Subsea7 have designed, fabricated, and installed Bundles (towed pipeline production systems) for over 33 years, with 69 installed to date.

Over the previous 3 decades operators choice of Bundles as a field development option has been steady but intermittent. However over recent years Bundles have been embraced by field developers as a technically and commercially attractive solution to allow difficult fields to be developed, they are now being proposed by operators and design houses at concept selection phase.

Subsea7 is currently experiencing the busiest period of Bundle design/installation activity ever; a record 8 bundles installed during 2011/2012 and further 8 confirmed installations by the Q2 of 2015. A number of the installed or currently in-design Bundles are firsts for Subsea7.

The paper will discuss the benefits of Bundle technology for rejuvenating and extending existing facilities or new developments. A number of case studies to demonstrate the technical and commercial advantages will be discussed;

- Apache Bacchus - Active Heating of Production Fluid using produced water,
- BP Andrew – Longest tie-back utilising Bundles, 4 bundles connected in series totalling 27.8km,
- COP Jasmine – Highest Temperature Bundle 155°C (to PD8010),
- Total West Franklin - Highest Design Temperature 160°C (to DNV) & Largest Diameter Carrier Pipe,
- BG Knarr - Deepest Water Depth 410m, and integrated flow assurance design,
- Shell FRAM – First Bundle with two midline structures,

The technical benefits driving the increased interest in Bundle Technology for field development will be discussed;

- Highly efficient insulation systems, heated bundles utilising Hot-Water or Electrical Trace-Heating,
- Design/construction method allows full system integration testing onshore allowing fast hook up and commissioning offshore, low stress installation method by CDTM (Controlled Depth Tow Method) minimizes stress and fatigue on internal flowlines,
- Design of bundle cross-section/system allows expansion at both ends, reducing build-up of axial forces, reducing the need for intermediate expansion spools, and allowing efficient design for HP/HT field developments,
- Eliminate requirement for specialized installation vessels (Reel-lay, S-Lay, J-Lay, and Heavy Lift) by utilizing readily available vessels, and incorporating subsea structures within the towed Bundle System.
1. Introduction

Towed Pipeline bundles involve the packaging of multiple flowlines, controls, and injection lines within a single outer carrier pipe. The bundle is terminated at each end by structures designed to accommodate the bundle operational requirements and transmit the launch & tow forces into the bundle. The end structures can incorporate various requirements from simple valve arrangements to complex structures incorporating multiphase flowmeters, HIPPS (High Pressure Protection Systems), & cooling spools, both diver and diverless towhead solutions have been installed. Figure 2 Details an example of a large complex towhead structure (500te+).

The carrier pipe performs multiple functions;
- Buoyancy for installation,
- Withstands the majority of the installation loads,
- On-bottom stability,
- Protection of the internal contents from dropped object and fishing gear interaction,
- Internal annulus sealed providing a corrosion inhibited environment for internal contents,

Figure 1 Details a typical pipeline bundle cross section.

A bundle can provide an effective means of insulating flowlines using low cost materials. Additionally there is greater operational flexibility for handling hydrate plugs and wax deposition.

Bundles are fabricated onshore in a single length whereby full onshore system commissioning and testing can be conducted prior to launch & installation. The fabrication site is 8km long ranging in width from 13 to 90 metres with fabrication sheds and office located at either end.
Bundles are launched down a fabricated launchway directly into the sea, utilising large anchor handling tugs. The size of tug required varies depending on the specific bundle elements of towhead weight and bundle length.

![Figure 5 Trailing Towhead Launch](image)

The bundle is then transported to its offshore location suspended between two tugs using the controlled depth tow method (CDTM). The bundle is suspended between two tugs. A further vessel accompanies the tow as a survey/patrol vessel. Figure 6 details the typical tow configuration for a bundle tow. To maintain control during the tow, the bundle is designed and constructed within specified tolerances with respect to its submerged weight.

![Figure 6 Typical Bundle Tow Arrangement](image)

The bundle is designed to have buoyancy, this objective being achieved by choice of the correct carrier diameter. Subsequently ballast chains are attached to the carrier pipe at predetermined intervals, providing additional weight to obtain the desired submerged weight. Careful design consideration is required, as apart from strength, towing characteristics, allowance must be made for tolerances in dimensions and weights of the component parts of the bundle.

The tow speed has a direct lift and straightening effect on the bundle. By controlling the tow speed in combination with the pretension maintained by the trailing tug, the bundle configuration and its deflections are kept under control. The towing mode of the bundle is determined by parameters such as tow depth, deflection, stresses, tow speed and dynamic movements. Essential parameters are continuously monitored during the tow and adjustments are made as necessary.

The towing mode can be adequately controlled by adjustments of the governing parameters such as tow wire lengths, tow wire tensions, tow speed and the tugs’ relative positions. In this manner the tow depth, bundle configuration, actual stresses and movements are kept within the specified operational limits under given environmental conditions.

During tow the bundle is kept clear of the seabed to enable a safe and unobstructed passage. Furthermore the towheads are kept below the water surface to minimise the effect of surface waves. Usually this is approximately 30m, but this controlled depth can be increased or reduced as desired.

After arrival on location in the field the bundle is gradually lowered by predetermined adjustment of the controlling parameters (tow wire lengths and tensions) and the bundle settles in a position of equilibrium above the seabed with the lower portion of the chains resting on the seabed. Once in this position the bundle can easily be manoeuvred in the off-bottom mode into its correct position with the end terminations in the required target areas. The nitrogen within the carrier pipe is then vented of and replaced with biocide dosed seawater to sink the bundle onto the seabed and provide permanent on-bottom stability.
2. Case Studies

This section describes a number of bundle projects that have recently been completed or are currently being designed, and highlights the advantages that bundle technology has brought to each of the developments;

2.1. Apache Bacchus

The Bacchus bundle is 5.5km long and ties the Bacchus Drill Centre back to the existing Forties Alpha Platform. The Apache Bacchus Bundle consisted of two 6” Production flowlines and two 4” Heating Water lines inside a 20” Sleeve pipe, with additional 4” Gas Lift, 3” Scale Squeeze, & 2” Methanol flowlines within the carrier annulus.

The flow assurance requirements for the field development made a bundle the ideal solution for the field. The standout feature of the bundle involved the heating lines that are included inside the internal sleeve pipe along with the production flowlines.

The design requirements are to deliver topside fluid arrival temperature for the production lines above the wax appearance temperature, maintain flowline temperatures above the hydrate formation temperature during operation, supply heating to the flowlines at start-up, and supply sufficient heat to dissolve the deposited wax within the production flowlines.

The field produces sufficient produced water at a suitable temperature therefore very little additional heat input is required in order to supply heating to the bundle. Figure 8 details the Olga model cross section utilised in the flow assurance analysis.

The re-use of the produced water as a heating medium reduces the CAPEX (capital expenditure) & operating costs of the field, as no additional heat generating plant is required to be installed on existing facilities and very little power generation is required through life to support the bundle heating.

The Bacchus Bundle consists of the components as detailed in Table 1 and Figure 7.

<table>
<thead>
<tr>
<th>Table 1 - Bacchus Bundle Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
</tr>
<tr>
<td>Carrier</td>
</tr>
<tr>
<td>Sleeve</td>
</tr>
<tr>
<td>Production (2 of)</td>
</tr>
<tr>
<td>Heating Line (2 of)</td>
</tr>
<tr>
<td>Insulation</td>
</tr>
<tr>
<td>Gas Lift</td>
</tr>
<tr>
<td>Scale Squeeze</td>
</tr>
<tr>
<td>Methanol</td>
</tr>
<tr>
<td>Control Tubes &amp; Cables</td>
</tr>
</tbody>
</table>

Main Advantages that Pipeline Bundles brought to the development,

- Indirectly heated flowlines to meet challenging flow assurance requirements,
- Bubi Lined Pipe reduced overall cost compared with solid CRA or Clad pipe,
2.2. BP Andrew

The combined length of the four Andrew Bundles connected in series is the longest tie-back to date utilising towed pipeline bundles. The bundles connect the new drill centre at Kinnoull back to the existing Andrew Platform. The total tie-back length is 27.8km and is built up of 4 pipeline Bundles (3 x 7.2km, & 1 x 5.5km). Bundle 3 incorporates a midline structure for future tie-in of additional wells. Additionally Bundle 3 also demonstrates the ability to deflect bundles into a curve to meet field layout requirements, with a deflection at either end of the bundle to 2000m radius (total deflection of 412m at either end). The bundle section has a high spec insulation requirement which is achieved with 50mm of LDPUF insulation to give a Uod of 0.8W/m²K.

The Andrew Bundle consists of the components detailed in Table 2 and Figure 9.

Table 2 – Andrew Bundle Cross Section

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimensions</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>34.7&quot; - 881.4mm OD x 11mm WT</td>
<td>API 5L X52 - SAWL</td>
</tr>
<tr>
<td>Production</td>
<td>14&quot; – 355.6mm OD x 14.3mm WT + 3mm Thk. Liner</td>
<td>DNV-SMLS-450 DFUL + UNS S31603 Liner</td>
</tr>
<tr>
<td>Insulation</td>
<td>50mm Thk.</td>
<td>LDPUF</td>
</tr>
<tr>
<td>Production Sleeve</td>
<td>20&quot; – 508mm OD x 10.5mm WT</td>
<td>API 5L X52 - HFW</td>
</tr>
<tr>
<td>Gas Lift</td>
<td>6&quot; – 168.3mm OD x 8.7mm WT</td>
<td>API 5L – X65 - SMLS</td>
</tr>
<tr>
<td>Methanol</td>
<td>3&quot; 88.9mm OD x 9mm WT</td>
<td>API 5L – X65 - SMLS</td>
</tr>
</tbody>
</table>

Main Advantages that Pipeline Bundles brought to the development,

- Bundle could be installed underneath the Flotel at Andrew Platform whilst on-site, therefore reducing development timescale,
- Increased flexibility of bundle installation method de-risked the schedule impact of other on-site operations,
- Bubi Lined Pipe reduced overall cost compared with solid CRA or Clad pipe,
2.3. COP Jasmine

The Jasmine bundles were the highest temperature bundles to be designed at the time of installation. The bundles tie the Jasmine Well-head platform to the Judy Riser Platform. The bundle consists of a single 16” insulated pipe-in-pipe flowline inside a carrier pipe. There are two bundles each 4.1km long, connect at intermediate towheads with pipe-in-pipe tie in spools. The design conditions 155°C and 150bar made the design of the flowline challenging, and resulted in a strain based design to PD8010. The design was conducted utilising advanced non-linear Finite Element Modelling which included modelling the Mechanically Lined pipe fabrication process.

The Jasmine Bundle consists of the components detailed in Table 3 and Figure 10.

![Figure 10 Jasmine Bundle Cross Section](image)

<table>
<thead>
<tr>
<th>Table 3 – Jasmine Bundle Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
</tr>
<tr>
<td>Carrier</td>
</tr>
<tr>
<td>Production</td>
</tr>
<tr>
<td>Insulation</td>
</tr>
<tr>
<td>Production Sleeve</td>
</tr>
</tbody>
</table>

The axial force generated from the temperature resulted in high axial forces, high equivalent stress, and high potential for global lateral buckling. Figures 11a & b detail the comparison of the combined system (buckle initiating) force and the buckling force (calculated force at which point a lateral buckle would be initiated, to DNV-RP-F110). This demonstrates that for the lower bound and upper bound soil friction estimates there is over 20% margin against global lateral buckles. Figure 11c details the extreme scenario of upper bound axial friction (higher axial force) and lower bound lateral friction (lower resistance force) which demonstrates a margin of 2%.

An option during the conceptual design phase was to utilise a single 8.2km bundle, however the utilisation of two bundles allowed for greater axial expansion in the bundles and therefore reduced the high equivalent stresses in the flowline, along with high system forces that could result in a global lateral buckle of the bundle.

The combination of the bundle expanding and providing resistance to lateral buckling makes the bundle solution ideal for this HT application, both design problems of high axial force and lateral buckling are accommodated without need for expansion loops or buckle initiators.

The detailed FEA of the bundle included the full life cycle of the bundle from formation of the Bubi Lined pipe to heat up and cool down during operation. The analysis considered a 200mm seabed imperfection which is the only location where plastic strain was displayed in the production flowline, the remainder of the flowline was within the allowable stress range of PD8010. The strain occurs in first operation cycle when the flowline reaches maximum temperature at the seabed imperfection, the seabed imperfection is a fixed feature and therefore the plastic strains in this location are not required to be considered for fatigue analysis.

![Figure 11a Lower Bound Axial & Lateral Friction](image)

![Figure 11b Upper Bound Axial & Lateral Friction](image)

![Figure 11c Upper Bound Axial & Lower Bound Lateral Friction](image)

Main Advantages that Pipeline Bundles brought to the development;
- Bundle expansion due to temperature reduces axial forces, resulting in lower WT,
- Bundle System weight & balanced forces prevent Global/Lateral Buckling,
- Bubi Lined Pipe reduced overall cost compared with solid CRA or Clad pipe,
2.4. Total West Franklin

The West Franklin Bundle is the highest temperature bundle designed to date, and consists of the largest diameter carrier pipe at 56.4" in the fortified sections. The bundle consists of a single 6.7km Bundle connecting the West Franklin Wellhead Platform to Elgin B Wellhead Platform. The bundle is separated into three sections consisting of ~500m fortified zones at either end. Internally the bundle consists of two pipe-in-pipe flowlines with high specification Aerogel insulation to attain a u-value of 0.99W/m²K. The flowlines design conditions are 160degC, with 200bar in the main bundle sections and 604bar in the fortified zones.

The primary design code for the bundle is DNV-OS-F101. As with the Jasmine bundle advanced non-linear finite element modelling was conducted to demonstrate code compliance with the displacement controlled criteria (DCC) within DNV-OS-F101.

High operational stresses caused by bending over a bolder/prop therefore not fatigue inducing

The West Franklin Bundle consists of the components as detailed in Table 4 and Figure 12.

<table>
<thead>
<tr>
<th>Table 4 – West Franklin Bundle Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
</tr>
<tr>
<td>Carrier (Main Section)</td>
</tr>
<tr>
<td>Production (Main Section)</td>
</tr>
<tr>
<td>Insulation (Main Section)</td>
</tr>
<tr>
<td>Production Sleeve (Main Section)</td>
</tr>
<tr>
<td>Carrier (Fortified Section)</td>
</tr>
<tr>
<td>Production (Fortified Section)</td>
</tr>
<tr>
<td>Insulation (Fortified Section)</td>
</tr>
<tr>
<td>Production Sleeve (Fortified Section)</td>
</tr>
</tbody>
</table>

Main Advantages that Pipeline Bundles brought to the development,
- Main & Fortified zones could be fully strength tested (onshore) to their respective pressure requirements, this could not have been conducted with a single flowline laid in-field,
- Bundle expansion due to temperature reduces the build-up of axial forces, and allowed field development without a cooling spool,
- System weight and tensile forces on sleeve and carrier prevent the bundle from global lateral buckling,
- Bubi Lined Pipe reduced overall cost compared with solid CRA or Clad pipe, (in main section)
- Highly Insulated Production Flowlines with Aerogel Insulation, giving $U_{id} = 0.99W/m²K$. 

Figure 12 West Franklin Bundle Cross Sections (Main & Fortified)
2.5. BG Knarr

The Knarr bundle will be the deepest bundle installed to date at 410m water depth. Bundles have been installed in water depths up to 360m previously therefore the requirements and methods involved have been proven, and are adapted for the new water depth. The bundle consists of a 5.1km tie back from the Knarr Production Manifold to the FPSO. The bundle cross section consists of two 25% Chrome pipe-in-pipe production, water injection and service flowlines. The large towheads at either end each contain 2 x 100m cooling loops, with all diverless connections.

The challenging flow assurance requirements of both maximum and minimum arrival temperatures, and required cool down time within the bundle section meant that the bundle was designed as a system rather than individual components. The cooling spool length is affected by the insulation properties within the bundle; similarly the insulation requirements to meet the cool down time are dependent on the inlet temperature into the bundle from the cooling spools.

Advanced CFD (Computational Fluid Dynamics) analysis has been conducted on the towhead structures and cooling spools to ensure that the cooling requirements are met Figure 14. Additionally cool down analysis on the bulkheads at the end of the bundle was conducted to ensure there were no cold spots at the bulkhead locations. The analysis resulted in the requirement of additional secondary bulkheads being introduced to meet the cool down requirements.

The Knarr Bundle design consists of the components detailed in Table 5 and Figure 13.

![Knarr Bundle Cross Section](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimensions</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>41.7&quot; - 1059.2mm OD x 15mm WT</td>
<td>ISO 3183 L360 - SAWL</td>
</tr>
<tr>
<td>Production (2 of)</td>
<td>8&quot; - 219.1mm OD x 15.9mm WT</td>
<td>DNV-SAWL-25Cr - SD</td>
</tr>
<tr>
<td>Insulation</td>
<td>10mm Thk. Rockwool Aquaduct CL9</td>
<td></td>
</tr>
<tr>
<td>Production Sleeve (2 of)</td>
<td>10&quot; - 273.1mm OD x 8mm WT</td>
<td>ISO 3183 L360 - HFW</td>
</tr>
<tr>
<td>Water Injection</td>
<td>10&quot; - 273.1 OD x 14.3mm WT + 10mm HDPE Liner</td>
<td>DNV-SMLS-450-SD + HDPE Liner</td>
</tr>
<tr>
<td>Service</td>
<td>4&quot; 114.3mm OD x 11mm WT</td>
<td>DNV-SMLS-450-SD</td>
</tr>
<tr>
<td>Control Tubes &amp; Cables</td>
<td>15 x Controls Tubes, 6 x Cables</td>
<td>Super Duplex</td>
</tr>
</tbody>
</table>

Main Advantages that Pipeline Bundles brought to the development,

- Increased flexibility of bundle installation method de-risked the schedule impact of other on-site operations,
- Bundle will be installed underneath the Drill Rig whilst on-site, therefore reducing development timescale,
- Integrated design of the bundle flowlines and structures (cooling spool length) allowed the system to be tuned to the clients specific flow assurance requirements,
2.6. Shell FRAM

The FRAM bundle was to be the first bundle to be designed with two midline structures. The proposed field architecture consisted of two drill centres tied-back to a single FPSO. The bundle design consisted of three sections; Section 1) 2.0km with a six slot manifold running to the 1st midline structure, Section 2) 0.5km between the two midline structures, Section 3) 2.0km from the 2nd midline structure to an eight slot manifold.

The carrier pipe in the central section of the bundle was optimised to account for increased dropped object loadings from the FPSO as this was to be located underneath the anchor pattern and within the swing radius of the FPSO.

The FRAM Bundle design consists of the components as detailed in Tables 16 & 17 and Figures 6 & 7.

Main Advantages that Pipeline Bundles brought to the development,

- Reduced numbers of risers, combined riser for Gas Lift and Test connected to each drill centre via either midline section of the bundle,
- Bundle could be installed underneath the Drill Rig whilst on-site, & FPSO, therefore reducing development timescale,
- Increased flexibility of bundle installation method de-risked the schedule impact of other on-site operations,
- Bubi Lined Pipe reduced overall cost compared with solid CRA or Clad pipe,
- Highly insulated Production & Test Flowline with Nanogel/Aerogel Insulation, giving $U = 0.65\text{W/m}^2\text{K}$. 

### Table 6 – FRAM Bundle Cross Section – West & East Section

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimensions</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>44” – 1117.5mm OD x 16.7mm WT</td>
<td>API-5L-L360-SAWL</td>
</tr>
<tr>
<td>Production</td>
<td>12” – 323.9mm OD x 22.2mm WT + 2.5mm CRA Liner</td>
<td>API-5L-L450-SMLS + Incoloy 825 Liner</td>
</tr>
<tr>
<td>Insulation (Production)</td>
<td>40mm Thk.</td>
<td>Nanogel/Aerogel</td>
</tr>
<tr>
<td>Production Sleeve</td>
<td>18” – 457mm OD x 9.5mm WT</td>
<td>API-5L-L360-HFW</td>
</tr>
<tr>
<td>Test</td>
<td>6” – 168.3mm OD x 12.7mm WT + 2.5mm CRA Liner</td>
<td>API-5L-L450-SMLS + Incoloy 825 Liner</td>
</tr>
<tr>
<td>Insulation (Test)</td>
<td>45mm Thk.</td>
<td>Nanogel/Aerogel</td>
</tr>
<tr>
<td>Test Sleeve</td>
<td>12” – 323.9mm OD x 7.1mm WT</td>
<td>API-5L-L360-HFW</td>
</tr>
<tr>
<td>Gas Lift</td>
<td>4” – 114.3mm OD x 11.1mm WT</td>
<td>API-5L-L450-SMLS</td>
</tr>
<tr>
<td>Control Tubes &amp; Cables</td>
<td>20 x Controls Tubes, 8 x Cables</td>
<td>Super Duplex</td>
</tr>
</tbody>
</table>

### Table 7 – FRAM Bundle Cross Section – Central Section

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimensions</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>36.4” – 924.6mm OD x 18mm WT</td>
<td>API-5L-L360-SAWL</td>
</tr>
<tr>
<td>Test</td>
<td>6” – 168.3mm OD x 12.7mm WT + 2.5mm CRA Liner</td>
<td>API-5L-L450-SMLS + Incoloy 825 Liner</td>
</tr>
<tr>
<td>Insulation (Test)</td>
<td>45mm Thk.</td>
<td>Nanogel/Aerogel</td>
</tr>
<tr>
<td>Test Sleeve</td>
<td>12” – 323.9mm OD x 12.7mm WT</td>
<td>API-5L-L360-HFW</td>
</tr>
<tr>
<td>Gas Lift</td>
<td>4” – 114.3mm OD x 11.1mm WT</td>
<td>API-5L-L450-SMLS</td>
</tr>
<tr>
<td>Control Tubes &amp; Cables</td>
<td>20 x Controls Tubes, 8 x Cables</td>
<td>Super Duplex</td>
</tr>
</tbody>
</table>
3. Technical Benefits

The technical benefits of utilising towed pipeline bundles are discussed in this section. The technical advantages of bundles can result in a bundle being the number one technical and commercial choice for field developments. Bundles generally are a lower cost alternative than traditional pipelay methods, where multiple flowlines or HP/HT conditions are present. The technical and commercial benefits are discussed below;

3.1. Highly Efficient Insulation Systems

The significance of flow assurance issues have become increasingly more relevant over the last few years as subsea developments have moved towards longer tie back distances, deeper water and difficult flow conditions. Managing these issues is a key in developing fields within this environment particularly within deepwater applications where low reservoir temperatures together with energy losses in risers can lead to significant production deferment.

Pipeline bundles and pipe in pipe systems offer enhanced production capabilities by incorporating such features such as active heating, high performance insulation and online production monitoring. This is highlighted by experience gained from installed bundle systems and is being further developed by testing of bundle configurations to meet functional requirements.

Bundle systems can also facilitate the utilisation of high performance ‘dry’ insulation materials (such as LDPUF, Aerogel, Izoflex) as well as accommodating active heating systems, which are being increasingly used where thermal management becomes critical.

From a flow assurance perspective a bundle gives several advantages:

- In terms of hydraulic considerations, fluid viscosity has a strong influence on pressure drop in the flowline and riser. Fluid viscosities become exponentially higher at lower temperatures and as a result the system pressure loss increases. If the system heat loss is reduced (as with the bundle system) or there is a heat input to the system (active heating) this will lead to lower viscosity therefore lower pressure drop, which could potentially lead to a reduction in the pipe diameter with associated cost savings in design fabrication and installation.

- A bundle can deliver higher arrival temperatures therefore can aid separation of fluids when they reach the topsides facility as higher temperatures aid in the breakdown of emulsions of oil and water. Higher temperatures can also reduce the heating duty required by process equipment topsides, therefore in conjunction with aiding separation the higher delivery temperatures can help facilitate the use of smaller less expensive process equipment.

- Arrival temperatures are a function of flowrate, therefore with more effective thermal management; higher arrival temperatures at a specified flowrate are experienced. This can lead to a bundle delivering fluids at the required arrival temperatures at a lower flowrate. This will decrease the possible production turndown rate and thus widen the possible operating envelope.

- Improved thermal management can also increase the cooldown time of the pipeline. This gives the operator more reaction time after a shutdown. This in conjunction with the lower turndown rates gives the process facility much more operational flexibility.
Several Bundle systems have been installed with active heating systems utilising both produced water re-injection as the heating medium or closed loop heating systems with expansion tanks on the topsides facilities. Figure 18 details a typical cross section including heating supply and return lines. Figure 19 details a typical CFD analysis output from the heat transfer analysis. Full scale test have previously been conducted to confirm that the heat transfer analysis is correct.
3.1.1. Pipe-in-Pipe vs. Wet Insulation (within a Bundle)

The majority of bundles installed have incorporated pipe-in-pipe flowlines. This is primarily due to the high insulation specification requirements (e.g. U-Values <2.0W/m²K) specified by field developers. Where the flow assurance requirements of the developments do not require the high specifications the operator may choose for a wet insulated solution to keep the costs down. This results in a cheaper solution for traditional pipelay techniques (Reel, S-lay or J-Lay) as it reduces top tension requirements, however for a bundle solution this is not the case.

The bundle components are all assembled at the manufacturing site therefore the linepipe, sleeve pipe and carrier pipe are transported directly to the fabrication site. For wet insulation systems the linepipe requires to be shipped to a third party contractor to complete the coating process and then shipped to the fabrication site, additionally once on-site field joint coatings are required at each site weld. The bundle fabrication process is a continuous production line therefore stopping to apply field joint coatings will delay the production schedule. For pipe-in-pipe solutions there is no field joint coating requirements as the insulation half shells or blankets are butted up against each other, and are not required to provide a corrosion resistant barrier.

Typically the flowline within the sleeve pipe will be supported with centralisers at a spacing of 3 - 4.5m to prevent local buckling, with the main steel spacers being located every 6 metres. For Wet insulated systems (within a bundle) the main spacer pitch would require to be reduced to 3- 4.5m to prevent local buckling. The cost of the main spacers is approximately 20 times greater than the cost of a centraliser.

Figure 20 details the relative cost of supplying the insulating materials required for insertion into a bundle, the pipe-in-pipe cost includes the LDPUF insulation, centralisers, main spacers, and sleeve pipe, the wet insulated costs account for the coating application, additional shipping cost and main spacers (all for ~40mm of insulation). The cost comparison does not consider the additional fabrication time attributed to applying filed joint coatings.

Therefore for Bundle applications pipe-in-pipe solutions are more cost effective than wet insulation and supply free U-value reduction.
3.2. Design & Construction

The bundle system is designed to be installed as a complete system, incorporating all of the flowlines, towheads (manifold) structures, and control systems.

3.2.1. Carrier Pipe

The majority of the installation loads are taken by the carrier pipe thereby providing a low stress environment for all of the internal flowlines. This is a key differentiator from traditional flowline installation methods whereby the flowlines are required to withstand all of the installation forces, plastic deformation and fatigue loading. Figure 21 details a comparison of the axial bending & tensile stress loading factors that apply to the components within a typical bundle cross section, this demonstrates how the bending stress and fatigue load applied to the internal flowlines are limited during the installation operations.

![Figure 21 Carrier Pipe & Internal Flowline Bending & Tensile Stress Loading Factors](image)

The fatigue damage incurred by the carrier and flowlines matches the stress loading factors that are applied. The stress loading factors are calculated as a ratio of the inertias of the individual components against the combined bundle inertia as per the method described in Ref.[3].

For a typical bundle the fatigue damage applied to the internal flowlines would be below the fatigue threshold as given in Table 2.1 & Section 2.11 Ref.[4], therefore the fatigue damage incurred by the internal flowlines for the installation activities is negligible.

The carrier pipe is designed to withstand the fatigue loadings imparted from the environmental loadings during the launch, tow & installation operations. The fatigue assessment is conducted utilising Orcaflex software and considers all phases of the operation. The carrier pipe fatigue is most sensitive when the bundle is near the water surface and therefore attracting higher loadings from the wave conditions. Typically the highest fatigue damage occurs during launch of the bundle where in water depth range of zero to twenty metres, and during CDTM where the bundle will be approximately forty to fifty metres below the surface. Once the bundle is below ninety metres the fatigue damage reduces rapidly to negligible values.

The installation operations are limited by wave height, not only to limit the fatigue within the carrier pipe, but also due to physical work limitations offshore. For example the Trail Tug deck operations cannot be conducted in greater than three metres significant wave height, therefore the bundle CDTM operation would be stopped prior at this time with the bundle slowed and lowered to seabed.

The fatigue is assessed in accordance with DNV codes Ref.[2 & 5] utilising alpha factors to calculate two loadcases, operational and design. The analysis is conducted on a worst case scenario that the bundle will always be subjected to the highest operationally permitted wave height, worst wave period and worst wave approach direction during the entire installation operation. The allowable fatigue damage for both loadcases is limited to 33% of the total allowable fatigue damage; the design loadcase always returns the highest fatigue damage result. The acceptance criteria are based on the requirements of Ref.[2]. The carrier pipe does not undergo significant fatigue damage during in-service conditions; bending stresses induced by seabed elevation are not of a cyclic nature. The high tensile loads in the carrier pipe occur at the ends of the bundle where thick wall carrier pipe is utilised at the transition to the towhead therefore axial stresses are lower. Additionally the areas of the carrier pipe that fatigue during installation and in-service are in at different locations therefore the fatigue damage is not cumulative. Figure 22 & 23 details typical fatigue damage values for the different phases of the bundle installation operation.
Table 22 Typical Fatigue Damage for Operational Wave Condition during Installation

Table 23 Typical Fatigue Damage for Design Wave Condition during Installation
3.2.2. Onshore Fabrication

Fabricated onshore in purpose built fabrication yard in Wick, North East Scotland. The Design/construction method allows full system integration testing onshore allowing fast hook up and commissioning offshore.

The complete bundle system is strength tested once fabrication of the bundle section is complete and connected to the towhead structures at either end.

The benefit of conducting the strength test onshore is that any repairs can be conducted in the protected environment, this will not increase installation/fatigue loads on the pipe sections already laid whilst the repair is on-going, as would be the case with Reel or S-lay pipe. The repair is quicker and cheaper to conduct and therefore contributes to reducing risk on the overall project cost. This negates the need for offshore strength testing as the installation method does not induce high stresses in the flowlines (as discussed earlier) in order for a failure of an internal flowline to occur during the installation phase then significant damage would need to have occurred to the carrier pipe, this would be highlighted during one of the many ROV surveys of the bundle conducted prior to and following final positioning in field. PD8010 Ref.[1] specifies this as acceptable method of demonstrating the strength of the system, leaving only a leak test to be conducted of the tie-in connections offshore.

3.2.3. Mechanically Lined Pipe

The low stress (CDTM) installation method does not result in plastic deformation of the flowlines, therefore allowing the use of mechanically bonded lined pipe to be utilised in Bundles, in-place of more expensive solid CRA or metallurgically Clad flowlines.

Buttings Bubi lined pipe has been used successfully on significant numbers of bundle projects. This results in significant savings for clients Table 8 demonstrates the illustrative cost of use of Bubi lined pipe against solid CRA and Clad pipe, the table compares the cost against a base level cost for carbon steel flowline and all for a 10” flowline.

<table>
<thead>
<tr>
<th>Table 8 Cost Comparison Lined vs. Clad vs. Solid CRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>X65</td>
</tr>
<tr>
<td>Lined</td>
</tr>
<tr>
<td>Clad</td>
</tr>
<tr>
<td>Solid</td>
</tr>
</tbody>
</table>

The table demonstrates the financial benefits available from utilising lined pipe within the bundle. A particular advantage to highlight is that 904L liner material can be used for lined pipe. Whereas there is currently no option to have a 904L clad flowline and therefore the next material grade up (825) is required to be chosen for a clad option, the relative cost for the 904L cladding in Table8 is based on 825 cladding to reflect this. No data is available at the time of writing for 625 Clad flowlines, the cost is anticipated to be greater than solid 25%Cr, and therefore not an option that is regularly priced.
3.2.4. De-risk Offshore Schedules

The bundles are installed in field whilst in off-bottom mode. Figure 24 shows the bundle configuration in off-bottom mode. In this mode the bundle is static at approximately 5m off the seabed, the drag chains which are attached to the bundle provide resistance to the current forces and prevent the bundle from moving laterally. The drag chain weight is designed to give sufficient stability in-field during the final positioning operations based on predicted currents. This operation is conducted at low speed one to two knots.

This method allows the bundles to be manoeuvred with a high level of accuracy, target box size for the lead structure is typically five by five metres. The two large anchor handling tugs used for the tow to fields would be used for these operations with one tug at either end to ensure control. This level of manoeuvrability allows for the opportunity to pull the bundle into position under existing floating assets. Bundles have been installed under flotels, drill rigs and FPSOs.

Typically a pre-laid pull-in wire would be installed prior to the floating asset being positioned, or if the floating asset was already positioned then a messenger can be installed via ROV.

The ability to conduct the installation under the above conditions de-risks the offshore schedule in situations where there may be uncertainty of FPSO delivery, Drill rig availability or on-going platform works. The bundle installation can be planned around these activities and as discussed in section 3.4 removes the reliance on specialised installation vessels.
3.3. Design for HP/HT

Pipeline systems laid on seabed, trenched, or buried, will expand when subjected to internal pressure and elevated temperature. The friction that develops between the pipe system and the seabed soil provides resistance to the expansion, which in turn develops compressive force within the system. The compressive or ‘effective axial force’ is a function of the internal and external pressure, the design temperature, the pipeline submerged weight, pipeline/soil friction, and the friction between the internal system components.

The prevention of expansion for a traditional pipeline system is primarily due to the weight of the back-fill or rock dump that is required to provide on-bottom stability or prevent global buckling. Bundles do not require trenching or rock-dumping (except in shallow water) the carrier pipe provides protection from dropped objects/fishing gear interaction, provides weight for on-bottom stability, and prevention of lateral bucking. The resistance to expansion for the bundle is due to coulomb type friction between the carrier and seabed, and between the internal components within the bundle.

The internal bundle components are held in the correct configuration by metal spacers. The spacers are mounted on rollers within the carrier pipe and are clamped to one of the internal flowlines, therefore providing a low friction interface with the carrier. The remaining flowlines are guided within the spacers to allow free expansion and movement between the internal flowlines with steel/steel contact. The pipe-in-pipe flowlines will be centralised within the sleeve pipes with polymer centralisers with typical coefficient of friction of the order of 0.43.

The combination of the lower resistance to expansion provided by the carrier/seabed interaction and the internal flowline interaction can result in up to a 15% reduction in axial force within the flowlines for Bundle solutions (dependent on bundle length and configuration). The resultant effect is that the wall thickness requirements for the flowlines can be reduced, or fields can be developed without the need for cooling spools to cool the product before transport.

Figure 25 demonstrates the effect of reduction in axial force on flowline wall thickness for a 12” flowline at 355barg. Where no axial flowline expansion occurs the figure demonstrates ‘chasing the wall thickness’ where at approximately 140°C the wall thickness starts to become un-realistically thick. For the particular design case considered the flowline wall thickness could be 25% thinner at 140deg. The wall thickness of the flowline is of particular importance to bundles as the carrier pipe OD (outside diameter) is sized to provide sufficient buoyancy to be able to launch and install the bundle. Any increase in flowline WT (wall thickness) automatically impacts on carrier OD.

![Figure 25 Flowline WT vs. temperature & pressure](image-url)
The reduction in axial force obtained with a bundle solution is driven by a four key factors:

- Bundle Length,
- Product Temperature
- Bundle Weight,
- Axial Stiffness,

Figure 26 ‘Advantage of Pipeline Bundles HP/HT Systems’ – Dr T Skriskandarajah, J.Brydon, W.Watt, R Wilkins, (Subsea7) [6] demonstrates the variation in effective axial force generated in bundle flowlines for varying lengths.

Two of the factors listed above; axial stiffness and bundle weight can be influenced by the bundle designer. These factors have other dependencies that may drive the design of these components (e.g. water depth, environmental conditions, seabed profile), but individually can be incorporated into the bundle design to aid design for HP/HT. Bundle system weight can also be tuned to prevent the effects of Global/Lateral buckling as demonstrated in section 2.3, Figures 11a & b.

The reduction in axial force due to expansion allows bundles to be designed within stress based design codes up to higher temperatures than pipe-in-pipe systems before switching to limit state/strain based design codes. This will reduce the material procurement costs due to the additional requirements for strain based design, and remove the more stringent demands required by strain based design on the welding and NDE requirements.

Bundles can be tuned to meet specific field development requirements specifically with regards to HP/HP applications, whether this is to allow axial expansion to reduce axial forces, or to increase system weight to prevent global lateral buckling.
3.4. Eliminate the need for Specialist Installation Vessels

The installation of towed pipeline bundles does not rely on the need for any specialist installation vessels. The typical Bundle launch, tow & installation fleet consists of the following vessels:

- Lead Tugs (2 x 280te bollard pull),
- Trail Tug (~35te bollard pull),
- RSV (ROV Support vessel)/Command Vessel,
- Guard Vessel,
- Work Boat (for near shore operations)

The advantage that this brings is that the planning of installation activities can have a degree of flexibility as they do not have to wait for a specific vessel to complete a previous project or complete dry docking.

Third party vessels are used for the tugs, a number of subcontractors have performed the bundle installation operations previously therefore there is a large pool of suitable vessels available, similarly third party RSV’s have been utilised on previous projects.

Where clients schedule requirements are not fixed the bundle solution can de-risk the activities. There would be no risk of having a high day rate vessel waiting with pipe on the reel that cannot get access to the field. Additionally as discussed in 3.2 the bundle could potentially be installed underneath floating assets that may preclude a Reel of S-lay vessel from gaining access, therefore further de-risking clients’ project where for example FPSO/Drill rig schedules are not fixed.

The incorporation of the large towhead into the pipeline bundle removes the need for a Heavy Lift Vessel to be incorporated into the installation fleet. Towhead structures greater than 500te have been installed in bundle systems. Installation of a structure of this size would require a vessel with a crane suitable of lifting over 700te offshore.

A comparison of the costs for a fleet of installation vessels for Bundles, Reel-lay & S-Lay are detailed in Table 9. The comparison is based on:

- Typical 7km bundle system
  - 3 x internal flowlines,
  - Internal controls system,
  - 500te lead towhead, 200te trail towhead,
- Reel Lay & S-Lay
  - 3 individual flowlines,
  - Control Umbilical,
  - All flowlines & umbilical’s trenched and buried,
  - 500te & 200te Structures/Manifold to be installed

Table 9 Demonstrates the financial benefits with regards to the Installation fleet costs of Bundle technology over traditional pipelay options.
4. Conclusion

- Bundle systems have several installation, fabrication and operational benefits compared to other flowline solutions,
- The Carrier pipe provides a low stress/fatigue installation environment for the internal flowlines during all installation activities,
- The low stress installation method allows the use of Mechanically Lined Bubi pipe to be utilised in place of solid CRA or Clad pipelines, therefore reducing cost,
- The bundle installation process de-risks the offshore schedule for field developers by removing reliance on specialist vessels, and allowing installation under floating assets,
- The installation fleet is significantly lower cost than traditional pipelay vessels, and do not have the same limiting schedule constraints,
- The bundle systems on-bottom weight resists global lateral buckling,
- Bundle expansion allows reduction in axial forces, therefore reducing the required internal flowlines wall thickness and reduced material costs, allows HT fields to be developed without additional infrastructure,
- The reduced stresses with the production pipes in a bundle system permit stress-based design criteria to be used whereas for a pipe-in-pipe system, a strain-based design may be typically be required,
- Stress-based design avoids the stringent welding and NDE requirements associated with a strain-based design,
- Flow assurance issues are increasingly more relevant due to the increased number of subsea developments. The overall objective is to keep the flow path open and maintain the production profile throughout the operating field life with minimal downtime,
- The main flow assurance issues concerning bundle design are the hydraulic and thermal design, slugging, hydrates, wax, sand deposition and erosion.
- Heat transfer is critical to bundle design as it determines whether hydrates or wax will form. Predictive tools are increasingly more complex and accurate.
- Active heating systems can now be incorporated into bundles. This provides various operational benefits and enables operation in deepwater environments
- Bundles systems allow the achievement of lower U-values utilising pipe-in-pipe systems at lower cost than wet insulated flowlines,
- Early engagement with Bundle design contractor allows the bundle design to be tuned to specific field development requirements,
5. **Nomenclature**

- CAPEX Capital Expenditure
- CDTM Controlled Depth Tow Method
- CFD Computational Fluid Dynamics
- CRA Corrosion Resistant Alloy
- DCC Displacement Controlled Criteria
- FEA Finite Element Analysis
- FPSO Floating, Production, Storage & Offloading Facility
- HIPPS High Pressure Protection System
- HP/HT High Pressure/High Temperature
- Km Kilometres
- LDPUF Low Density Polyurethane Foam
- OD Outside Diameter
- ROV Remote Operated Vehicle
- RSV ROV Support Vessel
- WT Wall Thickness

6. **Acknowledgements**

Ratnam Sathananthan, Peter Walker, Sam Watt, Stuart Gill, Jahangir Manzur, Sandy Willet, Alan MacLeay, Shahryar Kashani, Kevin Massie, - Subsea7 whom all contributed information to assist with the preparation of the paper.

7. **References**