Detail Design of Electrically Heat Traced Flowlines

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ABSTRACT

The primary flow assurance challenge for deepwater, long-distance tiebacks is to achieve cost-effective and efficient thermal management of the production fluids to avoid wax deposition and hydrate formation. ITP has developed an electrically heat-traced flowline characterized by its simplicity and low power requirement. The flowline system combines highly efficient insulation (U-value = 0.5 W/m^2 K) with electrical resistive heating to maintain fluid temperatures during steady state and transient operations. The system was tested through a JIP operated by ChevronTexaco with Shell, TOTAL, ExxonMobil, ConocoPhillips, and Marathon. During a TOTAL-sponsored study, a detailed design was performed with consideration to construction and reliability aspects.

INTRODUCTION

The primary flow assurance issues for deepwater, long distance, subsea tiebacks are hydrate formation during transient operations (shutdown and startup) and wax deposition during steady state production. Currently, subsea tiebacks often use dual flowlines to allow the line to be flushed with dry oil to prevent hydrate formation for an extended shutdown and for round-trip pigging for wax removal. To eliminate the second flowline, it is necessary to design a single flowline that can prevent or remediate a hydrate blockage and minimize wax deposition. Drawing upon past experience in the North Sea and in West Africa, ITP has developed an Electrically Heat Traced Flowline (EHTF) characterized by its simplicity and low power requirement.

Previously, the EHTF was tested at the Humble Flow Facility located in Houston, TX and owned by ChevronTexaco. Through a GPRI (Global Petroleum Research Institute) JIP performed at the facility, the thermal performance of the EHTF was validated.

Recently ITP and JP Kenny completed a comprehensive design study (sponsored by TOTAL) for two 10" (flowline OD) subsea tieback cases, one at 1500 m water depth and the other at 2500 m water depth. Both cases had tieback lengths of 35 km. The objectives of the study were:

- Review all heat tracing solutions and comparison against the ITP design
- Perform the pipe mechanical and thermal insulation design
- Design of the electrical system including power requirements for temperature maintenance and re-heating production fluids.
- Review of existing electrical equipment capabilities and installed systems
- Sizing of all electrical components both subsea and topsides
- Determination of the maximum flowline length (offset) without a technical step change
- Provide a detailed discussion of the electrical heating concept and the components
- Design the topsides electrical system to power EHTF
- Design detail fabrication methods of the EHTF system
- Determination transportation and installation methods
- Perform qualitative reliability assessment on the EHTF system
- Identify any risk posed by the EHTF to the flowlines or to personnel
- Determination of the maintenance operation dedicated to the EHTF
- Determination of maintenance and repair methods
- Estimate of CAPEX and OPEX cost of the EHTF including materials, fabrication, installation, and operation.

This paper discusses non-confidential highlights of that study including the design, construction, reliability, and installation of EHTF.

DESIGN OF THE EHTF

Reliability is a primary concern for all electrically heated flowline designs. The unique features of the EHTF are the simplicity of the electrical heating system and its high thermal performance. This section discusses the details of the insulation and the electrical power requirements.

Electrical resistive heating is used during shutdown to maintain the production fluids above the hydrate formation temperature (assumed to be 25°C for this study). The highly efficient insulation limits heat losses to the surroundings and consequently, reduces the electrical power requirements for maintaining the fluids above the hydrate formation temperature. If the flowline is allowed to cool to ambient temperature then, prior to restart, the electrical heating system is used to reheat the resident fluids in the flowline from ambient, seawater temperature to the hydrate formation temperature.

Wax deposition can also be prevented or remediated using the electrical heating system. If a modest power level (sufficient to offset the heat loss to the surroundings) is supplied, the heat flux from the production fluid to the pipe wall will be eliminated and wax deposition will be prevented. (Wax deposition is driven by heat flux). Alternatively, during shutdown, the EHTF can heat a wax deposit and production fluids to 48ºC which is typically 10 – 18ºC higher than the typical Wax Appearance Temperature (WAT). This temperature differential is commonly assumed to be sufficient to melt or soften a wax deposit. Upon restart, the wax could be flushed from the flowline.

Insulation

The ETHF uses the ITP patented, Izoflex^{TM} insulation (a highly efficient, microporous insulation) to achieve an overall heat transfer coefficient of 0.5 W/m² K (based on the pipe OD). The insulation ensures maximum arrival temperatures under steady state production and low power requirements during shutdown. A description of the insulation and its impact on the design and operation of the ETHF is discussed below.

Description of the Insulation

High performance insulation materials have a high level of porosity. Conventional high performance insulation materials (i.e. polyurethane foams, glass wool, etc.) strive to approach the thermal conductivity of still air.

Heat transfer is due to conduction in the solid, convection, radiation, and gaseous molecular conduction. Conduction in the solid is limited by a low density; convection is hindered by trapping the gas molecules in the pores; and radiation is limited by making the insulation opaque. It was originally thought that the only way to provide an insulating material with a thermal conductivity lower than still air would require the removal of all air, i.e. a hard vacuum, which is difficult to achieve industrially. However, it has been shown that microporous insulation, with very small pores, can achieve thermal conductivities less than still air by minimizing gaseous molecular conduction.

Microporous insulation reduces the gaseous molecular heat transfer because the pore sizes in the insulation are smaller than the mean free path of the gas molecules[1]. If the pore size is smaller than the mean free path of the gas molecule, the gas molecules are prevented from colliding with each other and transferring energy to each other thereby hindering heat transfer. These materials remained an academic curiosity until their fabrication process was perfected and industrialized.

Microporous insulations are now used in a wide range of industries including the nuclear and aerospace industries and in applications such as furnaces, electrical appliances, etc. Microporous insulation was first applied in a subsea flowline by ITP in 1998, for the high temperature/high pressure Shell ETAP flowline in the North Sea. The main advantages of the microporous insulation are:

- Low thermal conductivity (less than still air)
- Application at temperatures from -196 to 900ºC, therefore it does not need any protection during welding and can be used at cryogenic temperatures
- No aging as it does not contain organic materials
- Good mechanical behavior against compressive loads.

The microporous insulation, as applied in the EHTF design, has a thermal conductivity[2] of 0.006 W/m K which is more than a factor of three lower than the thermal conductivity of still air (0.025 W/m K). That translates directly into a factor of three lower heat losses. Due to the very low thermal conductivity of the microporous insulation, only 14 mm of insulation is required for a 10” pipe to achieve an overall U-value[3] of 0.5 W/m² K (based on the pipe OD).

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[1] The average distance traveled by a gas molecule between collisions is defined as the “mean free path”.

[2] The thermal conductivity quoted for microporous insulation is not a laboratory measured value, but rather “as installed” including all imperfections due to insulation tolerances, pipe-mill tolerances, and pipe-in-pipe manufacturing.

[3] The U-value is the heat loss per unit surface area and per degree of difference between the hot and cold sources.

Impact of the Insulation on the Performance of the EHTF

The impact of low overall U-value under steady state and shutdown conditions is demonstrated in Figures 1 and 2. Figure 1 presents the possible flowline length as a function of U-value. This calculation assumes an inlet temperature of 60ºC, an ambient temperature of 4ºC, and the desire to arrive above 32ºC at 10,000 BOPD for a 10" nominal pipe diameter. The arrival temperature of 32ºC was selected because it is a typical value for the Wax Appearance Temperature (WAT) of an oil. At a U-value of 3 W/m² K, the length of the flowline is limited to 9 km. With a U-value of 1 W/m² K, the flowline length can be increased to 27.5 km and with a U-value of 0.5 W/m² K, the flowline length can be extended to 55 km (These distances are dependent upon fluid gas-oil ratio, GOR). For steady state operating conditions, the thermal performance scales directly with the U-value.

Figure 2 presents the cooldown time from 40ºC to 25ºC for a gas-filled flowline with either a U-value of 0.5 or 1.0 W/m² K (based on pipe OD) assuming the same insulation material which has negligible thermal mass. For an insulation with negligible thermal mass (such as insulations used for all pipe-in-pipe flowlines), the cooldown time scales with the U-value. Consequently, the cooldown time at 0.5 W/m² K is 19.2 hours and at 1.0 W/m² K, the cooldown time is 9.6 hours. The calculations assume no electrical heating during shutdown.

Figures 1 and 2 demonstrate that a key component to the design of any electrically heated flowline is use of highly efficient, microporous insulation. The insulation minimizes heat losses during steady state and transient operations increasing the potential distance of the tieback and the cooldown time. The insulation is also key to minimizing the power requirement when the electrical heating is switched on.

Electrical Heating System

A schematic of the system is shown in Figure 3 below. The electrical heat is supplied via resistive heating from off-the-shelf, insulated, copper wires laid longitudinally along the inner pipe as shown in Figure 4. The number and diameter of the individual wires is determined by the power requirement. To achieve cost efficiency only commercially available wires have been considered. The design was voluntarily limited to 1000 V because this allows the use of low-priced, highly reliable and well known off-the-shelf components. Higher voltages are easily achievable but entail specific issues such as voltage breakdown, dielectric ageing etc.

Power Requirements for Hydrate Prevention

Equation 1 provides the power requirement per unit length to maintain the temperature above the hydrate formation temperature under shutdown conditions. Equation 2 provides the fluid temperature as a function of time during shutdown assuming that the fluid and the inner pipe are the same temperature and neglecting the thermal mass of the insulation.

Assuming the information in Table 1, Equation 1 is used to calculate the power requirement to maintain the fluid at 25ºC during shutdown. Under these conditions, the power input need only be sufficient to offset the heat loss to the surroundings (9 W/m) with a fluid temperature of 25ºC and an ambient temperature of 4ºC.

Using Equation 2, the temperature of the production fluid can be calculated as a function of time. Figure 5 presents the cooldown of a gas-filled pipe (gas is the most conservative) with an initial temperature of 40ºC assuming no power input and a power input of 9 W/m. Figure 5 demonstrates that 9 W/m is sufficient to maintain the fluids at 25ºC indefinitely.

$$P = U * \pi * D_i (T_{hyd} - T_{amb}) \tag{1}$$

$$T_f(t) = (T_{init} - T_{amb} - \frac{P}{U * \pi * D_i}) * (e^{\frac{-U*\pi*D_i*t}{M_f Cp_f + M_{cs} Cp_{cs}}} - 1) + T_{init} \tag{2}$$

where T_f = fluid temperature at time t (ºC)
T_{init} = initial fluid temperature at time of shutdown (ºC)
T_{amb} = ambient temperature (ºC)
T_{hyd} = hydrate formation temperature (ºC) = 25ºC for this study
P = Power (W/m)
U = overall U-value (W/m^2 C)
D_i = inner pipe ID (m)
M_f = mass of fluid (kg)
Cp_f = heat capacity of the fluid (J/kg ºC)
M_{cs} = mass of steel in pipe (kg)
Cp_{cs} = heat capacity of steel (J/kg ºC)
t = time (s)

While maintaining the production fluids at 25ºC during shutdown requires only 9 W/m, it is also desired that the electrical heating system be capable of warming the resident production fluids from ambient temperature to the hydrate formation temperature in a reasonable time frame. Assuming that no hydrates must be dissociated, Equation 3 allows the calculation of the temperature as a function of time during the warmup. This equation can be used to determine the time required to raise the production fluid to 25ºC as a function of the available power. Equation 3 was used to generate Figure 6 which presents the warmup time of an oil-filled flowline (oil is most conservative case for warmup) as a function of available power. As can be seen, with a power input of 9 W/m, the production fluid temperature asymptotically approaches 25ºC. However, as the available power is increased, the time to reach 25ºC is decreased and the maximum obtainable temperature is increased.

$$T_f(t) = \frac{P}{U*\pi*D_i}*(e^{\frac{-U*\pi*D_i*t}{M_f Cp_f + M_{cs} Cp_{cs}}} - 1) + T_{amb} \tag{3}$$

For the final design, a power input of 19 W/m was selected as the optimum which results in a total power requirement of 665 kW for a 35 km flowline. This power input allows a completely oil-filled flowline to be heated from 4°C to 25ºC in 60 hours and provides a maximum fluid temperature of 48ºC. Since it is unlikely that the flowline would be completely filled with oil with a density of 850 kg/m^3, Figure 7 presents the warmup time at 19 W/m as a function of the density of the fluid in the flowline. The warmup time to 25ºC is a linear function of the fluid density. Gas-filled sections will warmup in approximately 28 hours and predominately liquid sections will warmup in approximately 50 hours (650 kg/m^3 is a reasonable density for a "live" oil). This means that there is no risk of overheating as the time to reach the maximum temperature may vary along the pipe, but the maximum temperature is dictated by the heat losses (U-value). The heating durations provided here are extreme values – in most cases, the pipe will not reach the ambient temperature of 4°C. For example, without power, it will take 42 hours for the fluids to cool to 15°C. The warmup time from 15 to 25ºC is 33 hours.

Power Requirements for Wax Deposition Removal/Prevention

For an electrically heated system, it may also be desirable to either prevent or remove a wax deposit. Two options were considered:

- Preventing wax deposition by eliminating the heat loss from the production fluid to the pipe wall.
- Melting the wax deposit during shutdown

Wax deposition is driven by the heat flux from the production fluid to the pipe wall. If the heat flux from the production fluid to the pipe wall can simply be eliminated (i.e., reduced to zero), then wax deposition will not occur. Using the electrical heating system during steady state production to simply offset the heat losses to the surroundings will prevent wax deposition. Assuming a WAT of 32ºC (which is a reasonable WAT for a live fluid), the electrical power system would have to be operated continuously to offset the heat losses to the surroundings assuming a temperature differential of 28ºC (a fluid temperature of 32ºC and an ambient temperature of 4ºC). Since the system is very highly insulated, the heat losses to the surroundings are small. To eliminate the heat flux from the production fluid to the wall, and thus maintain the fluid temperature at the WAT of 32ºC, would require approximately 12 W/m as calculated by Equation 1 replacing T_{hyd} with the WAT. Not only would this prevent wax deposition, it would also result in a steady state, arrival temperature of 32ºC at the host facility.

If it is undesirable to operate the electrical heating system continuously, then an alternative is to allow wax to deposit during steady state production and occasionally shutin the flowline and turn on the electrical heating system. As was discussed above, if the system is designed to supply 19 W/m, the maximum temperature that can be achieved is 48ºC. It is commonly assumed that it requires a temperature at least 10ºC higher than the Wax Appearance Temperature (WAT) to melt a deposit. If the WAT were 32ºC, then the system, as designed, would be able to raise the pipe wall and the fluid temperature more than 10ºC above the WAT. Although the wax deposit would not completely dissolve at 48ºC, it should soften sufficiently to be removed from the pipe wall when production is restarted.

Choice of Electrical Components

To reduce costs and reliability issues, a primary objective was to provide a simple design for the electrical heat-traced system and to use conventionally available wires and equipment.

In the design of the EHTF, three options were obviously possible: monophase DC and AC power and three phase AC power. All options are acceptable to the system, the highest voltages will occur at the platform with a midpoint at ground voltage at the other extremity of the pipe.

In this study, the size and number of wires was optimized and, using FEA analysis, the temperature of the wires was calculated to ensure that the temperature did not exceed the temperature limit of the insulation material on the wires. At maximum power input (19 W/m); the temperature of the wires is only 5ºC greater than the temperature of the pipe wall.

The study also considered and recommended the sizing and construction of the feeder cable required to transfer the power from the platform power supply to the EHTF. Conventionally available subsea connectors were identified and the topsides power generation unit was sized. All necessary components related to the EHTF, both subsea and topsides, were identified and the costs were determined to provide a budgetary cost.

Limiting Parameters

While the design basis of the study was for a tieback length of 35 km, it was also necessary to determine the maximum tieback distance possible without a technological step change.

The primary parameters dictating the maximum tieback length are:

- Minimizing the annular space to reduce weight, steel costs, and laying costs
- Minimizing the reheat time from ambient temperature to 25ºC. If the reheat time could be extended, then less linear power is required for the same voltage rating and thus longer tiebacks would be achievable
- Number of wires that can be reasonably installed around a 10” inner pipe.

Analysis of the parameters listed above determined that, without any technological changes, the EHTF “as designed” can be used for tieback lengths up to 46 km. This length scales directly with the voltage.

FABRICATION AND INSTALLATION

Based upon ITP's fabrication experience for pipe-in-pipe, detailed fabrication procedures were developed. Many of the procedures are exactly the same as for the ITP pipe-in-pipe fabrication. The installation and connection of the electrical wires obviously required careful consideration in developing the fabrication and testing procedures. Quality control is critical, but unlike some other electrically heat-traced options, the EHTF design allows testing of the continuity of all of the wires both during fabrication onshore as well as after complete fabrication.

Two methods are possible for installation of the EHTF, reeling and towing. S or J-lay methods are not possible due to the continuous electrical wires.

An issue for any type of flowline in deepwater is the weight of the flowline. In the water depths considered for this study. there are only a few vessels capable of installing any type of pipe-in-pipe. An analysis was performed to determine the applicability of those vessels for installing the EHTF. It was determined that there were two vessels capable of reeling the pipe at 1500 m water depth. At 2500 m water depth, the tension capacity for both vessels needed further investigation.

To demonstrate the mechanical performance of the EHTF, reeling tests were performed by ITP. The reeling tests demonstrated that, due to the compressive strength of the insulation, no spacers were required as the insulation is capable of transferring the bending loads to the outer pipe. The performance of the insulation was only marginally affected (~5%) by the bending and straightening of the pipe. This impact is incorporated into the design. The bending tests also showed that the resistance of the wires was not impacted by the bending and straightening.

An alternative installation method is towing. Towing is a proven technology for installing pipe-n-pipe or bundled systems down to 1400 m water depth (e.g. Girassol and Troika) and has good potential for deeper waters. A 35 km offset would have to be installed in 3 or 4 sections and would require 2 or 3 mid-line tie-in spools with related heating or insulation issues as well as electrical continuity. The use of bottom tow requires the use of buoyancy to reduce the on-bottom weight. The correlative disadvantage is the number of subsea connection required; possible losses at the electrical connections; complex system to overcome buoyancy/weight issues and possible cold spots between bundles.

For an EHTF system, the main advantages of the towed and reeled installation methods is the ability to test electrically the system onshore prior to launch

RELIABILITY AND RISKS

As part of this study, a reliability and risk assessment was performed for all aspects of the fabrication, installation, and operation. Hazards were identified using brainstorming sessions and review of other projects involving electrical heating, pipe-in-pipe systems. and bundled flowlines. The reliability study addressed the design, manufacture, installation, operation, and testing. The risk assessment identified potential hazards and procedures or methodologies to minimize those risks.

CONCLUSIONS

This study provides the design of a pipe-in-pipe, electrically heat traced system including the identification, sizing, and cost of all key components (subsea and topsides). Due to the high thermal performance of the system, the power requirements for all operations are minimized including temperature maintenance during shutdown and reheating of the fluids from ambient conditions to the hydrate formation temperature. The power requirement is 19 W/m or 665 kW for a 35 km flowline. The electrical heating system was designed to use conventional equipment. To date, the technological limit is estimated to be a 46 km tieback distance.

In addition to the design of the system, all other issues including fabrication, installation, quality control, reliability and risk assessment, and total installed cost were addressed. The study demonstrated the technical and economic feasibility of the ITP electrically heat traced flowline design.

ACKNOWLEDGMENTS

The authors would like to thank TOTAL for funding this study and acknowledge JP Kenny for providing the review of lay methods, necessary topside electrical devices, and safety and reliability of the system.

Table 1: Study Parameters

Parameter	Value
Pipe ID (mm)	0.2365
Wall Thickness (mm)	0.01826
U-value (W/m² K) based on pipe OD	0.50
Ambient seabed temperature (ºC)	4
Hydrate Formation Temperature (ºC)	25
Initial Fluid Temperature (ºC)	40
Density of gas (kg/m^3)	18.9
Heat Capacity of gas (J/kg K)	2407
Density of liquid (kg/m^3)	850
Heat Capacity of liquid (J/kg K)	2407
Density of steel (kg/m^3)	7850
Heat Capacity of steel (J/kg K)	460

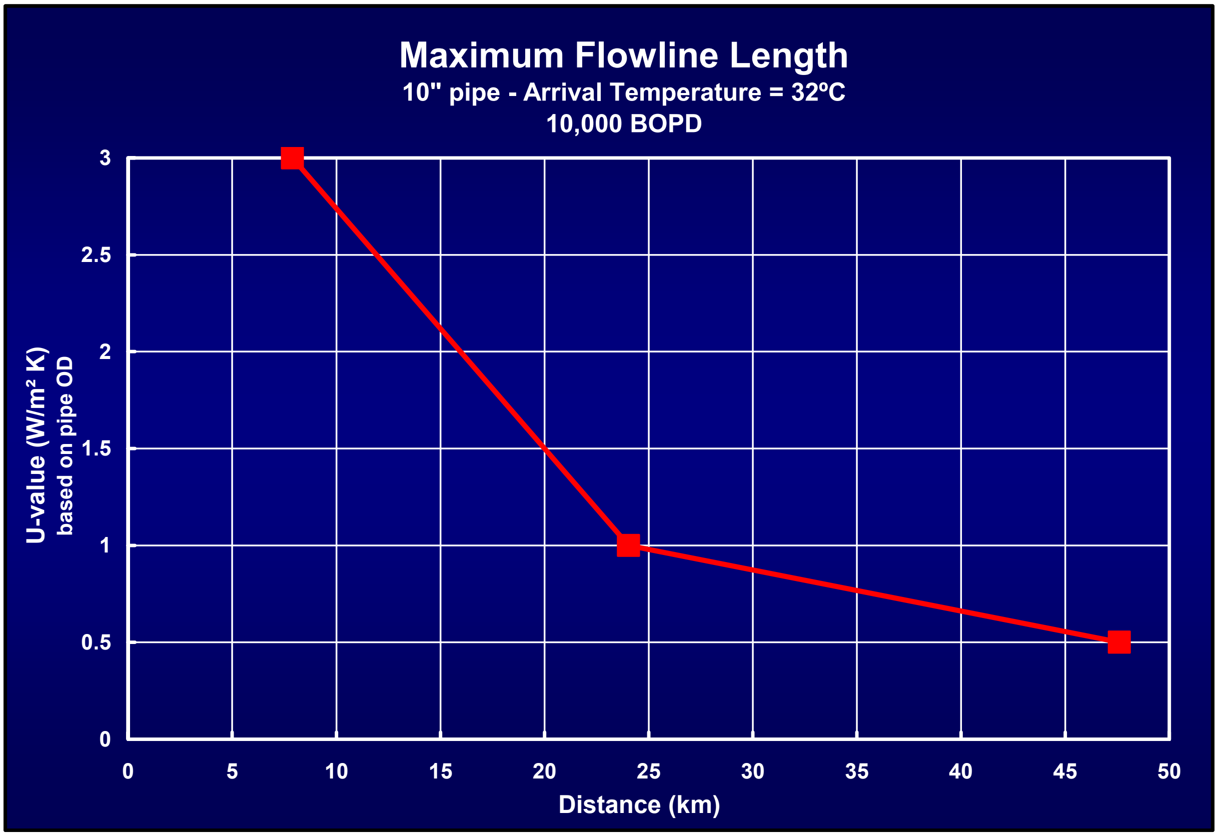

Figure 1 : Maximum flowline length as a function of U-value

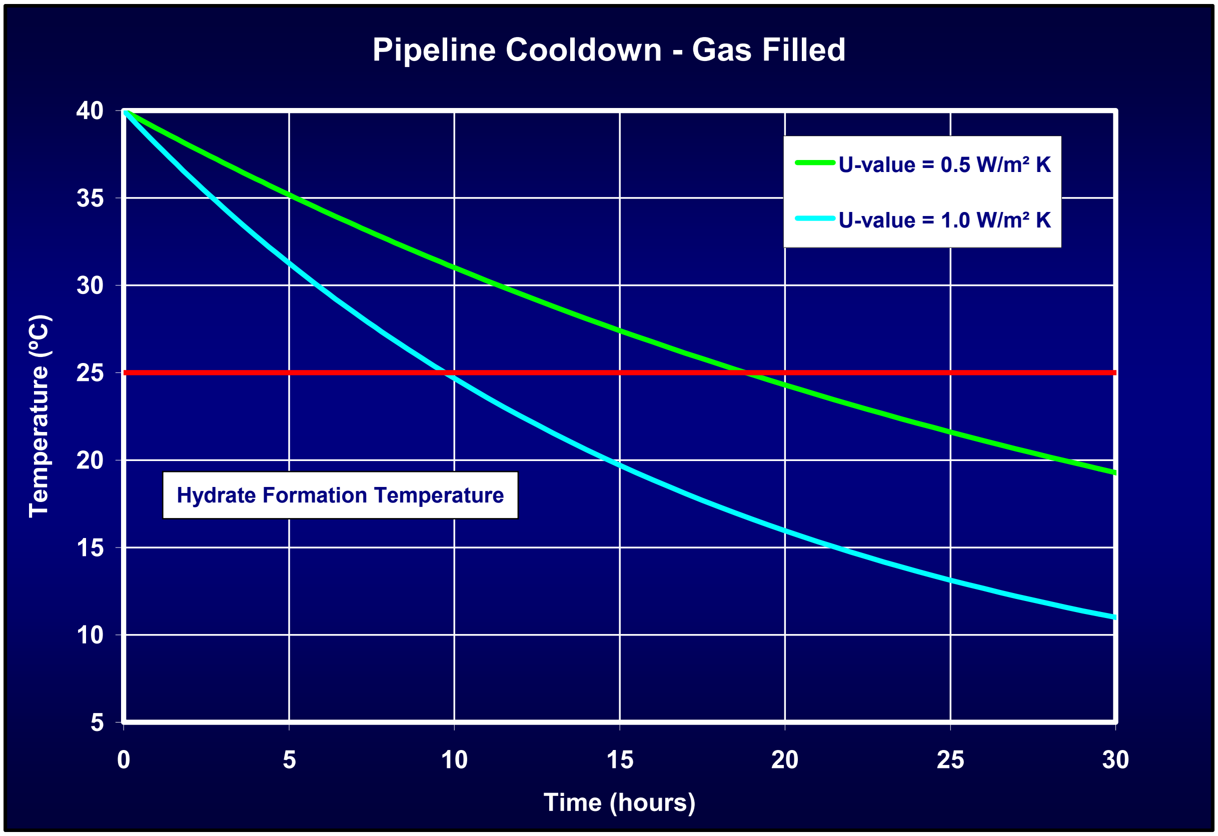

Figure 2 : Cooldown time as a function of U-value

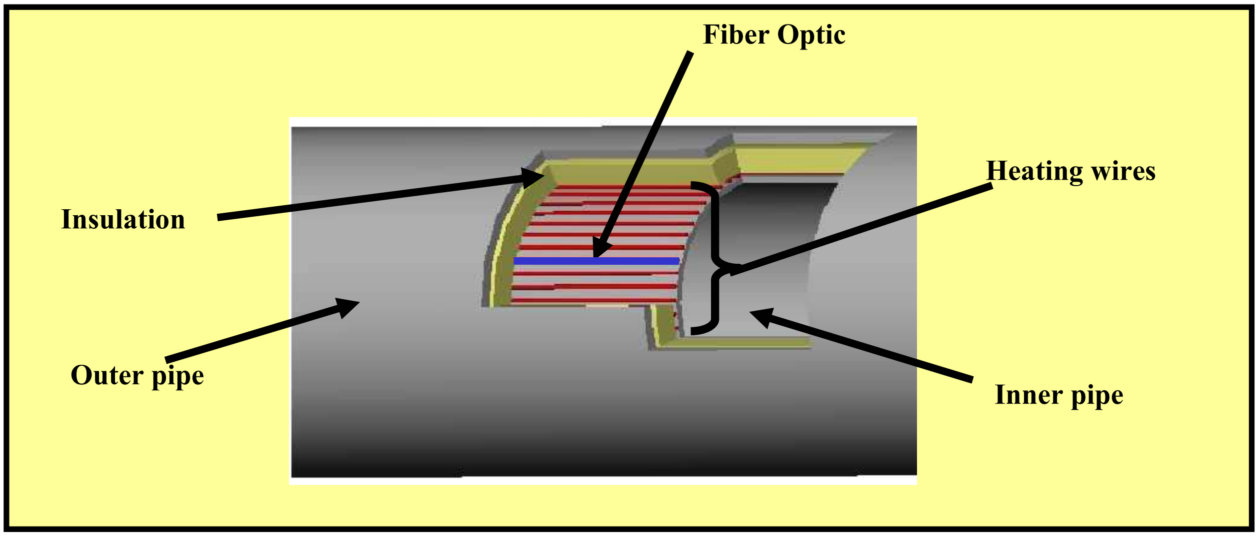

Figure 3 : Schematic of the electrically heat traced flowline

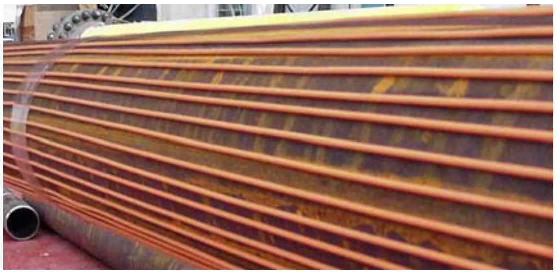

Figure 4 : The electrically heat traced flowline under construction (GPRI JIP at Humble Flow Facility, July 2001)

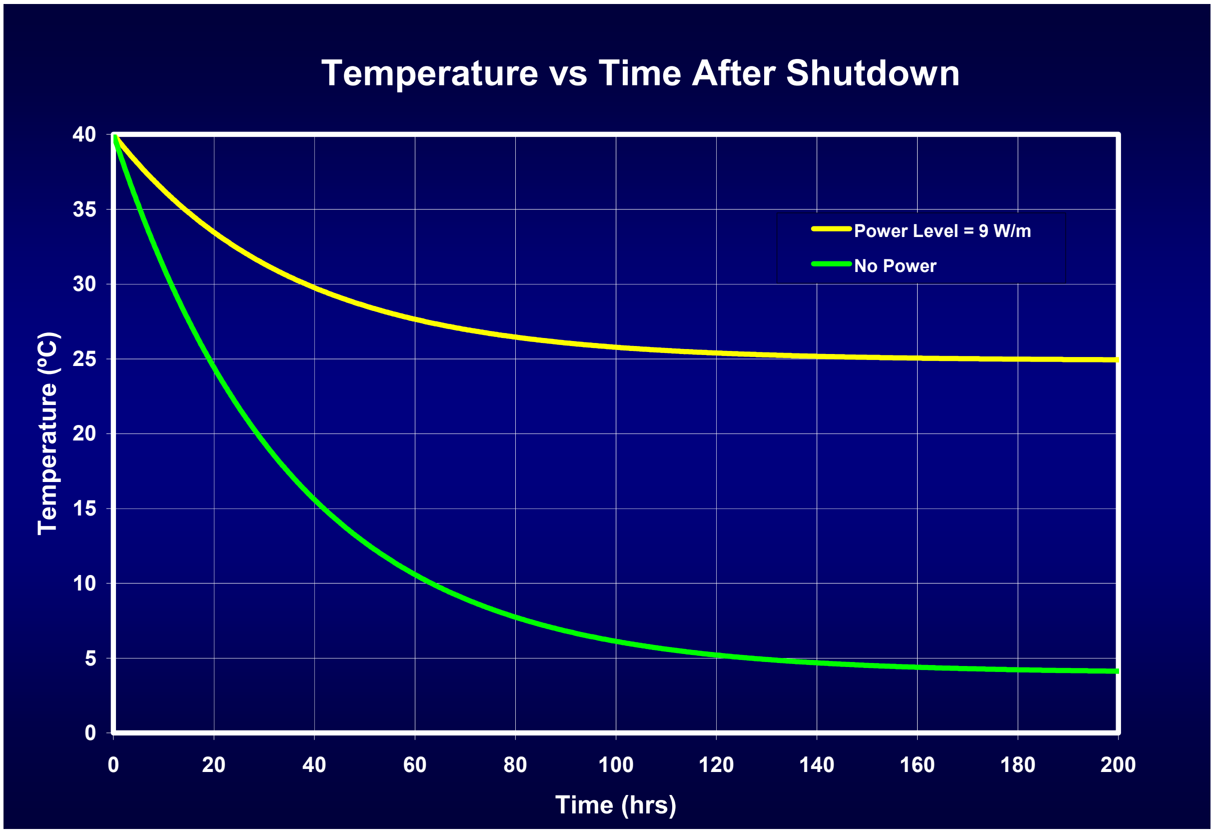

Figure 5 : Temperature of the production fluid as a function of time after shutdown

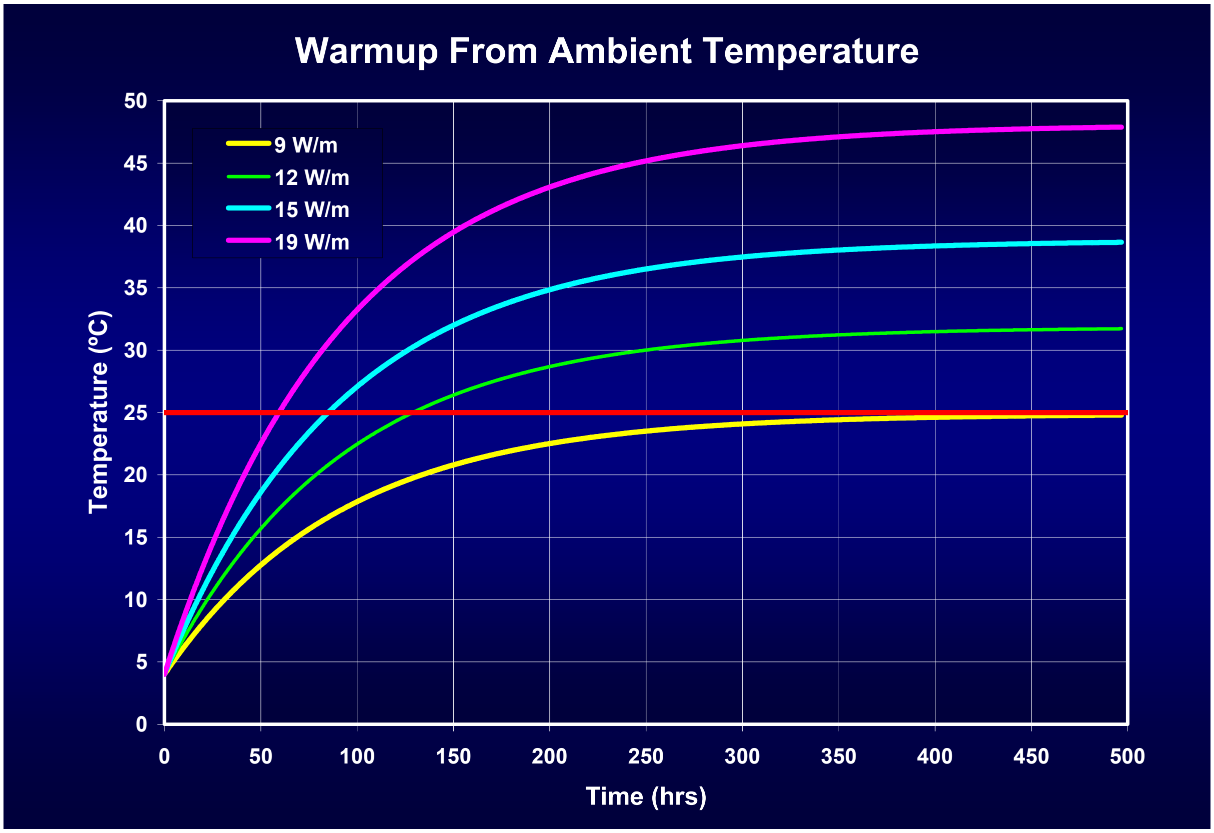

Figure 6 : Warmup time as a function of power

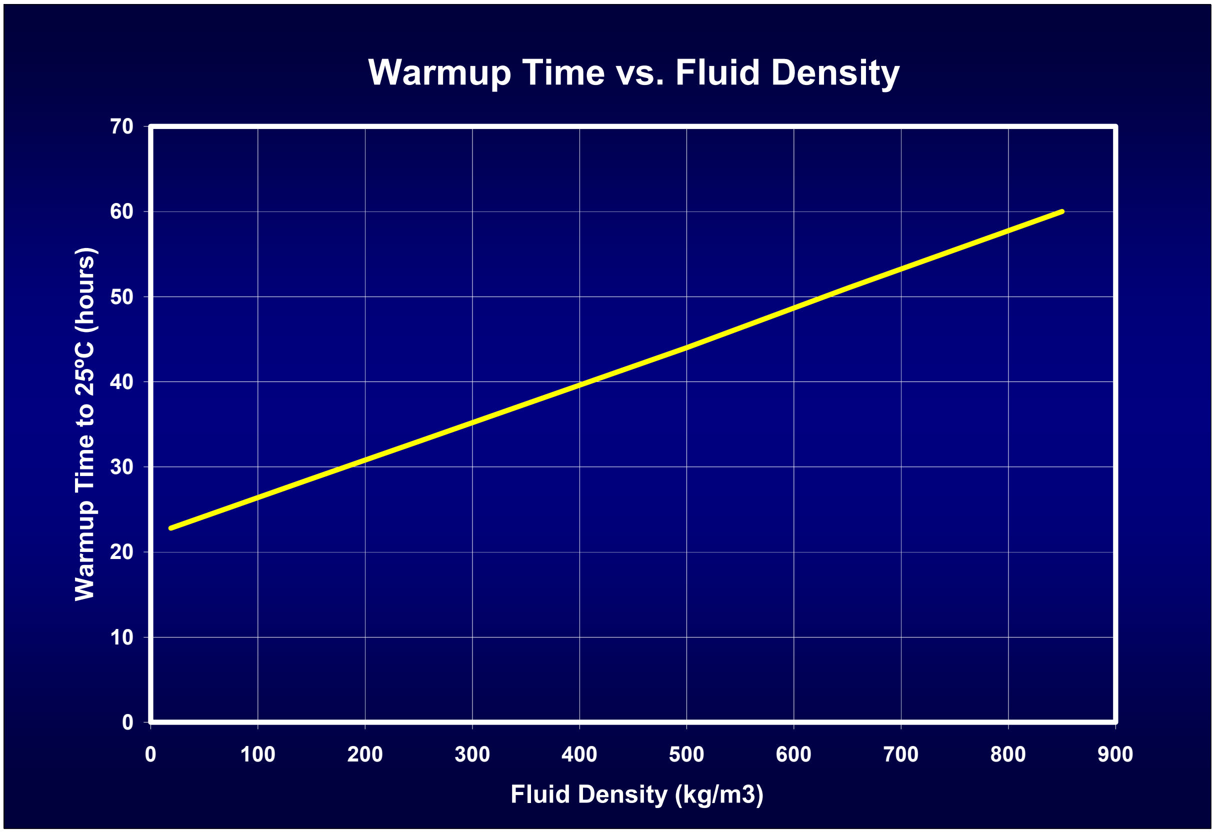

Figure 7 : Warmup time as a function of fluid density