid onto the seabed. This compressive load has been shown, by Harrison and McCarron (1), to reach 30% to 50% of yield strength and can reduce the inner pipe ultimate load capacity and the allowable inner pipe temperature.

### Inner Pipe Ultimate Load Capacity

A significant challenge is ensuring that the inner pipe loading does not reach an ultimate limit state (failure), and that there is an adequate operating margin before failure. The high inner pipe temperature can create large axial compressive loads that, combined with captured installation loads, could lead to gross deformation and collapse-rupture of the inner pipe. Detailed FE analyses were undertaken by McCarron (2) to investigate the effect of inner pipe compressive loads on the ultimate loading capacity of the inner pipe. In practice the inner pipe compressive load should be determined through the use of advanced FEA.

## Design Code Limitations

There are a number of pipeline design codes (3, 4, 5, 6) and each is different. Stress-based design is not applicable for high temperatures, and would lead to excessively thick pipelines. The use of strain-based design codes, and limit state-based design is more applicable for complex high temperature designs. The integration of analysis tools with design codes is a key challenge.

## Ultra Deepwater and Installation

Ultra deepwater presents real engineering challenges in terms of designing to resist hydrostatic collapse, and there are design challenges related to flow assurance, riser systems, installation techniques, component design and operational performance. For water depths down to 3,000 meters (10,000 ft), wall thicknesses have to be relatively thick, yielding a heavy pipe string that has a significant impact on installation lay vessels and existing equipment capability to be considered for deep-water installation (24). Also, if the flowlines are to be reeled, it is important to capture the reeling strain history and include this effect in the design for the inner pipe. The reeling strain history may affect the ultimate limit state of the inner pipe during operation at high temperatures (14).

## PIP Components

High temperatures present additional challenges for the choice of materials for PIP components such as thermal insulation, centralizers, waterstops, and loadshares (11, 15). For these components, it is necessary to ensure structural integrity and avoid long-term performance degradation. Design challenges for each of the PIP components are as follows:

**Waterstops.** The purpose of waterstops in a pipe-in-pipe design is to avoid the unacceptable result of flooding the entire annulus of a PIP flowline due to a single defect in the outer pipe. The industry does not currently have waterstops capable of maintaining annulus integrity at the maximum required operating temperature of 177°C (350°F). Any form of waterstops to be considered must be capable of sustaining functionality and integrity at high operating temperatures for the life of the pipeline.

**Insulation Material.** The insulation material, between the inner and outer pipes must provide an adequate thermal barrier to reduce heat loss. Existing insulation materials, such as polyurethane foam (PUF), are not rated for service at the maximum required temperature (177°C/350°F). Hence new materials, such as aerogels, are considered.

**Centralizers (Spacers).** The purpose of the centralizer is to effectively centralize the inner pipe to prevent damage to the thermal insulation during installation, and to minimize loads on the insulation during installation and operation. The centralizer material must be structurally sound during installation and not deform under operational temperature loads. It is a challenge to source an appropriate centralizer material as the previously adopted centralizer materials are only rated for approximately 130 °C (266 °F).

**Loadshares.** Loadshares combined with pre-tensioning of the inner pipe prior to establishing the load sharing of the pipes can redistribute the gravity loads to realize a much lower in-situ axial compression load in the inner pipe. The industry does not have a standard loadshare device. The loadshare can be either a mechanical clamp or a designate length of on-site poured quick-dry epoxy or polyurethane (PU). Comparing to the quick-dry PU, mechanical loadshare seems to be the preferred method of

choice since it can be quickly installed during the offshore J-lay installation.

### Soft Soils

The ability to model the interaction of the pipe in soft soils is particularly important. Seabed/pipeline friction interface, initial embedment, berming are key issues. Soil embedments, and appropriate friction factors, for both the axial and lateral directions, are important if the pipeline response is to be accurately predicted. Soil lateral resistance can be determined from soil shear strength and maximum pipe embedment, using methods developed by recent joint industry projects such as Safebuck and Hotpipe.

### Subsea HIPPS Systems

Subsea fields may require additional equipment, and technology such as high integrity pressure protection systems (HIPPS) which have been developed with the aim of reducing pipeline wall thicknesses, and enabling projects where extreme shut-in pressures may preclude a feasible pipeline. HIPPS has yet to be used in the GoM.

## 2. DESIGN SOLUTIONS

The ability to solve some of the most complex design issues is possible by innovation, experience, and the use of advanced analysis tools (10, 13, 20). This section briefly describes some of the significant solutions to design flowlines for XHPHT conditions.

### Ultra-Deepwater Solutions

Deep-water is a key design challenge, and the ability to resist hydrostatic collapse is fundamental. One solution is to determine the wall thickness using state-of-the-art DNV limit state design code (5) to facilitate optimization of the design. Pipeline collapse becomes a critical condition in deep-water and it is important to ensure adequate margin from failure through the inclusion of appropriate load factors.

### Limit State-Based Design (LSBD)

To accurately model and predict the ultimate failure of a pipeline at high temperatures requires determination of the limit states, to gain an adequate margin of safety for the design loads. Limit states are local buckling, hoop stress ratcheting, strain capacity, and fatigue (17). The goal is to investigate the ultimate limit states, and a FE model is used to provide the pipeline response data as input for each limit state. DNV OS-F101 (5), API RP 1111 (4), DNV RP-F110 (30) are utilised as the key guidance for limit states checks. Other codes and JIP works, such as Safebuck, and Hotpipe, also provide guidance.

### High-Pressure/High-Temperature and Thermal Expansion Management Solutions

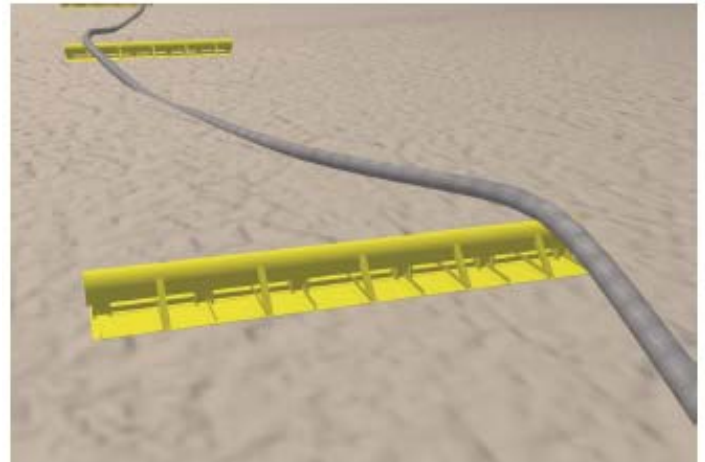
There are only a few design solutions for thermal expansion management of high-pressure/high-temperature applications (18). When a pipeline warms, it expands and, due to the resistance from soil friction, very large axial forces arise if the pipeline is unable to expand. These high axial forces can cause the pipeline to buckle laterally if exposed on the seabed or upheaval buckle if the pipeline is constrained in a back-filled trench. These high axial loads must be controlled, and potential solutions include expansion spools, buckle initiators, or vertical upsets, such as sleepers pre-installed to control the build up of axial loads.

### Sleepers

The vertical upset method capitalizes on the likelihood of a pipeline, laid over an intentional vertical support, experiencing an initial vertical movement that subsequently develops into a lateral buckle. The methodology introduces, deliberately, a number of significant vertical out-of-straightness (OOS) along the pipeline. The OOS is achieved using pipe sleepers, as shown in Figure 2, that

control the extent of the lateral buckle on start-up with the application of temperature.

With the sleeper technique, large-diameter single or double pipe joints are placed on the seabed perpendicular to the route, to provide the OOS. Sleepers must be installed, with special emphasis on accuracy of placement, prior to pipe-lay. Finite element analysis (FEA) is undertaken to determine the level of post-buckle displacement, bending moment, and strain, and is addressed as a design issue of thermal expansion management.



**Figure 2: A Typical Vertical Trigger Sleeper Arrangement**

Advantages of vertical trigger sleepers are the definite out-of-straightness (OOS), predictable critical buckling force, and reduced uncertainty of pipe-soil interaction. Use of sleepers to initiate lateral buckling is a proven technology and is particularly applicable to deep water (8, 12). Sleepers have been successfully employed on a number of projects.

### Buoyancy

Another method to reduce the lateral buckling resistance is distributed buoyancy. With the distributed buoyancy method, discrete lengths of the pipeline (60-200 m) are installed with added buoyancy, facilitating sites for controlled lateral buckle initiation. The amount of buoyancy is selected such that operational weight of the submerged pipeline is approximately 5-10 % of its typical submerged weight. The reduced submerged weight reduces lateral soil resistance to movement ensuring a lateral buckle preferentially occurs at the buoyant pipe section. The primary effect is to reduce lateral soil restraint. A concern in employing this method is possible hydrodynamic instability and, it presently has a limited implementation history. However, from an analytical point of view, it appears to be a robust solution.

### Thermal Performance Solutions

High-temperature well fluids with possible wax/ asphaltene/hydrate formation within the product stream, or long-distance tie-backs require high thermal performance. The overall heat transfer coefficient (OHTC) needs to be a low value ( $<1 \text{ W/m}^2\text{K}$ ). To maintain high temperatures, and long cool-down durations, requires the technology of pipe-in-pipe systems. New high-tech materials, such as aerogels, must be considered in the annulus space as they have far superior thermal performance compared to existing PUF, and provide excellent OHTC for PIP (15). However, as a result of this efficient insulation, thermal expansion challenges are increased and techniques such as probabilistic analysis (31, 32), upheaval buckling design, snake lay or cooling spools may be necessary to mitigate high

expansion loads. PIP with aerogel insulation has been used on a number of deep water projects around the world.

### **Subsea HIPPS Systems**

High-integrity pressure protection system (HIPPS) philosophy is used to enable flowlines to operate at reduced pressures, lowering risks and reducing line pipe costs. A number of designs for HIPPS systems have been completed. Of particular importance is the emergency shut-down logic control system, which demands careful design and testing to ensure that an appropriate level of reliability is achieved. Risk and reliability analysis techniques have been used to select the appropriate safety integrity level (SIL) and optimum pipe wall thickness.

### **Soft Soils**

The design of pipelines on soft soils is a challenge. Coulomb friction models are no longer valid, and complex non-linear pipe/soil load-displacement relations must be developed that include the peak and residual forces of the lateral and axial displacements for different cohesive soil types.

The ability to model the interaction of the pipe in soft soils is particularly important and includes seabed/pipeline friction interface, initial embedment, berming, etc. Soil embedment and the correct resistance, for both the axial and lateral directions is important if the lateral buckle is to be modeled and predicted correctly. Soil lateral resistance can be determined from soil shear strength and maximum pipe embedment, as developed by Safebuck.

### **Advanced Finite Element Tools**

The use of advanced finite element analysis (FEA) tools is key to the design of XHPHT pipelines (13, 16). The modeling of the flowlines, PIP components, pipe-soil interaction, material non-linearity, and large displacements is complex and warrants FEA tools. Inner pipe loading, lateral buckling and 3D seabed are design situations that require FEA. The required FEA models are highly non-linear and demand powerful computers to run in reasonable cycle times. Running models relatively quickly, and not waiting days for analysis results, is both important and a challenge. Advanced FEA models have been developed to allow complex XHPHT designs to be undertaken, and these models are described within this paper.

### **Loadshares**

Reduction of the inner pipe compressive load is achieved by use of a loadshare that intermittently connects the inner and outer pipes together, after the inner pipe has been tensioned to redistribute the pipe gravity loads during installation. The use of a loadshare has been shown to reduce the inner pipe compressive load (19). A mechanical loadshare is presented within this paper.

### **Qualification Testing of PIP Components**

It is important to determine the effect of high temperatures on the components that make up the PIP system. A PIP system consists of a number of additional components to the inner and outer pipes, such as centralizers, waterstop seals and loadshares. Qualification testing is essential (11). It is important to ensure a full understanding of the effects of temperature on the material strength and durability, and long-term structural performance (15). These issues are addressed within this paper.

### **Soft Soils Modeling using CEL Method**

The more sophisticated finite element approach involves modeling the seabed soil with an eulerian mesh, and the less deformable objects, such as the pipeline, are modeled with a lagrangian mesh. This coupled eulerian-lagrangian (CEL) formulation has the advantage of being able to model the extreme soil

deformations involved, while keeping good track of the stresses in the pipeline.

### **End Constraints for Flowlines**

Another component of the thermal expansion management system is the restraint (anchor) systems involving driven piles and suction piles, with fixed and chained connections. Pipeline-end restraint systems should be designed to match as closely as possible the axial stiffness assumed in the pipeline thermal expansion management analyses (18). Restraint systems that have been used in deepwater range from fixed connections to uni-direction restraint connections that comprise chained arrangements. Piles are usually the main elements that transfer loads to the foundation soil. Suction anchor piles or driven piles can be used for this purpose.

## **3. FINITE ELEMENT ANALYSIS DESIGN METHODS**

### **Advanced Pipeline Analysis and Design Tools**

The key to undertaking complex designs of pipeline systems is use of advanced analysis tools. A wide range of proprietary advanced FEA tools, termed Simulator has been developed (10) to enable accurate prediction of pipelines responses. The FE engine is ABAQUS (29). The models include elasto-plastic materials, 3D route geometry, and peak/residual modeling of axial and lateral soil pipe forces. PIP and single-pipe models have been developed to investigate upheaval buckling, lateral buckling, reeling pipe/soil interaction and expansion/span analysis. Each model is fully checked and validated. Many of the models have been benchmarked against observed pipeline behavior.

The 'Simulator' analysis is a static large deflection analysis and includes all relevant non-linearities such as large deflection and large rotations, elasto-plastic pipe materials interpolated over relevant temperature ranges, and non-linear pipe-soil interactions. The Simulator modules were used to undertake the design of the XHPHT PIP flowline.

### **Design of XHPHT PIP Flowline**

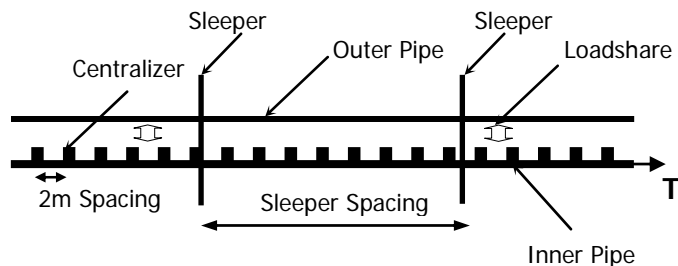
The project PIP flowline is designed to accommodate flowing temperatures to 177 °C (350 °F). A 8.625-inch (219 mm) inner pipe will carry primarily oil pressured to 6,500 pounds per square inch (44.8 MPa). A 12.75-inch (324 mm) outer pipe will contain the flowline at a 4,500-foot (1,370 m) water depth. The pipe material selected is API-5L X70. The temperature de-rating effect on the steel material properties was determined per DNV OS-F101 (5). An elasto-plastic material property was utilized.

The traditional limit state code checks for the flowline design were conducted in the first stage of design, and the works covered: pressure containment; collapse; bending and external pressure; and buckle propagation (22). The further study presented in this paper was focused on the following limit states: local buckling; hoop stress ratcheting; strain capacity; and low cycle fatigue (23).

A Simulator module was used to model a straight PIP flowline with lateral buckle initiator, the sleeper, installed at 1,500-meter (4,920 ft) or 1,000-meter (3,050 ft) intervals. A sleeper introduces a vertical upset that reduces the local lateral restraint to flowline. It controls the lateral buckle, smoothes the flowline lateral bending and deformation, and results in a lesser amount of strain and bending moment.

Figure 3 sketches the global PIP finite element model. Besides inner pipe, outer pipe, and the insulation in the annulus, other

components of the PIP were also modeled, such as the spacer that centralizes the PIP, and the loadshare that prevents the lock-in compressive load to be captured in the inner pipe.



**Figure 3: A Sketch of Global PIP FE Model**

The outputs necessary to conduct the limit state code checks are cyclic axial stress, hoop stress, effective axial force, bending moment, axial compressive strain and equivalent plastic strain.

### Local Buckling

Both the DNV load control (LC) and displacement control (DC) criteria were selected as a local buckling limit state. An API RP-1111 (4) combined load (bending strain and external pressure) limit state was also adopted for the outer pipe design. Table 1 presents the limit state unity check results.

**Table 1: Local Buckling Limit State Unity Check**

Sleeper Intervals	Design Code	Limit State Unity Check <sup>(1)</sup>	
		Inner Pipe	Outer Pipe
No Sleeper	DNV, LC	1.008	1.159
	DNV, DC	0.080	0.867
	API	N/A	0.382
1,500m (4,920ft)	DNV, LC	0.964	1.047
	DNV, DC	0.070	0.803
	API	N/A	0.281
1,000m (3,050ft)	DNV, LC	0.922	0.983
	DNV, DC	0.060	0.744
	API	N/A	0.196

Note: (1) The limit state check should not exceed unity.

A sleeper is an effective means to mitigate the flowline lateral buckling response. In such extreme operation condition, temperature of 177 °C (350 °F) and pressure of 44.8 MPA (6,500 psi), the sleeper is installed at 1,500-meter intervals in order to meet DNV DC limit state, and at 1,000-meter intervals to satisfy the DNV LC criterion.

### Hoop Stress Ratcheting

Recommendations from the Safebuck JIP were utilized to undertake hoop stress ratcheting limit state checks. An equation is used that determines the limit load that would initiate cyclic plasticity and also serves as a hoop strain ratcheting check such that no additional assessment is required. It can be used for both internal overpressure and external overpressure.

The limit state code check results listed in Table 2 again prove the effectiveness of a sleeper, in terms of thermal expansion buckle management.

**Table 2: Hoop Stress Ratcheting Limit State Unity Check**

Sleeper Intervals	Limit State Unity Check <sup>(1)</sup>	
	Inner Pipe	Outer Pipe
No Sleeper	1.125	1.030
1,500m (4,920ft)	1.073	0.995
1,000m (3,050ft)	0.987	0.885

Note: (1) The limit state check should not exceed unity.

### Strain Capacity

The strain capacity limit state was also undertaken in accordance with Safebuck JIP recommendations, which require the maximum nominal equivalent strain developed in the buckle not to exceed a limiting value. The results are listed in Table 3. Project pipeline presented no concern for strain capacity limit state.

**Table 3: Strain Capacity Limit State Unity Check**

Sleeper Intervals	Limit State Unity Check <sup>(1)</sup>	
	Inner Pipe	Outer Pipe
No Sleeper	0.279	0.293
1,500m (4,920ft)	0.273	0.306
1,000m (3,050ft)	0.178	0.180

Note: (1) The limit state check should not exceed unity.

### Low Cycle Fatigue

Fatigue is another major design issue for the XHPHT PIP. This limit state has to be rigorously checked, even if the pipeline deforms as desired and local buckling checks are satisfied, since the stress ranges developed during start-up / shut-down cycles are significant, due to over 100 °C temperature deviation. The nominal stress range can exceed yield strength as it changes from the tensile to the compressive. Hence the pipeline must be able to tolerate high stress and low cycle loading.

DNV RP-C203 (7) basic design S-N curve under F or D class was selected depending on the weld location. The PIP flowline design life was assumed as 20 years.

**Table 4: Allowable Low Cycle Fatigue**

Sleeper Intervals	Pipe	Allowable No. Cycles		DNV Factored No. of Cycles	
		Class D	Class F	Class D	Class F
No Sleeper	Inner	2,996	6,571	599	1,314
	Outer	1,376	944	275	199
1,500m (4,920ft)	Inner	3,458	7,586	692	1,517
	Outer	1,528	1,048	306	210
1,000m (3,050ft)	Inner	4,444	9,749	889	1,950
	Outer	2,170	1,489	434	298

Results in Table 4 present the allowable number of shut-down and start-up cycles and the table also lists the factored number of cycles per DNV OS-F101 (5) under the normal safety class with a factor of 1/5. Results indicate that outer pipe will have short fatigue life due to excessive axial stress range. Thermal buckle management reduces the axial stress range of outer pipe up to 14%, which results in an increase of fatigue life by 50%. During the 20-year design life, the

total allowable cycles for full start-up / shut-down should be less than or equal to 434 for weld class D and 298 for weld class F.

### Local PIP Finite Element Model

Utilizing ABAQUS CAE interface, a local 3D FE model is built for further studying the structural response at the component level. The model is composed of the following parts: inner pipe; outer pipe; spacers; and bulkhead. The pipe section is 30 meters (100 ft) long with an axis-symmetric setup, so that the structural response of a 61 meters (200 ft) section of PIP is simulated. Detailed 3D model is shown in Figure 4.

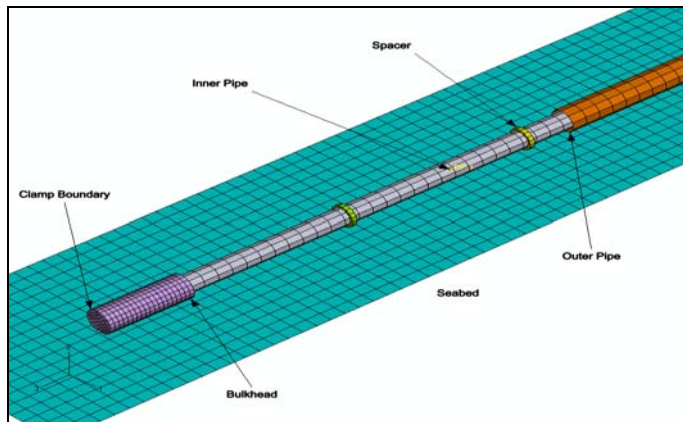


Figure 4: A Meshed Local PIP FE Model

It is noticed that under a thermal load the expansion of the inner pipe is restrained by a boundary, such as bulkhead, spacer, or outer pipe. As a result, the inner pipe has a compressive deformation and forms a 3D helical shape locally, in addition to pipeline global (lateral) displacement. Figure 6, on the next page, shows the inner pipe lateral displacement related to the outer pipe away from a lateral buckle region, whilst Figure 7 presents the magnified (x100) PIP deformation, in which the inner pipe displays the twisted formation. Such 3D helical deformation of the inner pipe was also recorded from the analyses conducted via the global FE model.

Table 5: Comparison of Global FE and Local FE

Pipe	Peak Stresses ksi (MPa)			
	Axial Stress		Hoop Stress	
	Global FE	Local FE	Global FE	Local FE
Inner	-36.6 (-252)	-33.6 (-232)	29.1 (201)	34.2 (236)
Outer	-7.3 (-50.3)	-9.3 (-64.1)	-21.5 (-148)	-19.2 (-133)

Table 5 gives a side-by-side comparison of the stress responses from global PIP FE analysis and local 3D FE model under the same load condition without any initial imperfection applied. Results present a tolerable agreement within 10%. The global FE is modeled at 1,500 meters (4,920 ft), while the 3D FE is only 61 meters (200 ft) long.

Under an extreme thermal load of 177°C (350°F) design temperature, the 3D helical deformation of the inner pipe has an average helical wave length of 18.6 meters (61 ft). The max helical radius is 2.5 millimeters (0.1 in). To emphasize the phenomena, simulations were conducted for two more cases:

- Increase the temperature up to 232°C (450°F). Results showed a shortened 3D helical with a wave length of 9.9 meters (32.5 ft) and a radius of 4.6 millimeters (0.18 in);
- Double the thermal expansion coefficient. Results showed an even shorter 3D helical wave length of 6.1 meters (20 ft) and a radius of 10.9 millimeters (0.43 in).

The advantage of a local FE model is to incorporate the details of the PIP components. The stress in the centralizers was examined and the model presented a Von Mises stress of 20 MPa (3 ksi) as an extreme load response. This is less than one-third of the selected material's tensile strength and demonstrated that the centralizer design was safe for the application.

### Reeling Finite Element Analysis

To capture the reeling process adequately, the FEA has to be non-linear (large displacements and material nonlinearity) to simulate the response of the pipeline due to the high curvature of the pipe on the reeling drum (14). After reeling, the pipeline has residual strains in both the inner and outer pipes. The effect of the strain in the inner pipe may reduce its ultimate load capacity when pressure and temperature are applied during the operational phase. Considering the reeling history, combined with the operational loading, will allow a greater level of confidence in the design capacity.

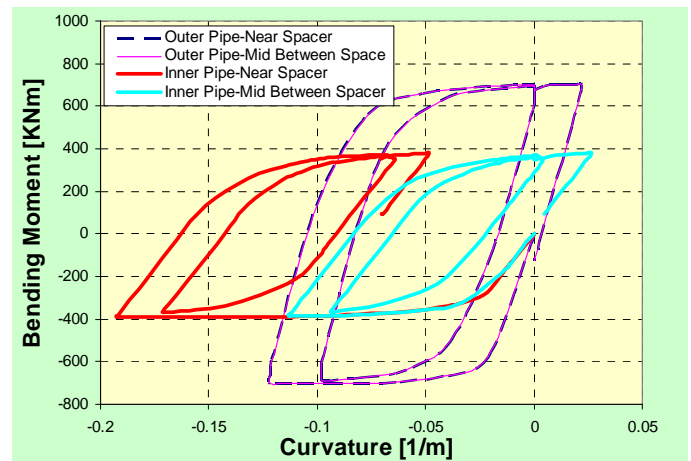


Figure 5: Moment - Curvature Histories for PIP Reeling

The moment-curvature histories for the PIP at different locations (near spacer or at middle between spacers) are plotted in Figure 5. The moment-curvature history plots for these two locations are almost identical for the outer pipe and the residual value of curvature is almost zero. However, the inner pipe moment-curvature behaviors vary at different section locations due to the existence of centralizers. The residual loads from reeling are shown to have a subsequent effect on the ultimate limit state capacity of the inner pipe, when temperature and pressure are applied, during the operational phase. Within this paper the reeling history increases the DNV load-controlled buckling check in operation by approximately 9%.

The reeling installation process of pipe-in-pipe (PIP) systems produces residual loading in both the inner and outer pipes that needs to be taken into account in any subsequent lateral buckling analysis. This is particularly important as flowlines are now being designed at high temperatures.

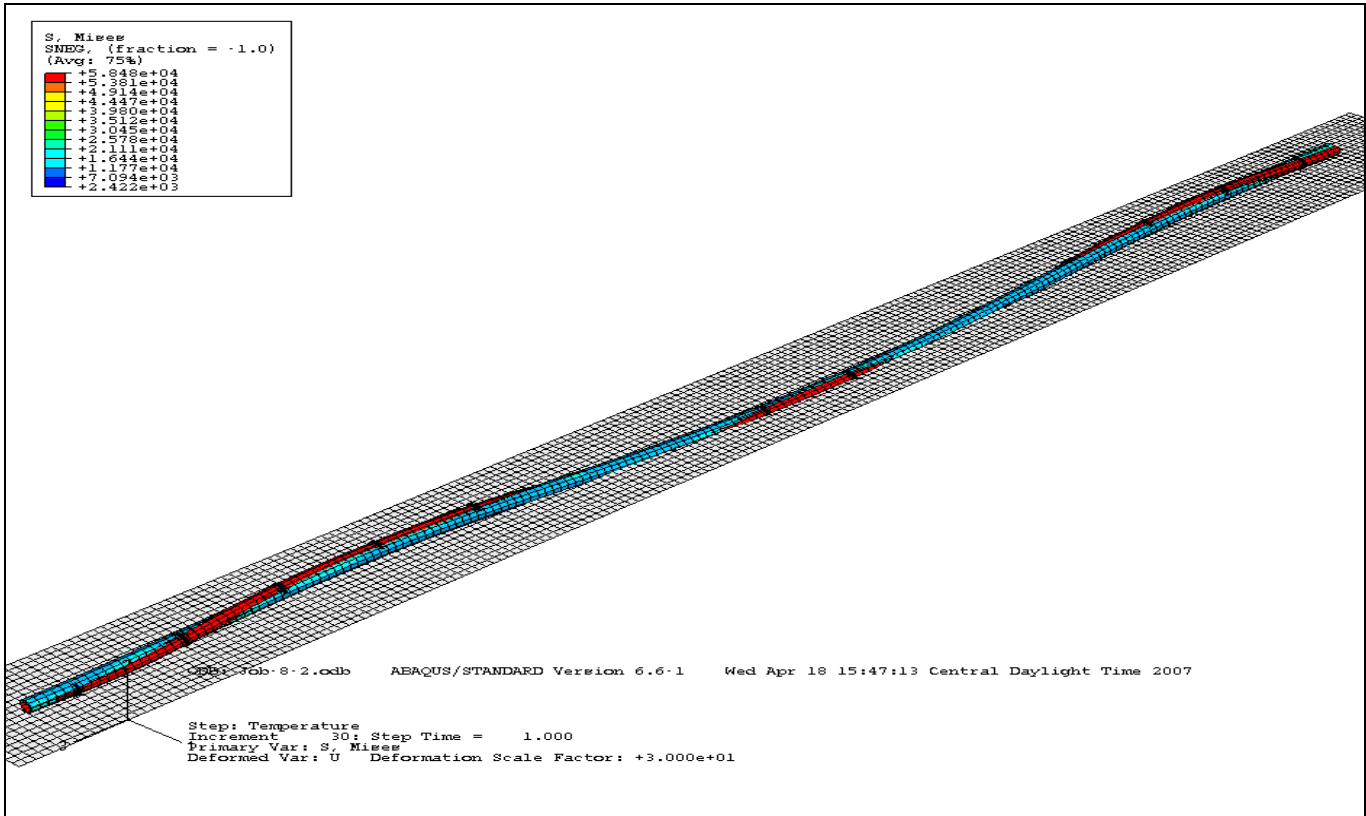


Figure 6: PIP Displacement Response (x30 magnification)

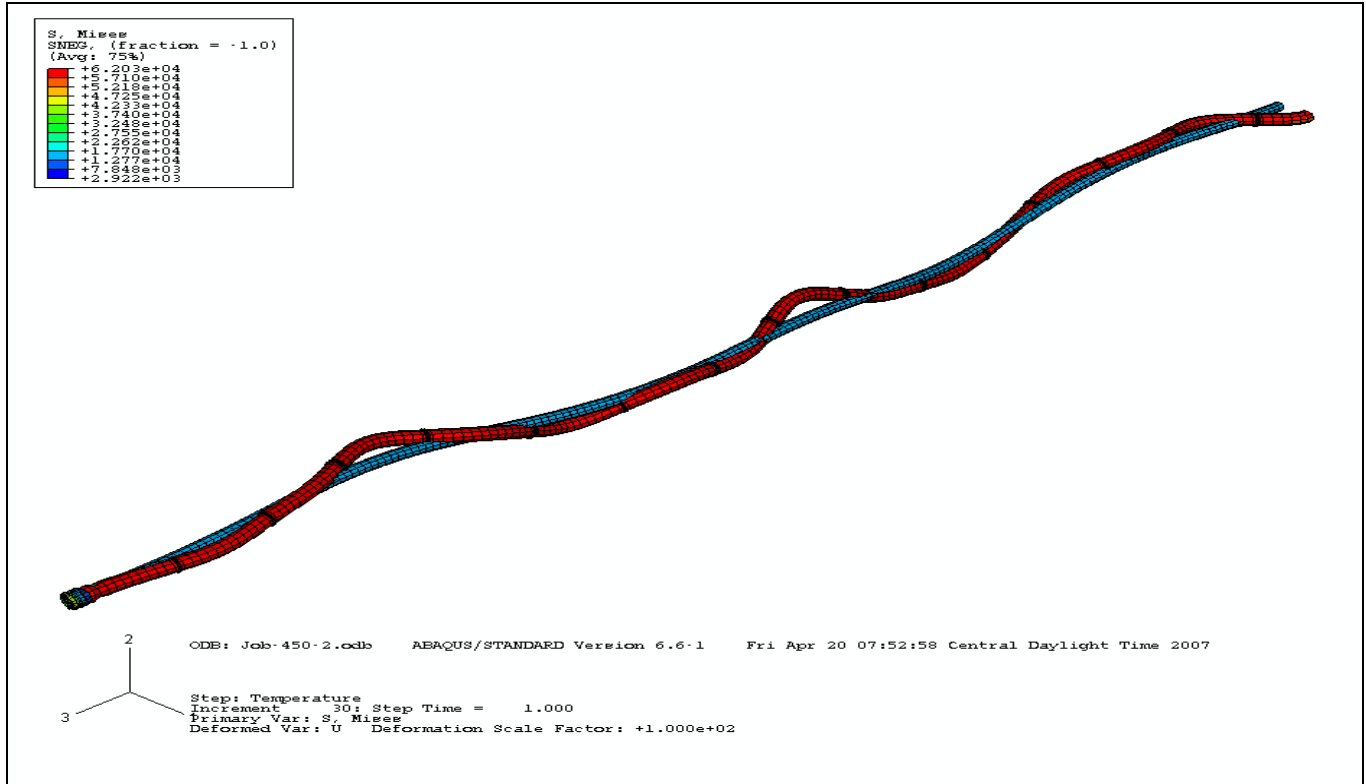


Figure 7: 3D Helical Deformation of Inner Pipe (x100 magnification)

#### 4. QUALIFICATION TESTING OF PIP COMPONENTS

This section describes a qualification testing programme for the testing of PIP components for 350°F (177°C) service, and includes the testing of centralizers (25), waterstop seals (26), thermal insulation (27, 28) and loadshares (26) to ensure structural integrity and long-term thermal and structural performance (11).

##### Centralizers

Centralizers are used to avoid loading that would crush the thermal insulation. Installation loads can be particularly large during reeling, and the centralizers are tested in compression for the maximum loads seen during the reeling process.

Operational conditions need to be considered, and degradation of the material due to temperature, long-term creep, and structural integrity are all issues related to the performance of the centralizer. High temperatures severely restrict the material options available for pipe-in-pipe centralizers. Based on the temperature, a modified polyphenylenesulphide (PPS) material was selected for testing, based on its characteristics of having high thermal mechanical strength, high hardness and rigidity, high creep strength and excellent wear characteristics.

**Slippage Tests.** The aim of the slippage test is to ensure the centralizer does not slip on the flowline under installation and in-service loads. Both sets of centralizers tested suffered brittle failures prior to reaching the weld bead, which meant that the test was abandoned and the centralizer could not pass over the weld bead. Figure 8 shows a failed centralizer specimen.

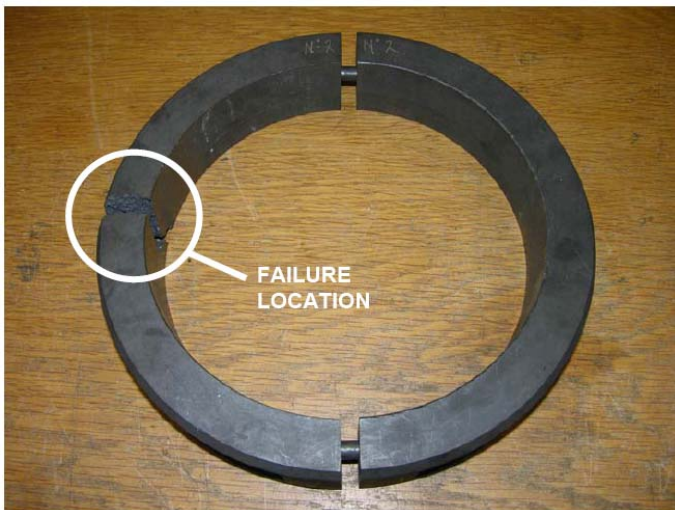


Figure 8: A Failed Specimen from Slippage Test

**Abrasion Tests.** The abrasion test consists of passing a centralizer over a number of weld roots. A winch is used to pull the flowline assembly along the length of an 80 ft (24 m) trough. A total of 17 runs were intended, equating to 119 weld beads passed. However, after five complete passes (35 welds), the centralizer suffered brittle failure. As a result of the brittle failures, for both the slippage and abrasion tests, the other tests were abandoned, and a search continues for an appropriate material suitable to 350°F (177°C) with acceptable ductility.

Conclusions following the centralizer tests are that there is no single thermoplastic capable of meeting the stringent demands covering both insertion case and service conditions for the centralizer.

The solution may require a substrate, possibly a pultrusion being overlaid with a cast polyamide material. Such a hybrid configuration could offer the temperature requirement local to the inner pipeline, and the necessary creep and abrasion resistance to cater for insertion.

##### Waterstop Seals

Testing of the waterstop seals is necessary to ensure the seal can withstand the hydrostatic loads in the event of annulus flooding. Due to the high-temperature of the inner pipe, sealing tests at temperature are also undertaken to ensure that material degradation does not impact the integrity of the seal. A test is performed to examine the integrity of the seal at temperatures of 350°F (177°C) and a water-depth pressure equivalent to 4500 ft.

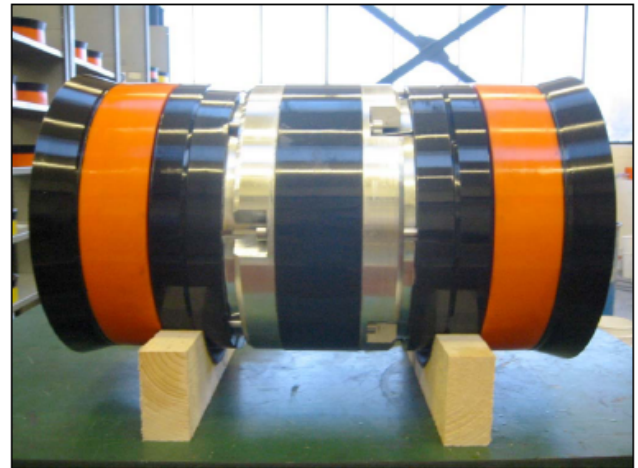


Figure 9: A Field-Proven Waterstop Seal

Figure 9 shows a proposed arrangement of the waterstop seal and clamp to be used in a PIP. The following tests were successfully undertaken for the PIP waterstop seals (25): load tests, hydrostatic pressure test, elevated temperature test and material aging test.

**Elevated Temperature Test.** In the event an outer pipe breach occurs, the water in the annulus will be heated due to the temperature of the inner pipe. Hence it was important to verify the temperature resistance capacity of the waterstop seal. A range of different seal materials was investigated. The final seal type used a hydrogenated nitrile butadiene rubber (HNBR) lip and a thermoplastic body. Hydrogenated nitrile butadiene rubber (HNBR) has an intriguing combination of properties. Like other elastomers, the HNBR material has high tensile strength, low permanent set, very good abrasion resistance and high elasticity. But in HNBR, these are complemented by good stability from thermal ageing and better properties at low temperatures compared to other heat- and oil-resistant elastomers. This combination of properties makes it particularly suitable for a high-temperature waterstop seal.

##### Aerogel Thermal Insulation Tests

The primary objectives of these tests are to evaluate the effect of exposure to extreme operating temperatures of 350°F (177°C) and compressive stresses (due to pipe laying and lateral buckles). The compressive stresses are applied for prolonged periods of time to determine the insulation performance and mechanical integrity of the aerogel material. Two different types of material tests were undertaken to examine this effect.

The first test evaluates the thermal conductivity of the material after aging at the maximum operating temperature, and the second evaluates the mechanical integrity of the material after thermal aging under installed conditions by unidirectional compression loading.

Aerogel is a particularly thermally efficient insulation material. It is an extremely lightweight and ultra-high performance insulation material that can be used in PIP systems as a substitute for typical insulation materials, such as PUF. Aerogel is produced by drying a gel to produce a solid material that consists of a lattice structure of the gel material with nanometer-sized pores dispersed throughout the material.

The size of the pores (~20-40 nm) is smaller than the mean free path of air (~60-100 nm) and consequently gas phase conduction is greatly reduced as a heat transfer mechanism. The thermal conductivity ranges from 0.008-0.013 BTU/hr.ft.°F (14 - 22 mW/m.K).

The results of the thermal conductivity testing demonstrated a very tight standard deviation in the test results; thermal conductivity increases with temperature; thermal conductivity was not affected by aging; effect of compression on thermal conductivity demonstrated some improvement in k-factor due to pore-size reduction.

Results of mechanical testing of aerogel material showed the following: aerogel material does not thermally age while operating continuously at temperatures up to 350 °F (177 °C).

The tests were successful and it can be concluded that aerogel is suitable as thermal insulation for XHPHT PIP systems.

## Loadshare

A loadshare (mechanical radial clamp) will be inserted in the annulus of the PIP during installation to connect the inner and outer pipes of the PIP, after tensioning the inner pipe to a pre-determined level. The purpose of testing a mechanical clamp loadshare is to ensure performance as a loadshare component in the PIP system. Load tests were successfully performed on the loadshare.

**Load Test.** The maximum expected axial load for the loadshare was determined using finite element analysis (FEA) (9, 19). For a water depth of 4500ft (1372 m), the test load was 193.6Te (1900kN) and this included a load factor of 1.1. A typical arrangement of a load share clamp is shown in Figure 10.



**Figure 10 A Mechanical Loadshare**

The load was applied using a series of four calibrated hydraulic pistons and a calibrated hydraulic hand pump. The full test load was applied for one hour. The results showed no slippage of the clamp, and no further movement occurred. No buckling of the inner pipe occurred, and the test was successful.

## CONCLUSIONS

This paper describes design challenges and solutions, finite element analysis models, and a qualification testing programme for the testing of PIP components for 350 °F (177 °C) service. The conclusions from this work can be summarized as follows:

- Limit state design proved to be a viable solution for the development of XHPHT flowlines.
- Advanced finite element methods, using global and local FE models, are essential to support the design of XHPHT flowlines integrated with limit state design.
- The effectiveness of thermal expansion buckle management was demonstrated to control thermal expansion, reducing the load response, and enhancing the flowline performance.
- The local PIP FE model showed the expected 3D helical arrangement of the inner pipe subjected to high temperature.
- Global and local FE models presented comparable results in term of pipeline stress response.
- The reeling installation process of pipe-in-pipe (PIP) systems produces residual loading in both the inner and outer pipes that should be considered in any subsequent lateral buckling analysis. This is particularly important for flowlines designed for high temperatures.
- The work demonstrated use of cutting-edge finite element models by projects for future deep water XHPHT PIP in Gulf of Mexico.
- **Centralizers.** The test program was not successful. The main challenge is finding a material suitable to 350° F. Materials tested to date have failed due to lack of ductility (brittle behavior).
- **Waterstop Seals.** Waterstop seals were tested for expected structural loading and thermal loadings, and the seal passed all aspects of the testing.
- **Thermal Insulation.** Aerogel materials tested did not thermally age while operating continuously at temperatures up to 350°F (177°C). The material is very well suited for PIP insulation applications in XHPHT systems.
- **Loadshares.** The tested design is suitable for accepting a load of 176 Te.

The FEA and qualification testing of the components presented within this paper extends the boundaries of what is possible with PIP designs and opens the possibility of XHPHT field developments in the GoM.

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