The safest and most efficient means of transporting crude oil or natural gas from wells is through subsea or buried pipelines. However, once exposed to subsea or soil environments, unprotected steel is rapidly corroded. To minimize this risk, pipelines are routinely protected by anti-corrosion coatings in conjunction with cathodic protection.

The coating provides the primary defense barrier, isolating the steel pipeline from its corrosive environment, while cathodic protection provides a backup if the coating is breached. While many pipeline coating systems have long, proven track records and have served the industry well, challenges still face the industry due to cold climates and rugged terrains, high operating temperatures, and deep water wells.

In addition to corrosion protection, many pipelines require thermal insulation to prevent the crude oil or natural gas from producing waxes or hydrates. If the pipeline temperature drops too low, heavy components in crude oil can solidify into waxy material that can clog the line, and natural gas can form hydrates that can also cause pipeline blockage.

Therefore, there is a continuous need for new product development as oil and gas exploration extends to depths in the range of 2,000 m (6,600 ft) and operating temperatures approaching 160°C (320°F). Deep water wells put stringent requirements on insulation products to withstand high compressive loads and to tolerate water exposure in a particularly aggressive environment.
This article presents information about both anti-corrosion coating systems and thermal insulation for oil and gas pipelines. Various types of pipeline coating systems are presented along with some of their key characteristics. For insulation systems, particular emphasis is given to selection criteria, and three types of insulation systems available today are described.

### Anti-Corrosion Coating Systems

Over the past 50 years, pipelines have been coated with a variety of coatings, and their performance has varied. Many older pipelines have operated for more than that long with their original coating products. The main factors resulting in the shifts observed in the types of coating products used today are construction requirements, environmental issues, and pipeline failures.

**Table 1: Comparison of Coating Systems**

<table>
<thead>
<tr>
<th>Coating</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt / Coal tar</td>
<td>• Easy to apply</td>
<td>• Subject to oxidation and cracking</td>
</tr>
<tr>
<td></td>
<td>• Minimal surface preparation required</td>
<td>• Soil stress has been an issue</td>
</tr>
<tr>
<td></td>
<td>• Long track record in certain environments without failure</td>
<td>• Limitations at low application temperatures</td>
</tr>
<tr>
<td></td>
<td>• Permeable to cathodic protection in event of failure</td>
<td>• Environmental and exposure concerns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Associated with corrosion and stress crack corrosion failures</td>
</tr>
<tr>
<td>Tape wrap (two layer)</td>
<td>• Simple application</td>
<td>• Poor shear stress resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Many documented failures related to corrosion and stress crack corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Shielding of cathodic protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Adhesives subject to biodegradation</td>
</tr>
<tr>
<td>Two-layer extruded polyethylene</td>
<td>• Excellent track record</td>
<td>• Limited temperature range</td>
</tr>
<tr>
<td></td>
<td>• Good handling</td>
<td>• Poor shear stress resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Limited pipe sizes (&lt;24 in. [610 mm] outside diameter)</td>
</tr>
<tr>
<td>Fusion-bonded epoxy</td>
<td>• Excellent adhesion and corrosion resistance</td>
<td>• Low impact resistance</td>
</tr>
<tr>
<td></td>
<td>• Does not shield cathodic protection</td>
<td>• High moisture absorption and permeation</td>
</tr>
<tr>
<td>Three-layer polyolefin</td>
<td>• Excellent combination of properties</td>
<td>• Best suited for electrical resistance welded pipes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High thickness to eliminate weld tenting</td>
</tr>
<tr>
<td>Composite coating</td>
<td>• Excellent combination of properties</td>
<td>• Suitable only for large diameter pipes and is not designed for</td>
</tr>
<tr>
<td></td>
<td>• Conforms well to external raised weld profiles</td>
<td>small diameter pipes (&lt;16 in. [406 mm] outside diameter)</td>
</tr>
</tbody>
</table>

While materials can be identified that will withstand both depth and temperature requirements, a not insignificant problem is to convert the materials technology into a coating application process that produces a cost-effective, installable system.
Fig. 1 summarizes the generic development of pipeline coatings, and following is a synopsis of the major types of systems used for pipeline protection, including asphalt and coal tar, tape wraps, extruded polyethylene, fusion-bonded epoxy, three-layer polyolefin, and a new, multi-component composite coating. A comparison of each type is presented in Table 1.

**Asphalt and Coal Tar**
In the early 1950s, the coatings of choice for pipelines were based on asphalt and coal tar products. These coatings were susceptible to moisture absorption, cracking, and soil stress damage. Nevertheless, pipelines coated with them did not usually experience much corrosion damage because cathodic protection was able to reach the underlying steel.

These coatings were generally hot-applied in the field, and pipe surface preparation was often poor. The asphalt or coal tar was reinforced with inorganic fillers and felt or fiberglass wraps. In cold climates, use of asphalt and coal tar was difficult because of their brittle nature.

In Europe in recent years, environmental and exposure concerns about the toxicity of asphalt and coal tar have prompted pipeline owner-operators to investigate alternative field-applied coatings, but they are still used in parts of the world today.

Coal tar and asphalt products also developed as plant-applied systems. As expected, performance of plant-applied coatings generally proved to be much better than that of field-applied systems.

**Tape Wrap**
In the early 1960s, tape wraps became popular for field application. These products were based on either polyvinyl chloride (PVC) or polyethylene (PE). They were often applied to pipe with minimal surface preparation. Ease of application was a feature that attracted pipeline operators to use such products extensively in this period. However, such tape systems have been shown to be susceptible to soil stress problems (Fig. 2).

In a two-layer PE tape system, the first layer is a primer, generally a thin-film asphalt- or bitumen-based adhesive. Systems based on PVC are susceptible to embrittlement due to loss of plasticizer over time. This can lead to cracking while in service and shielding of cathodic protection (Fig. 3).

As a result, pipeline companies embarked on development of higher integrity, mill-applied coatings. Two systems that became most popular in North America were extruded PE and fusion-bonded epoxy (FBE) coatings.

**Extruded Polyethylene**
Extruded PE coatings were introduced in the 1960s. Today they are one of the coatings of choice for pipelines less than 24 in. (610 mm) in outside diameter (OD). While they can be used on larger diameter pipelines, weld pre-heating during construction often dictates the upper diameter at which they are applied. Mechanical damage is also an issue when coating larger diameter pipes with these products because there is more stress on the pipes during handling.

However, because the asphalt- or bitumen-based adhesive mastic layer (the first layer in a two-layer extruded PE system) remains in a plastic condition, it can flow and fill any pinholes produced as a result of mechanical damage.

**Fusion-Bonded Epoxy**
Although FBE products were available in the early 1960s, they did not become widely used until the late 1970s. This type of coating is mill-applied, and for some companies, it is now the coating of choice for large diameter pipelines. This choice varies geographically, with North America favoring FBE coatings and most of Europe favoring three-layer polyolefin coatings, which are described below.

FBE coatings are thin and brittle and require good surface preparation. They exhibit excellent soil stress properties.

Experimental studies have also indicated that surface preparation imparts compressive residual stresses to the surface of the steel, thereby reducing the susceptibility of the steel to stress corrosion cracking.

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Fig. 2: The impact of soil stress on thin-film polyolefin tape
Three-Layer Polyolefin
Although three-layer polyolefins have not found wide acceptance in North America, they are used extensively in Europe, where they have a very strong operational history. They offer both excellent adhesion and good compatibility with cathodic protection.

Three-layer systems are based on either polyethylene or polypropylene (PP). Both systems have similar construction. A layer of FBE is applied to the steel followed by a copolymer adhesive and then a topcoat of either PE or PP.

Polypropylene systems, which are specified more often than polyethylene because of their resistance to higher temperatures, are used in subsea applications up to 100 C (212 F). With the addition of appropriate stabilizers, a PP adhesive can operate at temperatures up to 150 C (302 F), and solid PP can withstand temperatures of 130 C (266 F).

In the design of a three-layer anti-corrosion system, one must also consider the capabilities of the fusion-bonded epoxy layer. FBE products with glass transition temperatures of 150 C (302 F) are now available, thereby extending the operating temperature capabilities of three-layer PP systems.

Multi-Component Composite
A recent advance in multi-layer coating technology is a homogeneous multi-component system consisting of FBE, a copolymer adhesive, and a tough, medium-density PE. This system is engineered to provide maximum protection in severe environments. The major difference between a conventional three-layer PE system and this system is its proprietary application technology, which produces intimate mixing between the different components of the coating.

Insulation Systems
The purpose of pipeline insulation material is to ensure that the transported crude oil or natural gas remains above the wax appearance temperature and to prevent hydrate formation. This is an issue in a flowing pipeline, but it becomes more important during non-flowing conditions when the pipeline can cool down. The insulation must be able to prevent wax and hydrate formation during interruptions in service.

Thermal Insulation Selection
Selection of thermal insulation material for a particular application is always a balance between the required thermal and mechanical performance. However, this is a dynamic area of product development, and as the range of available materials increases, the selection of an appropriate technical solution becomes less constrained.

Offshore developments can involve many different pipe-laying techniques, and so the physical and mechanical properties of a selected insulation material must withstand the installation method used. In addition, the compatibility of the insulation material with the pipeline coating system and the field joint materials must be considered.

The following parameters are important in the selection and installation of a thermal insulation system.

- The flexibility requirements for the insulation are generally dictated by the installation method. More flexibility is needed for installing pipeline by reel barge than by the so-called J or S laying methods.
- The level of strain on the exterior of the insulation is directly related to its thickness. The thinner the insulation system, the more versatile it is in its application.
- Steel weight and thickness of the coated pipeline insulation system determine how much pipeline can be stored on a barge, how much can be suspended over the back of the barge during installation, and the load on the tensioner.
- The insulation system must be able to withstand the extreme squeeze loads of the tensioner that are required for deep water laying of pipeline.
- The system’s coefficient of friction affects how the ten-

Selected Definitions
- k-value: Thermal conductivity
- U-value: Thermal transmittance (The higher the U-value of an insulation material, the more heat transfer it allows and hence the less insulating protection it provides.)
- Waxy lines: Pipelines carrying crude oil that has the potential to form wax products at low temperatures
- Compression: Ability of a material to yield to pressure
- Creep: Tendency of a material to deform permanently under stress
Likewise, the system’s potential for water absorption must be known in order to gauge its impact on thermal performance over time.

The density of the insulation directly affects the negative buoyancy of the pipeline, which is its ability to stay submerged on the seabed.

Finally, the insulation must be able to resist abrasion from lateral movement of the pipeline across the seabed or exposure to sharp rocks, etc.

### Table 3: Deep Water Technical Requirements

<table>
<thead>
<tr>
<th>Location</th>
<th>Water Depth m (ft)</th>
<th>Temperature Range °C (°F)</th>
<th>U-Value (W/m²/K)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulf of Mexico</td>
<td>2,000 (6,600)</td>
<td>40–100 (104–212)</td>
<td>0.5–10</td>
</tr>
<tr>
<td>Brazil</td>
<td>3,000 (9,900)</td>
<td>40–100 (104–212)</td>
<td>4–10</td>
</tr>
<tr>
<td>Atlantic margin</td>
<td>1,000 (3,300)</td>
<td>50–150 (122–302)</td>
<td>1–10</td>
</tr>
<tr>
<td>West Africa</td>
<td>3,000 (9,900)</td>
<td>50–110 (122–320)</td>
<td>0.5–10</td>
</tr>
</tbody>
</table>

*1 m² = 10.874 ft²
With polyurethane, for example, the thermal conductivity value of the solid material is about 0.2 W/m/K, the syntactic is about 0.12 W/m/K, and the foamed is about 0.03 W/m/K. The solid material has a compressive strength in excess of 10 MPa (1,450 psi), the syntactic about 3 MPa (435 psi), and the foamed material less than 1 MPa (145 psi).

The operational depth and life of the pipeline become important in determining which coating system is cost-effective, and this generally limits the choice to one or two systems at any given U-value. Table 2 details the depth limit and temperature range for the most common insulation systems.

### Insulation Systems for Deep Waters

More and more exploration and production companies indicate that a significant amount of future production will come from deep water developments. Deep water can be considered any depth in excess of 600 m (1,980 ft); ultra deep water is any depth greater than 1,500 m (4,950 ft). However, considering that in the 1970s, deep water wells were in the 300-metre depth range, these arbitrary definitions will change with time. Each deep water development area has specific thermal and pipe-laying requirements that determine the type of insulation materials that can be used. There is no single solution to address every deep water scenario. Table 3 highlights requirements for various deep water locations.

Water depth, product temperature range, and required U-value play a very significant role in the choice of thermal insulation. Other parameters such as the length of pipeline also impact the choice of insulation materials.

Table 2 includes a range of systems for potential use in deep waters, including solid materials (polypropylene, polyurethane, rubbers); syntactic epoxies and polyurethane with glass beads; and pipe in pipe.

Table 4 compares the advantages and disadvantages of various insulation systems for deep water applications.

### Low Insulation Systems (High U-value)

Short lines or lines with high flow rates and non-waxy products generally require a low level of thermal insula-
Foamed Polypropylene

Foamed Polypropylene has found extensive use in the last few years as a thermal insulation system suiting most conditions. It offers excellent mechanical and thermal properties. In addition, it can be used at temperatures above 120°C (248°F) and in relatively deep waters.

As with all foamed systems, there is a depth–temperature relationship. The foam can work at higher temperatures in shallow waters and at reduced temperatures in deep waters. Foam is considered stable as long as compression/creep is below approximately 5%. Above this level, the foam cell walls buckle, leading to a fast collapse of the insulation system and a significant increase in U-value. Foamed PP can be used in water depths up to 600 m (1,980 ft) and still maintain a useful high temperature capability. This is based on a 25-year design life. Durations significantly shorter than this will increase the maximum operating temperature. In other words, the insulation can be used at higher temperatures for shorter time periods.

Burial of the coated pipeline to improve its overall thermal insulation will reduce the water depth at which it can operate by about 30 m (99 ft) because of the additional weight and pressure from the sea water and backfill.

Table 5: Typical Performance of Low Insulation Systems

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Temperature C (F)</th>
<th>k-value (W/m2/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polychloroprene</td>
<td>100 (212)</td>
<td>0.27 W/m2/K</td>
</tr>
<tr>
<td>EPDM*</td>
<td>150 (302)</td>
<td>0.33 W/m2/K</td>
</tr>
<tr>
<td>Polyurethane (solid)</td>
<td>120 (248)</td>
<td>0.2 W/m2/K</td>
</tr>
<tr>
<td>Polypropylene (solid)</td>
<td>120+ (248+), 60 (140)</td>
<td>0.22 W/m2/K, 0.3 W/m2/K</td>
</tr>
<tr>
<td>Polyethylene (solid)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*EPDM = ethylene propylene diene monomer

The first two products are solids; the last three are solid versions of each.

Medium Insulation (Medium U-value)

Where operating conditions of a pipeline require a greater level of insulation (i.e., waxy lines over short lengths or where a shutdown of moderate duration is required), materials with a higher degree of thermal insulation are needed.

These materials also provide anti-corrosion protection, but they are generally used in conjunction with a conventional anti-corrosion coating such as FBE.

Systems that can be considered include foamed polypropylene, glass bead syntactic polyurethane, and glass bead syntactic polypropylene. Their typical performance values are shown in Table 6.

Table 6: Typical Performance of Medium Insulation Systems

<table>
<thead>
<tr>
<th>Material</th>
<th>k-value (W/m2/K)</th>
<th>Maximum Temperature C (F)</th>
<th>Maximum Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass bead syntactic polyurethane</td>
<td>0.13–0.15</td>
<td>100 (212)</td>
<td>600–2,000 m (1,980–6,600 ft), grade dependent</td>
</tr>
<tr>
<td>Glass bead syntactic polypropylene</td>
<td>0.16–0.17</td>
<td>110 (230)</td>
<td>1,000 m (3,300 ft), grade dependent</td>
</tr>
<tr>
<td>Foamed polypropylene</td>
<td>0.16–0.18</td>
<td>120+ (248+)</td>
<td>Depends on temperature, but up to 600 m (1,980 ft)</td>
</tr>
</tbody>
</table>

* indicates performance beyond this point might be available under certain conditions (i.e., reduced life)

Foamed Polypropylene

Foamed PP has found extensive use in the last few years as a thermal insulation system suiting most conditions. It offers excellent mechanical and thermal properties. In addition, it can be used at temperatures above 120°C (248°F) and in relatively deep waters.

As with all foamed systems, there is a depth–temperature relationship. The foam can work at higher temperatures in shallow waters and at reduced temperatures in deep waters. Foam is considered stable as long as compression/creep is below approximately 5%. Above this level, the foam cell walls buckle, leading to a fast collapse of the insulation system and a significant increase in U-value.

Foamed PP can be used in water depths up to 600 m (1,980 ft) and still maintain a useful high temperature capability. This is based on a 25-year design life. Durations significantly shorter than this will increase the maximum operating temperature. In other words, the insulation can be used at higher temperatures for shorter time periods.

Burial of the coated pipeline to improve its overall thermal insulation will reduce the water depth at which it can operate by about 30 m (99 ft) because of the additional weight and pressure from the sea water and backfill.

Glass Bead Syntactic Polyurethane or Polypropylene

To overcome the problems of compression and creep associated with conventional materials and to increase a system’s operating limits, glass beads can be incorporated into a PU or PP matrix.

Glass beads are effectively incompressible and can be made with a hydrostatic crush pressure in excess of the equivalent of water depth of 2,000 m (6,600 ft). They form a material that has thermal properties similar to or better than foam but that behaves like a solid. In addition, they are inorganic and have very high compressive strength. They are creep-resistant in subsea operating conditions.

While the thermal performance of these two systems is
slightly different, overall resistance to the combined effects of hydrostatic load and temperature are similar.

Syntactic Epoxies
For certain deep water applications, a range of materials has been developed based on a combination of glass microspheres and epoxy fiberglass macrospheres within an epoxy matrix. The track record of these materials is extensive in terms of environmental performance over time, and they have exhibited good stability with subsea exposure. Typical thermal conductivity values for such products are approximately 0.11 W/m/K, which puts them in the medium to low U-value range.

High Insulation (Low U-value)
Where pipelines are long or the product is very waxy with a low flow rate, a high level of insulation is needed. The systems described above, while capable of meeting the insulation requirements, would result in an excessively thick coating, which could lead to instability of the installed flowline.

Therefore, materials with a low k-value (~0.03 W/m/K) are needed to reduce coating thickness and to give a low U-value. These materials include polyurethane (PU)/polyisocyanurate rigid (PIR) foams with low density and limited compressive strength that makes them unsuitable for use in a conventional stand-alone coating system.

For these materials to function correctly, they must be totally protected from the effects of hydrostatic pressure. For deep water applications, a steel carrier pipe can give this protection. Conventional protective barrier materials (i.e., PP, PE, or PU) do not give sufficient strength.

Pipe in Pipe
Such a system involves the flowline pipe inside a steel carrier pipe with insulation material filling the gap between them. The choice of filler material depends on the operating conditions and the level of insulation needed. Table 7 gives the range of possible materials and their k-value.

In cases where the filler material has very low compressive strength, the flowline must be supported centrally in the carrier pipe by means of spacers or welded bulkheads to prevent creep of the flowline through the insulation material.

Bulkheads are placed at pre-determined distances to ensure that the flowline pipe is kept locked to the carrier pipe and to prevent total flooding should the outer carrier pipe fail due to corrosion, impact, or poor welding. Increased heat loss at the bulkheads and spacers needs to be taken into account in the overall design.

Conclusions
This article has attempted to provide information about existing coating and insulation solutions available to pipeline engineers. In selecting an appropriate coating, consideration must be given to installation and operating requirements. The emerging opportunities for offshore wells in deep water and high temperature environments are driving continuous change and improvement in both corrosion protection coatings and thermal insulation.

References

Editor’s Note: This article first appeared in the April 2000 issue of PCE, pp. 53–60.