1 Introduction

Presently, remediation and mitigation solutions for flow assurance problems, having evolved gradually and incrementally as the offshore industry has moved into deeper waters, have come to rely on specific pieces of equipment and/or time consuming procedures; all of which translate into heavy equipment and personnel to operate and to maintain it on the production units.

All this of course translates into significant cost issues (CAPEX and OPEX) that must be addressed when implementing deepwater developments.

Drawing from past experiences in the North Sea and in West Africa, ITP has therefore developed a patented deepwater thermally insulated pipe system that shows considerable promise in simplifying operational procedures for the operator in case of shutdown, all the while realizing considerable weight and installation savings (30% less steel for the outer pipe) over conventional systems. The following paragraphs will examplify how systems for shallow water applications can be adapted for deepwater developments with the same materials. Thanks to the steel double wall configuration, this means that the ageing issues
in the harsh deepwater environment are no different from what they could be in shallow waters.

2 Present situation for flow assurance

As an example we shall examine four different flow assurance strategies and their associated equipment. In reality, the operational strategy chosen on a specific oilfield may consist on a combination of several systems.

a) Chemicals injection

This system requires pumps to move the chemicals to the wellhead and buffer storage tanks for a given number of days of production. There are also costs associated with the transport of chemicals to the production facility and with the possible separation from the crude.

b) Heating

These systems, either direct heating, induction heating or skin effect heating are generally associated with an inefficient thermal insulation (U-values of 0.54 to 1.1 BTU.hr⁻¹.ft⁻² (3-6 W.m⁻².K⁻¹)). This translates into power requirements of 15 to 35 W/ft (50-100W/m) for hydrate-prone crudes, and twice that for crudes with waxes, which scales up to several megawatts when more than 10 miles of pipelines need to be heated. The exact values are of course project dependent, but we can work out on an example for a deepwater project including several flowlines:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Thermal data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project depth</td>
<td>U-value</td>
</tr>
<tr>
<td>5000' (1500 m)</td>
<td>0.8 BTU.hr⁻¹.ft⁻² (4.4 W.m⁻².K⁻¹)</td>
</tr>
<tr>
<td>Overall length of flow lines</td>
<td>Power to heat longest flowline above hydrate temp.</td>
</tr>
<tr>
<td>25 miles (40 km)</td>
<td>800 kW</td>
</tr>
<tr>
<td>Longest flowline</td>
<td>Power to heat all flow lines above hydrate temp.</td>
</tr>
<tr>
<td>5 miles (8 km)</td>
<td>4 MW</td>
</tr>
<tr>
<td>Flowlines OD</td>
<td></td>
</tr>
<tr>
<td>12'' (324 mm)</td>
<td></td>
</tr>
</tbody>
</table>

*Table 1: Typical characteristics for a Gulf of Guinea project*

This power requirement can only be met with specific power generators installed on the topsides and will also need storage tanks for fuel to be able to keep the flowline heated in case of shutdowns. Furthermore, in order to actually carry this power,
several conductors and high voltages/high currents are required, this being a problem in itself.

c) **Circulating the crude out of the flowlines.**

This option requires the installation of pumps to replace the live crude with treated oil that is not prone to hydrate or wax formation as well as the storage tanks for maintaining appropriate levels of this inert fluid. Given typical reaction and circulation times, it requires an efficient insulation of the flowlines: indicative cooldown times of 15-20 hours are necessary, and most importantly, the production facility must be able to treat the live crude when it arrives on the platform, even in case of an unplanned shutdown.

d) **Thermal Insulation**

This method is inherently passive, therefore it imposes little weight constraints on the topsides in itself, but it can keep the crude over the critical temperature for a given duration only. If that duration is exceeded, the pipeline may plug and prove extremely difficult (or impossible) to restart. If we use the above-mentioned example we get the following figures:

<table>
<thead>
<tr>
<th>Wellhead temperature</th>
<th>113°F (45°C)</th>
<th>Insulation (typical production tested U-value)</th>
<th>.072 BTU.hr⁻¹.ft⁻².°F⁻¹ (0.4 W.m⁻².K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrate formation temperature</td>
<td>72°F (22°C)</td>
<td>Arrival temperature at riser bottom</td>
<td>102°F (39°C)</td>
</tr>
<tr>
<td>Flowrate</td>
<td>25,000 bbl/d (4000m³/d)</td>
<td>Cooldown time for gas filled pipe section at riser bottom</td>
<td>36 hours</td>
</tr>
</tbody>
</table>

**Table 2: Thermal data for a 2.5 miles (4 km) 12” flowline, bundle or reeled, insulated with 15-20 mm Izoflex.**

3 **The insulated and traced pipeline (itp)**

All of the above-described flow-assurance systems have a significant impact on the design and operation of the topside production facility with specific added equipment and/or procedures in case of shutdown.

The conclusion is that, if existing systems are to be simplified, either by diminishing topside weight or by simplifying the operational constraints, it is not sufficient to improve incrementally on either of these systems, the underlying system philosophy has to be changed.
This has lead ITP to develop and patent an insulated and traced pipeline. The step forward has here come from the understanding that there is not necessarily a trade-off between insulation and heating, but that an efficient insulation actually strengthens the case for tracing the pipeline.

If we consider the above example of an efficiently insulated pipeline (Table 2), only 2.5W/ft (8 W/m) are needed to keep the pipeline above the hydrate formation temperature (by calculating the heat loss at the hydrate formation temperature).

This scales to only 320 kW for the whole flowline grid (25 miles). Such a power requirement that, in most cases, will not generate extra payloads on the production platforms. In difficult situations, it might even be produced from a support vessel during start-up phases.

### 3.1 Implementation

The ITP objective has been to implement a cost-efficient and inherently safe design for heating a pipeline extending more than ten miles. This can best be achieved in a double walled pipe with a continuous annulus or where bulkheads are few and far between, because the insulation can be performed efficiently. The traced design is therefore considered primarily for pipes that are intended to be laid by either reeling or towing.

In principle the design comprises a double wall steel pipe assembly with the following elements extending longitudinally along the pipe arranged from the centre to the outside:

1. hydrocarbons
2. inner pipe
3. insulated electrical conductors (wires)
4. Izoflex insulation
5. outer pipe with corrosion protection

This provides for a robust design with only minimal extra cost over conventional (passive) double-wall pipe.
3.2 Choice of insulation material

3.2.1 Identification

Supported with its design & fabrication experience (over 45 miles (75 km) of double wall pipe already operating in the North Sea and 15 miles (25 km) operating in the Gulf of Guinea), the consideration of all the aspects of design and fabrication leads ITP to conclude that, to secure the design and cost aspects, it is generally advantageous to minimise outer pipe diameter and therefore to use the best industrially available insulation material which combines high thermal performances and good mechanical behaviour.

The cost benefits are straightforward:

- less steel
- less steel related works (welding etc.)
- no need for centralizer
- less offshore field jointing works
- easier fabrication process (easier handling etc.)

Additional benefits in terms of mechanical design are:

- less bending stresses for the same radius of curvature;
- better collapse resistance;
- better stability.

3.2.2 Izoflex and its thermal performances

Classical insulating materials draw their efficiency from their opacity and their ability to imprison air (or other thermally efficient gas) and keep it from installing convection cells. The only way to go further in thermal efficiency is then to drastically reduce gaseous conduction. Physically this means to increase the mean free path of the gas molecules so that they do not interact and exchange energy, but spend their time rebounding on solid walls.

This is achieved by using a material with cell sizes is smaller than the mean free path of the gas molecules. This is the founding principle for the Izoflex patented microporous thermal insulation which outperforms conventional insulation by a factor between 3 to 10 as demonstrated by the
following tables based on data obtained from full scale thermal tests performed during
development phase and regular quality control testing during production.

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical thermal conductivity BTU.hr⁻¹.ft⁻¹.°F⁻¹</th>
<th>Typical thermal conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP syntactic</td>
<td>90.10⁻³ – 110.10⁻³</td>
<td>0.15 - 0.20</td>
</tr>
<tr>
<td>PU syntactic</td>
<td>60.10⁻³ - 90.10⁻³</td>
<td>0.1 - 0.15</td>
</tr>
<tr>
<td>Glass fibre</td>
<td>18.10⁻³ - 24.10⁻³</td>
<td>0.03 - 0.04</td>
</tr>
<tr>
<td>PU light foam</td>
<td>11.10⁻³ – 18.10⁻³</td>
<td>0.02 - 0.03</td>
</tr>
<tr>
<td>IZOFLEX</td>
<td>4.10⁻³ - 6.10⁻³</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

*Table 3 Thermal properties of conventionally used insulating materials.*

Regular thermal tests performed for quality control purposes during the Tchibéli Project,
(100 assemblies tested out of 2100) have demonstrated a U-value of 0.072 BTU.hr⁻¹.ft⁻².°F⁻¹
(0.4 W.m⁻².K⁻¹) with only 0.6” (15 mm) Izoflex around a 10” pipeline.

The Izoflex material also shows excellent mechanical behaviour against compressive
loads (there are no cells that may collapse and make the material creep).
In particular this means that the material has:
- resistance to vibrations;
- resistance to compression (to withstand laying loads and even hydrostatic pressure);
- resistance to high temperatures for HP/HT field developments.

This enables to use every laying method (S-lay, J-lay, reeling, bundle) and to withstand
hydrostatic pressure as we shall show later on.

3.2.3 High temperature resistance

The core material can withstand up to 900°C. Therefore the product is suitable for HP/HT
developments and is not damaged during tube welding operations (ie Shell ETAP double
wall pipeline in operation since 1998).

3.2.4 Ageing and safety

Ageing properties are excellent as the material is mineral based and does not contain
organics but mainly stable oxides.
The base material of Izoflex has been used for 25 years in other industrial markets
(including Oil & Gas) and therefore has an extensive positive track record.
4 Electrical system design

4.1 Principle

Heating is purely through Joule heating from electrical heating wires (copper conductors) laid out between the insulation and the inner pipe. The very efficient Izoflex insulation and the evenly distributed heating ensure that a uniform temperature is maintained over the length of the pipe with no cold or hot spots.

The patented system is designed for maintaining a temperature differential with the environment. Typical values would be 20°C if the crude is hydrate-prone, and 40°C if waxes are the problem.

4.2 Operational procedure

The power supplied can be switched on either before the flowline has cooled down (to prevent solids formation) or when the pipe has completely cooled down to melt out the solids. The first mode of operation is recommended because the characteristic time to melt out a pipe that has cooled down to the sea temperature is several days. The equilibrium temperature is the same in both cases.

4.3 Typical electrical lay outs

Electrical power is supplied to the electrical wires at one end of the pipeline via a subsea electrical cable connected to a watertight feedthrough.

The power is distributed either in a closed-loop scheme bringing the current back to the surface facility, or in an open-loop scheme with the electrical wires grounded in the seawater at the other end of the pipeline, through another watertight connector.

Corrosion considerations are to be taken into account if the open-loop scheme is considered an option.

4.4 Worked-out example

The idea is to tailor the section of electrical conductor to the requirement.

For a given pipe of length $L$, diameter $D$, insulated to U-value $U$, the required power to obtain a temperature differential $\Delta T$ in the effluent is:

$$P = U \pi D L \Delta T$$
If we impose a maximum voltage $V$ the section $s$ of conductor of resistivity $\rho$ is the defined as follows:

$$s = \frac{2 \rho U \pi D L^2 T}{V^2}$$

For the 12” flowline previously described, with :

- a U-value of .072 BTU.hr⁻¹.ft⁻².°F⁻¹ (0.4 W.m⁻².K⁻¹)
- a temperature differential with seawater of 36°F (20°C)
  - Power required for a 2.2 mile line (3.5 km): 28.5 kW
  - Power required for a 12.5 mile (20 km) line: 163 kW

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Open loop scheme</th>
<th>Closed loop scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of 1.5 mm² copper conductors</td>
<td>Current density A/mm²</td>
</tr>
<tr>
<td>440 V</td>
<td>370 A</td>
<td>225</td>
<td>1.1 A/mm²</td>
</tr>
<tr>
<td>1000 V</td>
<td>163 A</td>
<td>44</td>
<td>2.5 A/mm²</td>
</tr>
</tbody>
</table>

*Table 4: 12.5 mile (20 km) insulated and traced pipeline: characteristics of the electrical heating system as a function of voltage*

4.5 Other design considerations

**AC/DC**

The choice is mostly a question of availability: given that conductors are laid out in parallel to the pipeline, inductive effects are very small (less than 1%). An advantage of DC current is that peak voltages for a given power are smaller by 30%.

**Voltage**
High voltages should be eliminated as they are conducive to different phenomena that affect long-term ageing characteristics of electrical systems - dielectric breakdown of insulators, accelerated ageing of polymer sheaths, risks of electrical arcing at feedthroughs and connectors. Medium voltages up to about 1 kV are generally easy to handle.

**Electrical conductors**

Should be kept as small as mechanical strength permits in order to limit overall diameter of the system and to limit maximum wire temperature.

**Feedthroughs and connectors**

Systems, including ROV operable, exist on the market and have been used in harsh downhole conditions. A number of solutions have been implemented for years in harsh downhole drilling environments, and their integration in our scheme is therefore not considered a problem. A typical solution would consist in welding a feedthrough onto the outer tube and connecting the power cable either at sea-bottom with a ROV or before laying at atmospheric pressure.

**Redundancy**

Depending on the number of feedthrough pins, each power loop can be handled as an individual electrical circuit. This allows isolation of heating conductors failing for fortuitous reasons without compromising the integrity of the heating system as a whole. For example, a typical feed through allows to feed 25 kW through 12 pins. This allows to create 6 independent circuits.

**Production control and automation**

The flowline can be considered as the first element of the processing facilities. It will be advantageous to instrument the pipeline to be able to assess its temperature continuously. Laying out a fibre optic temperature sensor in between the heating wires can do this. Given the highly efficient thermal insulation, the pipe will be very homogeneous in temperature, therefore two to four measuring points per mile (1-2/km) will be enough to give an accurate picture of the temperature distribution.

**Risk assessment.**

There are basically three situations that should be considered in the design of the pipeline:

*a) Breaching of the outer pipe*
The typical response would be to install bulkheads/waterstops in the pipeline annulus. This is feasible, but must be balanced against the extra cost incurred and the advantage it brings. With the above flow figures, an uninsulated length of 750' (250m) is enough to bring the crude into the hydrate formation domain. It may therefore prove less expensive in some cases to replace the whole line.

b) Failure of the feedthrough  
Sufficient care should be given to design and ageing tests of this element. It is well-known that dry mateable connections (make-up of the connection onshore or on the barge prior to laying) are more secure.

c) Failure of the power cable  
If the power cable is ruptured it must be changed, which means that the connector shall be wet mateable. This must therefore be balanced against 2).

5 Systems trials
ITP has fabricated and tested a 40’ joint 12”/16” double wall pipe traced according to the above principle.
The electrical system was designed to provide 6W/ft (20 W/m), in accordance with a requirement to heat a wax-prone crude above 105°F (40°C).
Electrically insulated wires were laid out around the inner pipe, before installation of the insulation and insertion in the outer pipe.
With the heat tracing turned off, the U-value was measured to 0.09 BTU.hr⁻¹.ft⁻².°F⁻¹ (0.5 W.m⁻².K⁻¹).
This measurement was performed with the qualified fabrication testing for the insulated pipe of the Dunbar project (operator TotalFinaElf) and the Shell ETAP and Elf Tchibéli projects. The validity of the method has been confirmed by a Texaco-led JIP in Humble, TX (with partners BP-Amoco, ExxonMobil and TotalFinaElf).
When the heat tracing was turned on, the temperature evolution of the test joint showed that 5.6 W/ft (18.5 W/m) were input to the system, in good accordance with electrical measurements showing an average of 5.9 W/ft (19.5 W/m). The voltage drop was 28 mV/ft (93 mV/m), in line with heating a 3 mile (4800m) line of this design with a 440 V power supply.
The principle of the method is therefore considered as validated.
6 Further possible applications

In addition to improving performance or operability of existing development schemes, the patented ITP heat tracing concept opens up new possibilities, especially for long tie-backs. With the technology as it is today, we can easily consider tracing 20 mile long flowlines (30 km). For a 12”/16” system this requires 250 kW. Under a 1500 Volt option, the length can be increased to 30 miles, thus enabling tie-backs even to onshore facilities in some cases.

7 Deepwater development: the ITP DWP system.

7.1 Principle

Most of the above can be applied equally well to deep or shallow water systems. When designing double-wall systems for deepwater developments, two requirements are working in opposite directions: the system shall resist the hydrostatic pressure, but the submerged weight of the system shall be compatible with existing laying methods. ITP has addressed both of these requirements with the development of its patented Deep Water Pipe (DWP) system.

This system is based on the basic engineering principle that, for a given wall thickness, a double curvature will have a better pressure behaviour than a single curvature (a sphere has twice the bursting pressure of a cylinder of same diameter and wall thickness). The patented ITP DWP system is therefore grooved at regular intervals along the outer pipe to introduce this double curvature, which gives the outer pipe an overall bellows-shape. In practical terms, the DWP system shows a pressure resistance increase of up to a factor of about 6, compared with standard engineering codes. The following tests have been conducted on 12’-15’ long samples.

<table>
<thead>
<tr>
<th>Nominal pipe diameters</th>
<th>Outer pipe thickness</th>
<th>DNV ’96 buckling pressure</th>
<th>Plastic buckling pressure</th>
<th>Measured buckling pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>10”/12”</td>
<td>6.35 mm</td>
<td>28 bar</td>
<td>140 bar</td>
<td>150 bar</td>
</tr>
<tr>
<td>12”/16”</td>
<td>8 mm</td>
<td>27 bar</td>
<td>141 bar</td>
<td>150 bar</td>
</tr>
<tr>
<td>12”/16”</td>
<td>10 mm</td>
<td>51 bar</td>
<td>176 bar</td>
<td>190 bar</td>
</tr>
<tr>
<td>12”/16”</td>
<td>12.5 mm</td>
<td>94 bar</td>
<td>223 bar</td>
<td>&gt;200 bar</td>
</tr>
</tbody>
</table>

Table 5: Compared buckling values for the DWP ITP pipe system.
Further testing and FEA calculations have shown that the compression of the outer pipe onto the Izoflex is essential to these performances as it makes a sandwich structure.

7.2 Reeling capacity

In order to show that the system is layable by reeling ITP conducted a bending/straightening test on a 12”/16” DWP system. This test was performed on a non-optimised configuration with a hydrostatic collapse pressure of 175 bar. The pipe was bent over a bending shoe to a radius of 9.4 m, and then straightened. Ovalization of the outer pipe was less than 2.4 mm after straightening.

Pipe specimens were also subjected to hydrostatic collapse tests after bending/straightening and showed a reduction in collapse pressure of only 10%. For thermal performance, a loss of 5-7% in insulation performance was recorded.

7.3 Conclusions on the DWP system

7.3.1 Mechanical behaviour

a) The combination of grooves and Izoflex increases significantly the buckling pressure as measured against the results of conventional calculations, as per DNV ’96, for example.

b) The grooves play the role of buckle arrestors, which means that accidental buckles will not propagate over great lengths.

7.3.2 Thermal performance

The thermal performance of the above pipes has also been tested. Given that the 20 mm Izoflex layer is somewhat compressed by the grooving process U-values are about 20% higher than what they would be for a straight outer pipe, but they still remain acceptable at 0.08 BTU.hr⁻¹.ft⁻².°F⁻¹ (0.42 W.m⁻².K⁻¹).

Heat tracing as described above is therefore perfectly compatible with the DWP system and has also been tested.

7.3.3 Fabrication and laying considerations

Compared with conventional engineering codes, the weight gain for the DWP system is 40-50 lbs/ft (60-80 kg/m) translating into savings of about 100 tonne of top tension if S, J or reel-lay is chosen for a 5000’ (1500m) waterdepth development. The same savings on
submerged weight is of course also applicable for laying by a towing method, thus leading to very significant cost savings by reducing buoyancy requirements. The savings encountered are of course not only limited to the laying but also to the fabrication, both in procurement (less steel) and in welding, handling, etc.

8 General conclusion

Through an innovative use of the compressive strength of its proprietary Izoflex insulation material, ITP has developed an innovative double wall system that shows considerable promise for deepwater projects, and that could, if installed with a unique low-power heat tracing, considerably simplify operations for the operator. The system can readily be included in any deepwater development plan as it relies on well-known industrial materials (steel, Izoflex and electrical wires) for which ageing issues are well documented.

Note 1 : ITP proprietary rights encompass : microporous material application; swaging process; tulips; offshore threaded and sliding connection; Ultimate systems.

Note 2 (References) :
(2) C. Bouchaud-Ayral, “Pipe Insulation Authorising Low Temperature Transportation, Then Inhibiting Hydrate Formation, Wax Deposit And Corrosion” CORPIPE ’96, Aberdeen
(3) L. Villatte, “Combining Thermal and Mechanical Principles for Highly Insulated Pipeline Design” Risk Based & Limit State Design & Operation of Pipelines ’99, Oslo
(4) C. Geertsen, “Proposing “Standard” Products for Thermally Insulated Pipelines”, OPT 2000, Oslo