Richard Voight, Executive Engineer, INTECSEA, explains why direct electric flowline heating is a viable option for flow assurance.

Go with the flow

Flow assurance - a critical component for industry's increasing water depths and greater distances associated with today's subsea production tiebacks - requires robust, thorough planning and the aggressive development of reliable technologies for future production. Electric flowline heating systems provide a cost-effective approach to flow assurance for the design of current and future offshore field developments, particularly for projects that involve long-distance flowlines.

Importantly, the use of electric flowline heating can greatly extend the offset distance from wellhead to offshore facility and diminish concerns associated with production and shut-in, including dead oil circulation, hot-oiling and blow-down.

Introduction

This article discusses the basic design principals and current state-of-the-art systems for pipe-in-pipe–based, direct electric heating, as first developed by Shell and employed in the Gulf of Mexico. The article also addresses technical qualification status of necessary equipment and the electro-mechanical features and facilities required to assure economic, reliable operation of direct EFH installations.

One of the major issues in flow assurance is the prevention of hydrates and wax deposits for long-distance production. Flow resistance, caused by high viscosity oils, also impacts flow assurance. Historically, the most common solids formation prevention techniques have included thermal insulation to retain produced fluid temperature. Coupled with chemicals - hydrate inhibitors and/or paraffin inhibitors - developers can lower the temperatures at which hydrate formation and wax deposition can occur.

But this design technique has its limitations in terms of distance and economic viability. Long flowlines, typically more than 150 miles for gas lines and approximately 100 miles for oil and condensate lines, require innovative cost-effective insulation techniques.

Indeed, thermal insulation becomes impractical to hold flowline temperatures at acceptable levels without adding heat to the produced fluid. And for flowlines with high-water production rates, the cost of chemicals becomes prohibitive in the prevention of solids formation at seabed temperature.

Long-distance developments require more than insulation to prevent wax and hydrate issues from dominating operability-based design and facility decisions. Electric flowline heating uses electric current, adding heat to an

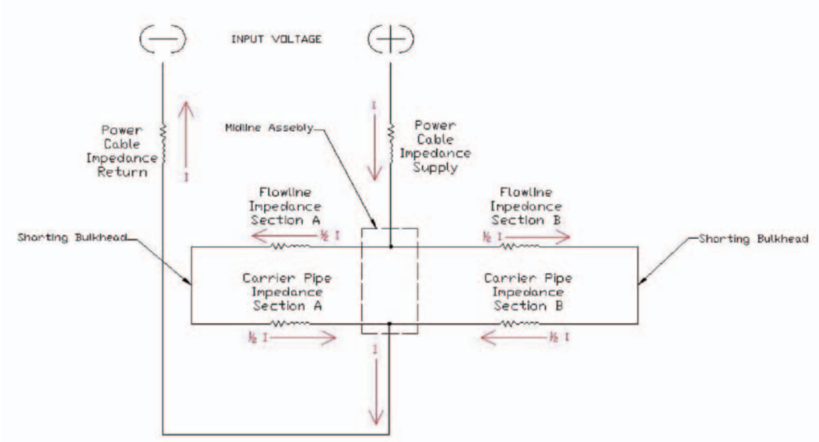

Figure 1. Pipe-in-pipe centre-fed electric flowline heater (EFH) schematic.

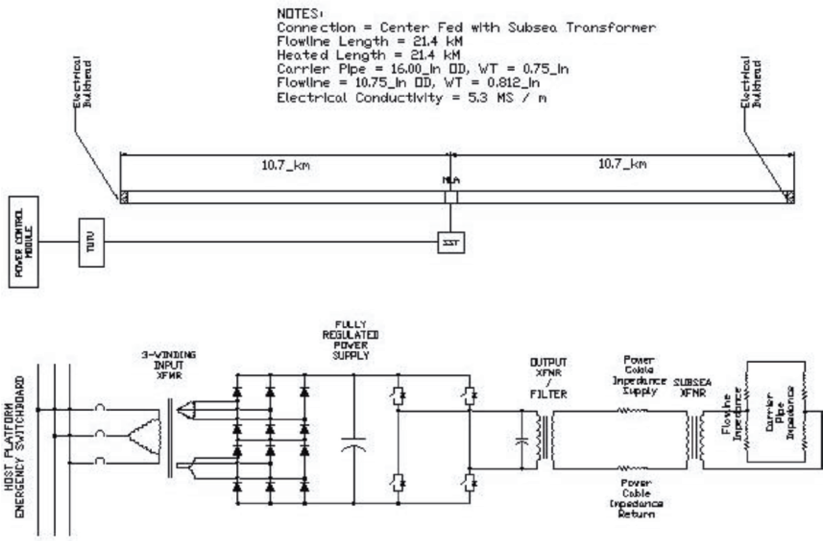

Figure 2. Centre-fed EFH one line diagram.

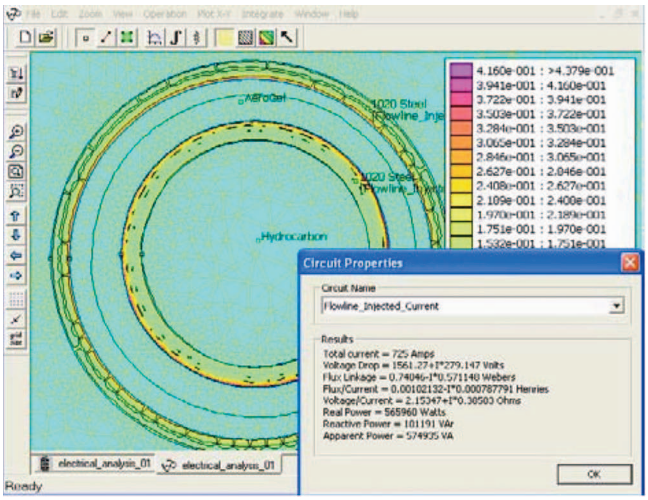

Figure 3. Current density plot showing skin and proximity effect.

insulated pipe-in-pipe flowline system and offsettting heat loss through flowline insulation. This process retains fluid temperature at system flow assurance and operability design requirements.

PIP-based EFH systems combine the flowline, flowline insulation system, carrier pipe and electrical flowline heating system into a single integrated hydrocarbon transportation system. Depending on the application, EFH can be used to add heat continuously under flowing conditions or to add heat only intermittently during shutdown conditions.

Shell developed and patented the PIP-based EFH system in 1999, with first implementation in 2002. The two types of PIP EFH systems include 'end-fed' and 'centre-fed'. End-fed designs call for electrical power connections to the PIP flowline and carrier pipes at the topside end of the flowline system. Centre-fed designs make electrical connections to the PIP flowline and carrier pipes subsea at the midpoint of the powered flowline or flowline segment.

Shell installed a centre-fed EFH system on the BP-operated NaKika Field and its own Habanero Field. Both installations are intervention-ready systems intended for continuous but infrequent use. Electrical power is not permanently connected to the mid-line assembly at the subsea flowline. Instead, power is delivered to the midline assembly through a power cable and transformer. This process requires a vessel of opportunity equipped to handle electrical reels.

Operational experience with the centre-fed system is limited; however, the intervention-ready systems deployed are not yet in use, primarily because of the cost impact associated with an available vessel and the capital expenditures of installation.

Because end-fed EFH designs make electrical connections at the topsides end of the system, these systems are most suitable for applications requiring heating only during shut-in. The issue here is the practical inability to fully isolate the platform and/or topsides downstream piping system from the EFH power supply during operation. Shell has installed and operated an end-fed EFH system for the Serrano flowline system at the Auger Field tension leg platform.

Centre-fed systems are not limited in this respect and can be deployed and energised during shut-in, start-up, normal operation and shutdown. The versatility and suitability of the centre-fed system for general application make the technology a centre point of these remaining discussions, including primary design features and considerations for the centre-fed EFH configuration.

PIP design principles

For PIP-based EFH systems, the flowline (inner) and carrier (outer) pipes are used as electrical conductors. Insulation in the annulus between inner and outer pipes provides the thermal insulation required to control heat loss from the flowline system and electrically isolates the inner and outer pipes. The inner pipe is heated by the current flowing through it.

The amount of heat is generally determined by the required fluid temperature and the insulation value. Heat generated by return current flowing in the outer pipe, however, is lost to the environment. Even with this loss, the superior insulation provided by PIP designs significantly reduces the amount of power required to maintain a given fluid temperature in the flowline as compared to wet-insulated EFH systems.

The PIP segment selected for heating is electrically defined by steel shorting bulkheads at each end of the segment. Water stops and centralisers deployed in the annulus must be nonconductive and must maintain the required electrical insulation. In the centre-fed application, the power source is connected at the midpoint of the segment. When alternating current (AC) power is applied, current flows through the inner and outer pipes.

The electrical current splits at the MLA and travels along two parallel flowline circuits defined by the shorting bulkheads. The majority of the current flowing is confined to the annulus surfaces with the inner flowline pipe producing the useful heat.

The first step in designing a new EFH system is quantifying EFH load requirements - obtained with reliable results using finite element analysis software. While 2D FEA modelling - systems that include an 'X' and 'Y' axis - is generally sufficient and preferred, 3D FEA platforms yield additional resolution in the Z-direction, involving the 'X', 'Y' and 'Z' axis. This bulk data becomes less valuable, weighed against the variability of inherent manufacturing tolerances associated with steel pipe manufacturing.

Analysis begins with a 2D model for importation to the FEA software that facilitates both material selection and electrical parameters. The software also accommodates empirical data, including the ability to quantify magnetic response of nonlinear permeability pipeline steels - a crucial component to accurately model a flowline heating system.

The software specifically considers nonlinear B-H curve data points or magnetic permeability, representing the relationship or ratio between magnetic flux density 'B' versus the magnetic field strength or intensity 'H'. This pronounced ferromagnetic behaviour in pipeline steels enhances proximity and skin effects to levels normally reserved for high frequency application and produces useful heating without the need for generating excessive AC current levels.

In conventional design, a linear or single value of permeability is assumed, which can result in significant errors in prediction. In light of this difficulty, INTECSEA obtained critical pipeline material data, subjecting multiple samples

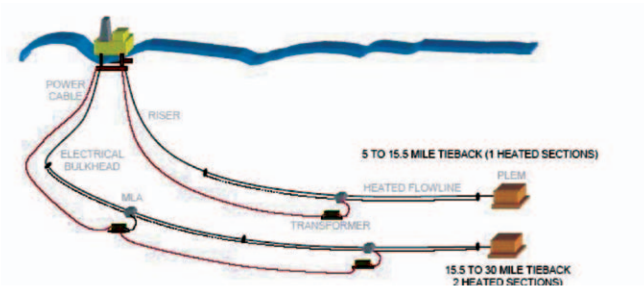

Figure 4. Offshore field layout with EFH.

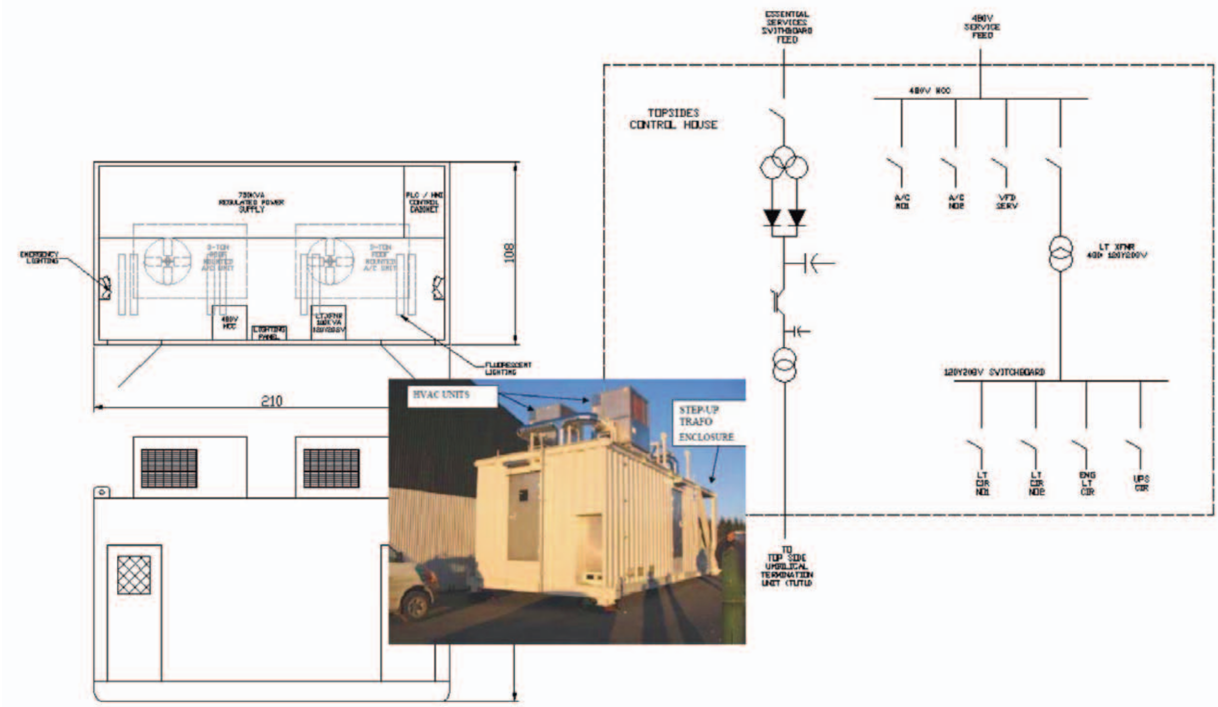

Figure 5. Typical topsides power module.

to independent laboratory testing. This exercise established baseline magnetic properties for input data to the FEA software platform.

The complete FEA analysis platform, including magnetic permeability, proximity and skin effects, is then fully captured and integrated into the I^2R solution.

The transfer of heat is fundamental to electrical current flow and the passage of electricity through a flowline system. This principle, in accordance with a variant of Ohm's law - the amount of energy passed to an object by passing an electrical current through it is proportional to the square of the current flowing through it multiplied by the resistance of the object - creates the required electricity and heat, per the equation:

$P = I^2 * Rac$, derived from Ohms Law

Where:
P = Real power in Watts.
I = Current in Amps.
Rac = AC resistance in Ohms.

Current tends to flow on the outer surface of the inner pipe and inner surface of the outer pipe. This tendency becomes pronounced in carbon steel pipes because of the high relative permeability of the material. The AC resistance of a conductor differs from the direct current (DC) resistance of a conductor as a consequence of skin and proximity effects.

Skin effect is the tendency of electrons to flow at the surface of a conductor subject to an AC signal. Proximity effect is the tendency of electrons to move in close proximity to those in a return circuit path in the presence of an AC signal. Both effects tend to increase current density, thereby raising the apparent conductor resistance.

The next step is to run the mesh-generator and perform the analysis. Results are obtained fairly quickly, depending on node density, and include a number of valuable outputs facilitating remaining system design work. Figure 3 details the 2D FEA output from one such analysis.

Aspects/components of standard center fed PIP EFH system include:

- 1 x topsides power module (PM).
- 1 x topsides umbilical termination assembly (TUTA).
- 1 x power umbilical (PU).
- 1 x subsea umbilical termination assembly (SUTA).
- 2 x subsea transformer primary side power flying leads (PS-PFLs).
- 1 x subsea transformer (ST).
- 2 x subsea transformer secondary side power flying leads (SS-PFLs).
- 1 x midline termination assembly (MLA).
- 1 x PIP flowline assembly with shorting bulkheads at each end.

Topsides power module

The topsides power module typically comprises a climate-controlled control building housing low and medium voltage distribution switchgear, a fully regulated EFH power supply, an EFH control system with HMI interface, normal and emergency lighting, as well as a fire and gas detection system. Figure 5 shows a G&A for a typical 750 KVA topsides power module and its associated oneline diagram.

The fully regulated power supply indicated in Figure 5 is an off-the-shelf, three-phase voltage source drive configured with a multi-pulse harmonic friendly input and with its output modified for single-phase operation. The system is configured for constant frequency operation at 60 Hz. Major drive vendors provide modifications with little or no cost impact. The fully regulated power supply affords a number of significant benefits, including:

- Single-phase EFH operation with balanced three-phase loading on the source. This feature facilitates normal power from the vessel with no requirement for additional isolated stand-alone engine-generator supply (unless operations during black-out are required).
- Minimal harmonic loading on source via multipulse front-end.
- Short-circuit fault limiting and trip.
- Fully programmable digital control module with door-mounted LCD for the following inputs, functions and indications:
  - Output frequency (set and monitor).
  - Output voltage (set and monitor).
  - Output current (set and monitor).
  - Output power.
  - Output KVA.
  - Output power factor.
  - Start-up ramp rates (set and monitor).
  - Shut-down ramp rates (set and monitor).
  - Trips and alarms.

Topsides umbilical termination assembly

The TUTA is a stand-alone module bolted to the platform deck adjacent to the umbilical hang-off. The module provides a convenient point for hard electrical termination and connection between the power umbilical and the topsides power module.

Power umbilical

The power umbilical serves as the transmission line for power to the EFH system. Power umbilicals are typically designed for medium voltage power one-phase transmission to reduce voltage drop and losses along the length of the umbilical. Figure 6 is a 150 mm^2 10/20 kV

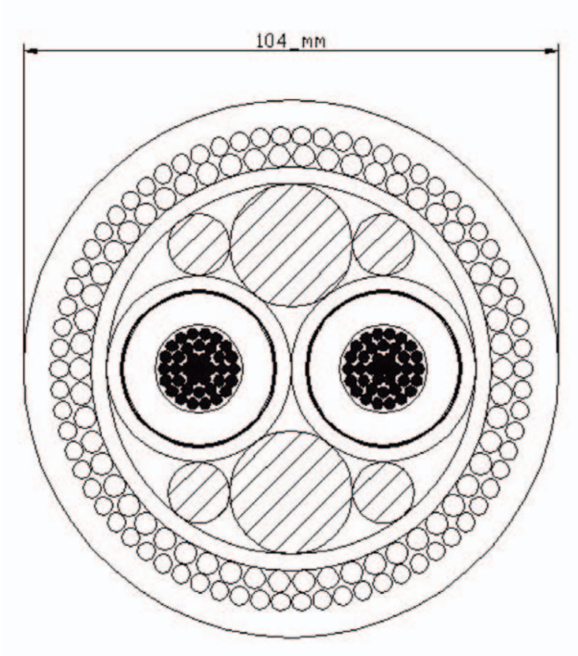

Figure 6. Typical cross-section of EFH power cable.

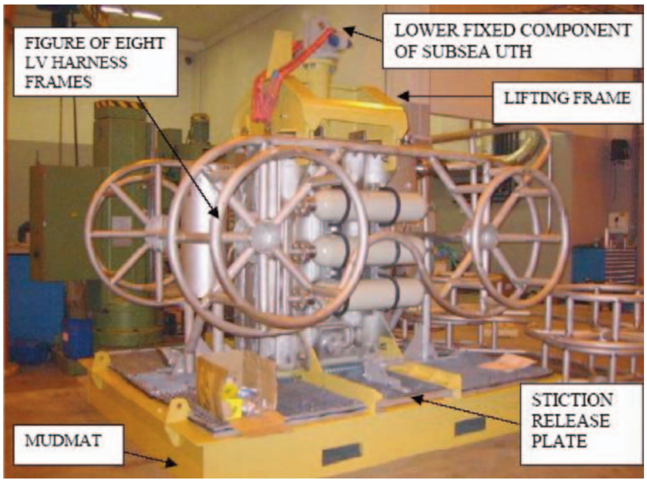

Figure 7. Subsea transformer – front view.

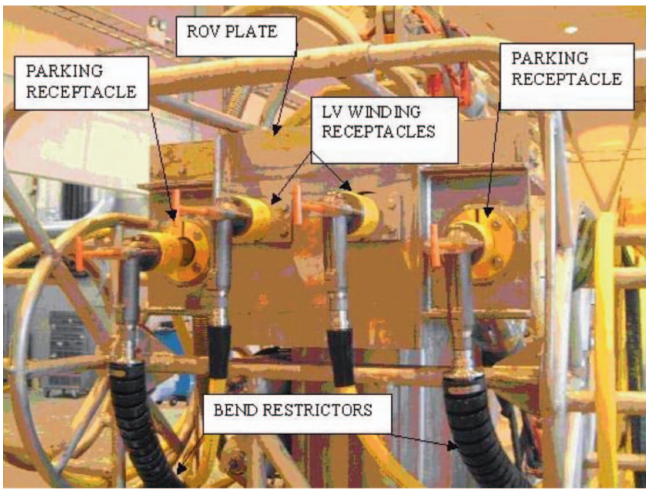

Figure 8. Subsea transformer – end view with wet mate connectors in parked position.

one-phase armored power umbilical and is representative of a typical power umbilical cross-section for a PIP EFH application.

Primary side power flying leads

The two primary side power flying leads electrically connect medium voltage service from the SUTA to the primary side of the subsea transformer.

The flying leads allow ease of connection between the two components upon their installation.

Subsea transformer module

Subsea voltage transformation is crucial to minimising transmission losses while also maintaining a reasonable cross-section of copper.

Transmission at medium voltage, for example, 10 kV, keeps the I^2R losses reasonable in the cable, and the required low voltage level is conveniently and economically acquired via a judicious choice of the primary to secondary transformer turns ratio.

The subsea transformer module consists of the pressure-compensated transformer, a subsea umbilical termination head, a mud mat, two figure-eight carrying frames for the electrical low voltage leads and a lifting frame mounted on top of the transformer which also supports a hinge mechanism.

Secondary side power flying leads

The two secondary side power flying leads are similar to the PS-PFLs, except they are rated for a lower secondary side voltage and have a substantially larger cross-sectional area.

The SS-PFLs electrically connect low voltage service from the secondary side of the subsea transformer to the MLA. The flying leads allow ease of connection between the two components upon their installation.

Midline assembly

The MLA is a fabricated assembly that connects electrical supply to the PIP flowline. The MLA, as designed and qualified by Shell, utilises two Tronic single pin 1.9 kV, 1100 A connectors. The first connector is electrically connected to the inside of the MLA outer shell. The second connector is made with a copper braid connected to the outer surface of the inner pipe, facilitating a degree of movement between the outer and inner pipes without compromising electrical connectivity.

The actual connection to the inner pipe is made via a steel plate and welded to the inner pipe, which is sprayed with a copper coating to aid the electrical conductivity of the interface. Note: The existing MLA design does not incorporate a temperature-sensing element. Future design, however, may include a spare port suitable for connection of a fibre-optic temperature-sensing device.

PIP flowline assembly

Upon completion of the PIP installation, the annulus between the pipes electrically isolates the pipes, but at the ends of the segment the concentric pipes are electrically connected. The inner pipe is thermally insulated.

Electrically insulated water stops provide flood control barriers in the event the outer pipe is breached. Collars on

Table 1. Summary of planned demonstration for EFH system			
System	**Component**	**TRL rating**	**Planned demonstration for this project**
Power control module	Fully regulated power supply	5	1. Design review of the vendor data, including load test 2. Perform FAT and SIT to demonstrate the functionality in an EFH application
PIP assembly	Dry insulation	5	1. Qualification for the dielectric properties of dry insulation 2. Bench test of PIP EFH system
PIP assembly	Dry insulation	5	Develop and qualify a rigorous installation procedure to ensure integrity of annulus isolation properties. This procedure should include testing of every quad joint and continuous monitoring during pipe lay.
PIP assembly	Line pipe	5	1. Establish B-H curve for pipe steel at 60 Hz to verify the design assumptions 2. Test the permeability at different frequencies to establish the relative permeability histogram 3. Perform a survey of the permeability of pipe steels at multiple mills to establish the statistical variance
PIP assembly	Line pipe	5	Bench scale test to verify temperature profile, OHTC value, AC corrosion potential, and design methodology
Midline assembly (MLA)	MLA	5	For continuous application, perform a bench scale ALT/HALT qualification test in the simulated project-specific operation envelope (current, voltage and external pressure)
Midline assembly (MLA)	MLA	5	Verification of design methodology and certification by CA
Subsea power distribution	Power cable umbilical	5	Design verification required and qualification typical for dynamic umbilicals required
Subsea power distribution	Subsea transformer	5	Verify continuous use of subsea transformers and compare specifications to evaluate any necessary qualification

seals around the water stops may prevent electrical shorts and packets of super-absorbent may further reduce the risk of electrical faults.

A primary concern surrounding EFH is the reality of achieving a uniform heating profile along the entire length of the flowline. Heating variation can result from pipe-to-pipe permeability variations, as manufacturing tolerances for pipe permeability are not normally controlled. Raising the applied system frequency, however, significantly damps out unwanted effects resultant from permeability variations, thus improving overall system performance.

Technical qualification status

Qualification demonstrates that the EFH system has reached a particular technology readiness level for use in future projects. Qualification also assures compliance with applicable integrity management standards and quality management requirements for the life of a field. Technology qualification is required to achieve compliance with reliability and maintainability goals and to minimise technical risk.

INTECSEA recently completed a qualification study for an industry major, evaluating the technical readiness level of a system. Addressing the above system components, INTECSEA assigned a technology readiness level of five in a range of one to seven. Activities included development of a technology qualification matrix based on industry-accepted criteria with evidence to support claims as described.

While the preliminary qualification matrix is omitted because of its size, Table 1 summarises the results of the preliminary qualification matrix. Only components with TRL ratings below six are included in the planned demonstration.

Quality control during installation

It is very important to ensure electrical isolation between the inner and outer pipe. Some of the quality control measures used in previous projects include:

- Use time domain reflectometry equipment to detect any short circuit in the PIP annulus for every quad joint and at the firing line.
- Prevent condensation from forming in the annulus by adding bags of anhydrous material at frequent intervals.
- After installation of the system, hook up the power cable to the MLA and perform system test.
- Use conductive coating (copper spray) on the inner pipe at MLA to minimise localised heating.
- Monitor internal temperatures due to radiated heat when girth welding (MLA).
- Use MLA connectors with receptacles and four mechanisms to remove possibility of jamming during installation.
- Install interfaces of steel sleeves that engage over the receptacles to avoid damage during installation.

Conclusion

Current PIP EFH systems have an overall qualification status of five, meaning EFH systems are designed and built as production units or full-scale prototypes. These systems are integrated into intended operating systems with full interface and functional testing but are not necessarily focused on specific field environments.

PIP-based EFH technology is ready for implementation worldwide and should begin to take its place alongside its chemical and wet-insulated EFH counterparts as a viable means for solids mitigation and prevention. PIP-based electric flowline heating is a concept that should be given full consideration for deepwater and long-distance subsea tieback systems.

Both current and future field development projects will benefit with PIP-based EFH systems, gaining improved flowline efficiency and facilitating expansive options for asset development. WP