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Optimized Design of Pipe-in-Pipe Systems

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Summary

Deepwater subsea developments must address flow-assurance issues, and these increasingly form a more critical part of the design. Pipe-in-pipe (PIP) systems, one of the options available in the designers' toolbox for overcoming these problems, are recognized as thermally efficient, reliable, and proven technology for insulated, subsea transportation of wellbore fluids. Although extremely low *U* values are achievable, PIP systems come at a cost, with increased weight as a penalty for use in deepwater developments.

By applying an "inside-out" optimization process for the design of PIP systems, the top-tension loading on the surface vessel (installation or production) can be reduced significantly while minimizing procurement expenditure on raw materials. Specifically, the design optimization of each component reduces steel volumes as well as the overall outer diameter (OD) of the system.

This paper presents the methodology for optimized design of PIP systems and illustrates the potential cost savings in terms of raw materials and installation through a case study for a typical large West African field. Commercial savings related to surface platform hull costs also are presented for a case in which the development employs PIP in catenary risers.

Introduction

At present, the PIP market is dynamic, with numerous projects requiring PIP solutions and many more examining PIP as a development option.

The objective of this paper is to present an optimization design process for PIP systems for deepwater applications, specifically 1000 m or deeper. Rather than employing API standard sizes, this paper focuses on establishing the actual required pipe diameters for the flowline and carrier by performing the thermal and mechanical design in an integrated manner. In this way, the design meets project requirements for production rate and steady-state thermal performance while minimizing the as-installed system cost. Although an important and often driving design consideration in all deepwater developments, cool-down considerations have not been included in the designs generated here.

The inside-out design methodology is presented along with the as-installed costs, which have been used as the ultimate comparison condition. The following parameters are investigated, with PIP designs and costs generated for each variable combination.

- *U* values of 1.0, 1.5, and 2.0 W/m^{2}K.
- Flowline lengths of 5, 10, 20, 40, and 60 km.

- Water depths of 1000, 1500, 2000, 2500, and 3000 m.
- Two types of insulation material—polyurethane foam (PUF) and microporous (MP) material.

In addition to presenting the results for the parametric matrix detailed previously, a project with typical characteristics for a large west African development is discussed, including the cost and top-tension implications on the host platform when employing PIP steel catenary risers (SCRs).

With a large number of PIP systems available, it is increasingly difficult to evaluate options rapidly when determining or identifying the most appropriate features on a technical and economic basis.

What follows is a brief definition and classification of PIP systems, and two specific criteria can be used to describe any particular one.

- Insulation type (material-dependent).
- Structural compliance (configuration-dependent).

Associated with each criterion are compatible types of field joints and installation methods.

Table 1 is the overall compatibility matrix showing the possible combinations of insulation-material type, field joint, and installation method for the main structural categories because the structural compliance drives the choice of insulation and installation method, with the latter of these heavily influencing field-joint selection.

PIP systems are more installation-vessel-dependent than conventional pipe. This dependency is more pronounced with:

- Increasing water depth.
- Extreme requirements, such as high-pressure/high-temperature (HP/HT) applications.
- Use for steel catenary risers.

Table 2 presents the pros and cons for the three structural classifications. The definitions for structural classification and a description of the insulation-material types are continued in Appendix A.

Optimized PIP Design—The Inside-Out Method. The inside-out process for designing focuses on optimizing each layer, from the flowline internal bore outward, so that thickness is minimized. In this way, the cost and weight of the final system are also minimized. This requires the use of non-API-sized pipe for the carrier. The use of non-API size for the flowline is also advocated because it leads to additional cost and weight savings for deep water, particularly for PIP SCRs.

For shallow-water applications, the benefits of this approach are limited and may not justify the additional design and procurement complexity. For a deepwater project, significant cost benefits are obtainable.

Fig. 1 represents the design methodology for a PIP system with standard API pipe sizes. **Fig. 2** represents the design methodology for an optimized PIP system. There is a certain amount of iteration required in this process because the contribution of the carrier pipe's wall thickness to the overall heat-transfer coefficient (OHTC) changes with variations in its diameter and wall thickness. This change in contribution affects the insulation required to achieve the desired U value, which then necessitates recalculation of the carrier diameter and wall thickness. The iteration continues until the optimized combination is achieved.

The previously described process is based the calculation of the OHTC (U_o), as provided by the basics of heat-transfer theory and the relative equations. These can be found in Appendix B. It must be stated that this process is based on the simplified 1D heat-transfer rate for convection, conduction, and radiation. Although the OHTC is affected by the fluid and its surroundings' resistance to heat transfer, these are negligible when compared to the insulation and pipes' properties. Furthermore, the process does not take into consideration the Joule-Thomson coefficient, which affects the temperature behavior of the fluid.

$$\mu = \left(\partial T \middle/ \partial p \right)_h . \qquad \text{...(1)}$$

The Joule-Thomson coefficient could vary from negative to positive values,[1] so its estimation requires knowing the mixture's properties.

Parametric Study

Case Descriptions. Five cases have been selected to illustrate the cost benefits that the inside-out design-optimization methodology offers. It has been assumed that hydraulic design calculations indicate that the flowline inside diameter (ID) must be no less than 8.825 in. This results in selecting a 10.75-in.-OD flowline from the API range for an unoptimized flowline case. **Table 3** provides the main dimensions and components of the five cases, illustrating those with API and non-API flowline and carrier pipe.

The five cases have combinations of standard API and optimized pipe sizes for the flowline and carrier along with variations in insulation material.

Case 1. Case 1 is considered the base case. It comprises standard API pipe sizes for both the flowline and carrier pipe with PUF insulation material.

Case 2. Case 2 comprises standard API pipe sizes for the flowline with an optimized carrier pipe; the insulation material is PUF.

Case 3. This case comprises an optimized flowline and an optimized carrier pipe with PUF insulation material.

Case 4. Case 4 comprises an optimized flowline and carrier pipe with MP insulation material.

Case 5. This is similar to Case 2, comprising a standard API pipe size for the flowline and an optimized carrier pipe. The main difference is that the insulation material used is MP. **Table 4** summarizes the relevant comparison cases.

Design Parameters. As well as comparing different levels of pipe optimization, each case was run for all combinations of the following parameters to demonstrate the influence of each on the system's cost.

- *U* values of 1.0, 1.5, and 2.0 W/m^{2}K.
- Flowline lengths of 5, 10, 20, 40, and 60 km.
- Water depths of 1000, 1500, 2000, 2500, and 3000 m.
- Two types of insulation material—PUF and MP.

To calculate the flowline wall thickness, the internal design pressure is taken as 300 bar (30 MPa).

Insulation-Material Selection. Of the five cases, three have PUF insulation material and the other two have MP.

The two insulation materials were chosen because their thermal conductivity and costs are from either end of the insulation-material spectrum. Additionally, they are the most common insulation materials used in PIP systems, and relevant publications are available.[2]

The PUF system considered is an injected system whereby the entire annular gap between the flowline OD and the carrier ID is filled with foam, leaving no air gaps.

The MP insulation is wrapped onto the flowline, and the system contains a minimum radial gap of 10 mm between the outside of the insulation and the ID of the carrier pipe to account for tolerances while inserting the flowline into the carrier.

Cost Breakdown. A cost model has been developed that includes the procurement, onshore fabrication, and installation of PIP systems for all combinations. Some of the key cost assumptions are shown in **Table 5.**

For situations in which PIP SCRs are employed, the cost associated with the top tension required at the vessel has been estimated from the hull cost per kg of uplift. The riser lengths for a given water depth are calculated with simple catenary equations and are shown in **Table 6.**

Results of Parametric Study

The data generated from the five cases and the various design parameters are evaluated in two sections. First, the results relating to a typical west African development are considered; second, all the results are considered and analyzed to draw conclusions relating to the cost savings involved with PIP optimization.

Typical West African Development. The west African development considered here has the following field parameters.

- 1500-m water depth.
- FPSO (Floating Production Storage & Offloading) host.
- *U* value of 1.5 W/m^{2}K.
- Six producing wells located in pairs.
- Dual PIP system tied back to FPSO by means of SCRs (piggable loops).

- 40-km total flowline length.

Fig. 3 represents the cost comparison of the five cases, showing the breakdown and contribution of the following cost centers.

- Line pipe.
- Insulation.
- Retooling (if applicable).
- Onshore fabrication.
- Installation.
- Host hull cost for risers.

The onshore fabrication and installation costs for each case are the same as the variation in pipe diameter; therefore, the increased welding time is small in comparison to the overall time, and the cost of these operations is, therefore, neglected.

The host cost refers to hull-form cost owing to the risers. The water depth and, therefore, the riser line length are constant for this west African development; the cost variation is dependent on the submerged weight of the riser.

Table 7 presents the total costs for each case (without riser costs) as well as the percentage saving vs. the base case (Case 1).

The results clearly show that Case 3, with the optimized flowline and carrier and using PUF insulation, offers the most cost-effective solution, at USD $16.3 million. Case 4, which uses the more expensive MP insulation material but also has an optimized flowline and carrier, is the closest solution to this at U.S. $17.0 million, with the difference between these two cases being 3%.

By comparing the steel costs of these two cases (shown in **Fig. 4**), there is a greater saving with the MP insulation (approximately 5.3%); however, the increased cost of the insulation material makes the total onshore and, therefore, the overall cost higher than Case 3 (see **Figs. 5 and 6,** respectively).

Cases 2 and 5, each with the standard flowline and optimized carrier but with PUF and MP insulation, respectively, represent the third and fourth most cost-effective systems. The cost difference between these two cases is in the region of 3.7%.

Case 1 represents the least cost-effective option, with a total cost of approximately U.S. $18.7 million. The overall cost saving achieved by full optimization of the system (i.e., optimizing the flowline and carrier) is 14%, a saving of U.S. $2.5 million.

By only partially optimizing the system (i.e., optimizing the carrier only), a significant saving can still be achieved. When compared with Case 1, Cases 2 and 5 offer a cost savings of U.S. $1.3 million (7%) and U.S. $0.5 million (3%), respectively.

By referring to Figs. 4 through 6, graphical comparisons for steel, onshore, and total costs can be seen.

PIP SCR Costs. The total costs, shown in Fig. 3 for the host hull form, are difficult to rationalize as specific values because of their complex dependence on host type (FPSO, semisubmersible, TLP (Tension Leg Platform), or SPAR (Single

Point Anchor Reservoir)) and project requirements for topsides processing, storage, etc. They are presented to give a feel for their magnitude.

Figs. 7 and 8 are more useful in that the top-tension saving vs. the base case is clearly identified for the optimized designs. Case 4 has a reduction in top tension of 325 metric tonnes, and for Case 3, this value is 316 Te, allowing greater host deck load. This is particularly important for top-tension-sensitive host types, such as TLPs, semisubmersibles, and SPARs.

Discussion of General Trends. The following evaluation of the five cases is for the range of water depths, U values, and pipe lengths, as described previously in this paper.

Case 1 is the base case with API-sized flowline and carrier and PUF insulation.

Cases 2 and 5 are comparable because they have optimized carrier pipe and employ PUF and MP insulation, respectively.

Cases 3 and 4 are comparable because they have optimized flowline and carrier pipe and employ PUF and MP insulation, respectively.

U-Value Trend. For a U value of 1.0 W/m^{2}K, use of the more expensive MP insulation (Cases 4 and 5) is consistently the cheapest option. The cost differential increases with increasing water depth and line length. **Figs. 9 and 10** show the total installed cost for U = 1.0 W/m^{2}K with line lengths of 5000 and 60 000 m, respectively.

As the U value increases, there is a switchover, and the PUF-insulation costs drive the cheapest solution (Cases 2 and 3). The cost differential between PUF and MP solutions decreases with water depth but increases for greater line length. As the influence of water depth decreases, the U value increases from 1.5 to 2.0 W/m^{2}K. **Figs. 11 and 12** show the total installed cost for U = 2.0 W/m^{2}K with line lengths of 5000 and 60 000 m, respectively.

Retooling Cost. Retooling has the greatest cost influence for solutions in which the water depth is 2000 m or less. After this depth, the base case requires a jump to the next API size for the carrier, reinforcing the benefits of optimizing pipe diameter.

Steel Costs. For U = 1.0 W/m^{2}K, there is a crossover from the base-case steel cost being cheaper to the carrier-optimized cases (Cases 2 and 5) being less expensive. This happens at a water depth of 2000 m or for flowline lengths greater than 10 km.

For all U values greater than this, steel costs are lower for Cases 2 and 5.

Water Depth. Generally speaking, as water depth increases, the cost savings achieved from PIP optimized design increase vs. the base case. Depending on the various parameters (water depth, U value, line length, and insulation type), these savings range from 0 to 35% at the extremes.

Conclusions

1. As the U value decreases to approximately 1 W/m^{2}K and less, the more expensive insulation (MP material) provides the most economic and the lightest systems.
2. To offset the additional cost for retooling to non-API-sized pipe for the carrier only, either of the following conditions are required.
    - Flowline length must be greater than 10 km.
    - Water depth must be greater than 2000 m.
3. For PIP SCRs, top tension savings of more than 20% are achievable through full design optimization.

Nomenclature

A_o = area of heat-transfer surface, ft^2, m^2

d_i = ID of a specific layer, ft, m

d_o = OD of the pipe, ft, m

D = OD, ft, m

D_o = overall OD of the pipe, including all layers, ft, m

E = Young's modulus, ksi, GPa

g = gravity, lb ft/sec^2, kg m/sec^2 Eq. B-12

h = convection heat-transfer coefficient, Btu/hr·ft^2·°F, W/m^{2}K

H = water depth, ft, m

k = thermal conductivity of specific layer mixture, Btu/hr·ft·°F, W/mK

L = length of pipe section, ft, m

p = pressure, Pa, psi Eq. 1

p_b = burst pressure Eq. B-9

p_C = collapse pressure, ksi, MPa

p_d = design pressure, ksi, MPa

p_e = elastic collapse pressure, ksi, MPa

p_o = design hydrostatic pressure, ksi, MPa

p_y = plastic collapse pressure, ksi, MPa

Q = average heat-transfer rate, Btu/hr, kJ/hr

R_F = fluid resistance to heat transfer, ft·°F·hr/Btu, mK/W

ΣR_{Layers} = sum of all layers' resistance to heat transfer, ft·°F·hr/Btu, mK/W

R_S = surroundings' resistance to heat transfer, ft·°F·hr/Btu, mK/W

s = volume/surface ratio, ft, m

t = wall thickness, in, mm

T = Temperature, °F, °C Eq. 1

T_F = temperature of fluid flowing in pipe, °F, °C

T_S = temperature of pipe surroundings, °F, °C

U = heat-transfer coefficient, Btu/hr·ft^2, W/m^{2}K

U_i = OHTC at ID, Btu/hr·ft^2, W/m^{2}K

U_o = OHTC based on the area, Btu/hr·ft^2·°F, W/m^{2}K

μ = Joule-Thomson coefficient, K/Pa

ν = Poisson's ratio

ρ = density lb/ft^3, kg/m^3 Eq. B-12

σ_U = ultimate tensile strength of the pipe, ksi, MPa

σ_y = yield strength of the pipe, ksi, MPa

Subscripts

h = enthalpy, Btu/lb, J/kg Eq. 1

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Appendix A—Definitions for PIP Classification

Structural Compliance Definitions. ***Sliding.*** The sliding configuration is so named for the capability of the carrier pipe to slide over the flowline and insulation such that consecutive joints of carrier can be butt welded.

Sliding systems usually have spacers for aligning and centralizing the two pipes, but the system can work without them.

An additional requirement is a temporary clamp (or similar device) to axially hold the flowline and carrier during transportation, handling, and loading into the firing line. This device is removed before welding and may be located at either end of the joint, depending on the installation-vessel setup.

Typically the field jointing sequence is as follows.

- Weld and inspect the flowline.
- Corrosion-coat the flowline-weld region.
- Insert half-shell insulation (or equivalent); this is often the same as the main body's insulation.
- Position weld-backing strip.
- Slide carrier over field joint and perform butt weld.
- Inspect and coat the carrier weld.

Suitable vessels for sliding systems include J-lay vessels, such as the Saipem FDS (Field Development Ship) , and S-lay vessels (e.g., the Allseas Solitaire), but adapting other vessels is possible. PIP strings for reeling can be fabricated with the sliding approach.

The sliding configuration does not have any regular axial connection between the flowline and carrier, but it can easily accommodate bulkheads to lock the pipes together axially and to compartmentalize insulation against carrier breach.

Fixed. The fixed type of PIP system uses either swaged connectors, forged bulkheads, or forged tulips that are welded to both the carrier and the flowline. This fixes the flowline and carrier both axially and laterally at the end of each joint length—hence, a “fixed” system.

The swaged connectors and forged tulips are initially welded to the carrier pipe and then to the outer surface of the flowline at both ends of the joint. With a forged-bulkhead arrangement, the following sequence must occur for onshore fabrication of double, treble, or quad joints:

1. Butt weld the first bulkhead to the flowline.
2. Insert the flowline into the carrier pipe (non-bulkhead end first).
3. Butt weld the carrier to the bulkhead upstand.
4. Butt weld the second bulkhead to the end of the flowline protruding from carrier.
5. Place the insulation over the flowline-weld region.
6. Close the gap between the carrier and upstand on the second bulkhead with steel half shells.

Offshore construction involves:

- Butt welding flowline ends together and then applying insulation on the outside of the joint (i.e., insulation is exposed to the seawater).
- Repeat Steps 4 through 6 (as described previously).

This structural category of PIP system can be installed by almost any S- or J-lay vessel but cannot be reeled because of the structural discontinuity at the field joint’s location.

One major advantage of this type of construction is the automatic compartmentalization of the system every double, treble, or quad joint. The primary drawback is the additional heat loss through the steel connection between the flowline and the carrier.

Restrained. The restrained structural category for PIP systems consists of the flowline located concentrically inside the carrier by spacers in the main body of the joint and by some form of nonmetallic bulkhead at either end, typically a rubber/EDPM (Ethylene Proylene Diene Monomer) material. The term “restrained” is used because the bulkheads provide some axial and lateral compliance between the flowline and carrier, primarily during installation, but differential axial movement of the flowline and carrier may occur during operation.

The insulation material is either attached to the flowline before insertion into the carrier or the annulus is filled once the flowline has been inserted.

The purposes of the bulkheads are as follows.

- To prevent relative axial movement of the flowline and carrier during fabrication, transportation, and handling.
- To contain the insulation when filling the assembled joint (flowline already inserted in carrier).
- To concentrically align the flowline in the carrier.

The offshore field-joint arrangement usually uses steel half shells to close the gap between consecutive joints of carrier pipe, requiring two circumferential and two longitudinal welds. The field-joint insulation may be of polyurethane foam half shells or rockwool.

Installation of restrained PIP systems is relatively independent of S- and J-lay-vessel setup, and work is ongoing to prove this type of system for reeling.

Insulation-Material Categories. ***PUF.*** PUF is a common and cheap material that can be sprayed onto the flowline before insertion in the carrier pipe or injected into the annular space between the preassembled flowline and carrier pipes. These two methods of insulation are distinctly different and determine the type of structural system that can be used.

For example, the injected version cannot be used for sliding PIP systems because the PUF bonds to both the carrier and flowline, thereby eliminating the axial movement required to achieve butt welding of the carrier pipe. Sprayed PUF, however, permits the sliding option.

Thermal conductivity of PUF material is in the range of 0.03 to 0.04 W/m^{2}K, depending on the cell size and foam blowing agent.

Granular Materials (e.g., microspheres). This category consists of granular material that is poured into the annular space between the flowline and carrier pipe. The granules are usually alumina silicate microspheres, also known as fly ash, which is a waste product from coal-fired power stations. The microspheres range from 10 to 150 µm in diameter, are almost perfectly spherical, and are completely inert.

The microspheres’ thermal conductivity is between 0.09 and 0.11 W/m^{2}K.

The pipe assembly can consist of single or, more often, double joints and is normally inclined to a specific angle and vibrated at a specific frequency to ensure compaction and optimum filling. To fill the annulus, a stopper is required at the bottom of the PIP section being filled to contain the granular material and to hold the flowline and carrier pipe concentrically and axially aligned during filling.

MP Materials. MP material is formed from spherical particles of fumed silica that are bonded together at their point of contact with one another, minimizing heat conduction through the solid. The interstitial voids between the particles trap air molecules and prevent heat transmission through convection. The panels are prepared for application to the pipe with parallel saw cuts and then sealed in either a polyethylene polyamide film or aluminium-foil packet. This packet/film may be filled with air, inert gas (e.g., argon), or a drawn vacuum. The insulation needs to remain dry.

The thermal conductivity of MP materials ranges from 0.025 to 0.015 W/m^{2}K for air-filled systems, 0.015 to 0.01 W/m^{2}K for gas-filled ones, and down to 0.006 W/m^{2}K for a vacuum system.

Vacuum (Full or Assisted). A perfect vacuum provides the best insulation possible, but creating and maintaining a near-perfect vacuum is difficult because diffusion of gases (mainly hydrogen) through steel creates partial pressures. These pressures significantly affect the OHTC and require inclusion of special "getters," types of material that absorb the diffused gases. Getters are typically granules or tablets and are added during the fabrication process.

This method leverages on vacuum-insulated-tubing technology, which has been used extensively since the early 1980s.

Phase-Change Materials. This is a new class of material under consideration for use in subsea pipelines. Essentially, the insulation material stores heat that is released during shutdown as the material crystallizes. This technology is currently being investigated for use in other areas of the industry.

Appendix B—Basic Principles of Heat Transfer

Explanation of Heat-Transfer Theory. The average rate at which heat is lost from the fluid flowing through a section of pipe because of steady-state heat transfer between the fluid and the pipe surroundings is generally calculated with the following equation.[3–5]

$$Q = U_o \cdot A_o \cdot \left(T_F - T_S\right). \quad \text{(B-1)}$$

Eq. B-1 and all subsequent theory are based on 1D conduction only. For a particular length of pipe, L, the heat-transfer area is given as:

$$A_o = \pi \cdot D_o \cdot L. \quad \text{(B-2)}$$

If L is relatively small, U_o essentially defines the local heat-transfer rate.

A reasonable estimate of U_o can generally be obtained from the following relationship.

$$U_o = \frac{1}{d_o \cdot \left(R_F + \sum R_{\text{Layers}} + R_S\right)}. \quad \text{(B-3)}$$

The product and its surroundings' resistance to heat transfer is not considered in the design calculations performed in this paper because their contribution to the OHTC is small based on the application of the lumped-capacity analysis. A uniform temperature distribution throughout the oil and solid flowline is assumed. This is equivalent to saying that the surface-convection resistance is large compared with the internal-conduction resistance.[5] This is a reasonable assumption when

$$h \cdot s / k \leq 0.1, \text{ Biot number,} \quad \text{(B-4)}$$

in which h=convection heat-transfer coefficient, W/m^{2}K; k = thermal conductivity, W/m^{2}K; and s = the volume/surface ratio, m.

Resistance to Heat Transfer of the Insulation Layer and Pipe Walls. The pipe layers' resistance to heat transfer is calculated with the following equation.

$$R_{\text{Layer}} = \frac{1}{2\cdot k}\cdot \ln\left(\frac{d_{o\text{Layer}}}{d_{i\text{Layer}}}\right). \quad \text{......................................(B-5)}$$

Generally, the thermal conductivity of insulating materials increases with increasing temperature, and this dependence on temperature must be included in the evaluation of Eq. B-5.

Calculating the OHTC Referenced to the ID or OD. As part of the supplied project information, the required OHTC will be specified with reference to either the ID or OD of the pipe. As a rule of thumb, Gulf of Mexico projects reference the OD, and the rest of the world references the OHTC to the ID. Eq. B-3 calculates the OHTC at the OD of the pipe.

To calculate the OHTC referenced to the ID of the pipe, use the following equation.

$$U_o \cdot d_o = U_i \cdot d_i . \quad \text{..(B-6)}$$

Rearranged, Eq. B-6 provides the OHTC referenced to the ID.

$$U_i = \frac{U_o \cdot d_o}{d_i} . \quad \text{..(B-7)}$$

Calculation of Flowline Wall Thickness (Internal Pressure). The following equation can be used to calculate the flowline wall thickness to withstand internal pressure.[4]

$$p_b = 0.90\cdot\left(\sigma_y + \sigma_U\right)\cdot\frac{t}{D-t} . \quad \text{.................................(B-8)}$$

$$p_b = \frac{p_d}{0.72} . \quad \text{..(B-9)}$$

Calculation of Carrier-Pipe Wall Thickness (External Pressure). The following equations can be used to determine the carrier pipe's wall thickness to withstand external hydrostatic pressure.[6]

$$p_C = \frac{p_y \cdot p_e}{\sqrt{{p_y}^2 + {p_e}^2}} , \quad \text{..(B-10a)}$$

$$p_y = 2\cdot\sigma_y\cdot\left(\frac{t}{D}\right), \quad \text{.. (B-10b)}$$

and $$p_e = 2\cdot E\cdot\frac{\left(\frac{t}{D}\right)^3}{\left(1-\nu^2\right)} . \quad \text{...(B-10c)}$$

$$p_C = \frac{p_o}{0.7} , \quad \text{... (B-11)}$$

and $$p_o = \rho\cdot g\cdot H . \quad \text{.. (B-12)}$$

SI Metric Conversion Factors

bar	×	1.0*	E+05	= Pa
Btu	×	1.055 056	E+00	= kJ
ft	×	3.048*	E–01	= m
°F	x	(°F–32)/1.8		= °C
in.	×	2.54*	E+00	= cm

*Conversion factor is exact.

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Figure Captions

Fig. 1—Methodology for designing a PIP system with standard API pipe sizes.

Fig. 2—Design methodology for an optimized PIP system.

Fig. 3—Cost comparison for a typical west African development.

Fig. 4—Steel cost vs. water depth (U = 1.5 W/m^{2}K, L = 40 000 m).

Fig. 5—Onshore cost vs. water depth (U = 1.5 W/m^{2}K, L = 40 000 m).

Fig. 6—Total cost vs. water depth (U = 1.5 W/m^{2}K, L = 40 000 m).

Fig. 7—Top tension for six risers (U = 1.5 W/m^{2}K, water depth = 1500 m).

Fig. 8—Top-tension percentage comparison for six risers (U = 1.5 W/m^{2}K, water depth = 1500 m).

Fig. 9—Total cost vs. water depth (U = 1.0 W/m^{2}K, L = 5000 m).

Fig. 10—Total cost vs. water depth (U = 1.0 W/m^{2}K, L = 60 000 m).

Fig. 11—Total cost vs. water depth (U = 2.0 W/m^{2}K, L = 5000 m).

Fig. 12—Total cost vs. water depth (U = 2.0 W/m^{2}K, L = 60 000 m).

Tables

TABLE 1—COMPATIBILITY MATRIX

		Sliding	Fixed	Restrained
Insulation Group	Injected PUF	×	✓	✓
	Sprayed PUF	✓	✓	✓
	Granular material (e.g., microspheres)	×	✓	✓
	MP material	✓	✓	✓
	Vacuum (full or assisted)	×	✓	×
	Phase-change material	×	✓	×
Compatible Field Joints	Half shells	✓	✓	✓
	Carrier to carrier butt weld	✓	×	×
	Threaded	(✓)	✓	✓
	Flowline weld only (wet field joint)	×	✓	×
Installation Methods	Reel	✓	×	(✓)
	S-lay	✓	✓	✓
	J-lay	✓	✓	✓
System Usage	Flowlines	✓	✓	✓
	Risers	✓	×	×

TABLE 2—ADVANTAGES AND DISADVANTAGES OF THE STRUCTURAL CLASSIFICATIONS

PIP Classification	Pros	Cons
Sliding	Butt weld on carrier pipe Greater fatigue life for riser applications Small reduction in thermal efficiency between the main body and field joint Compatible with all installation methods Compatible with sprayed PUF, MP blanket, and aerogel insulation Possible use of mechanical connectors on carrier pipe instead of welding Suitable for single, double, or quad joints	Requirement for pup pieces Need for some flexibility in welding position (S-lay only) Intermittent or no axial connections between the flowline and carrier Requires spacers Not compatible with vacuums, granular-material or phase-change-material insulation Offshore sequencing is highly installation-vessel-dependent
Fixed	Regular axial constraint of flowline and carrier Compatible with all types of insulation Exceptional insulation capability can be achieved Flowline-only weld at field joint in conjunction with a “wet” field joint Good track record Almost entirely independent of installation-vessel setup Most suitable for double joints	Requires either welding to the outer surface of flowline (swages and tulips) or additional forged components (bulkheads and tulips) “Cold spots” where the flowline and carrier are welded together Localized cool-down time driven by cold spots Cannot be reeled Good insulation required at field joint to counter cold spots
Restrained	Compatible with most installation methods Good track record Relatively independent of installation-vessel setup Most suitable for double joints	Not compatible with vacuums or phase-change-material insulation Cannot be reeled Limited axial compliance between the flowline and carrier Requires spacers and stoppers, such as rubber bulkheads

TABLE 3—SUMMARY OF MAIN PARAMETERS FOR CASES

	Case Number				
	1	2	3	4	5
Flowline OD (in.)	10.75	10.75	9.84	9.84	10.75
Flowline wall thickness (mm)	14.11	14.11	12.92	12.92	14.11
Carrier pipe OD (in.)	16.00	14.32	13.30	12.70	13.73
Carrier pipe wall thickness (mm)	18.19	16.28	15.03	14.44	15.61
Insulation material	PUF	PUF	PUF	MP	MP
Carrier size	API	Non-API	Non-API	Non-API	Non-API

TABLE 4—COMPARISON OF CASES

Comparison Reference	Compared Cases	Difference Between Cases
A	1 vs. 2	Non-API carrier, both PUF
B	1 vs. 3	Non-API flowline and carrier, both PUF
C	1 vs. 4	Non-API flowline and carrier, Case 4 MP
D	1 vs. 5	Non-API carrier, Case 4 MP
E	2 vs. 5	PUF vs. MP, both non-API carrier
F	3 vs. 4	PUF vs. MP, both non-API flowline and carrier

TABLE 5—SUMMARY OF COST ASSUMPTIONS EMPLOYED

Cost Center	Value	Units
Line pipe	1,000	\$/tonne
Retooling for non-API sized pipe	100,000	\$ per size
Insulation		
PUF	150	\$/m^3
MP	1,700	\$/m^3
J-lay vessel, day rate	250,000	\$/D
Host hull cost	3	\$/kg buoyancy

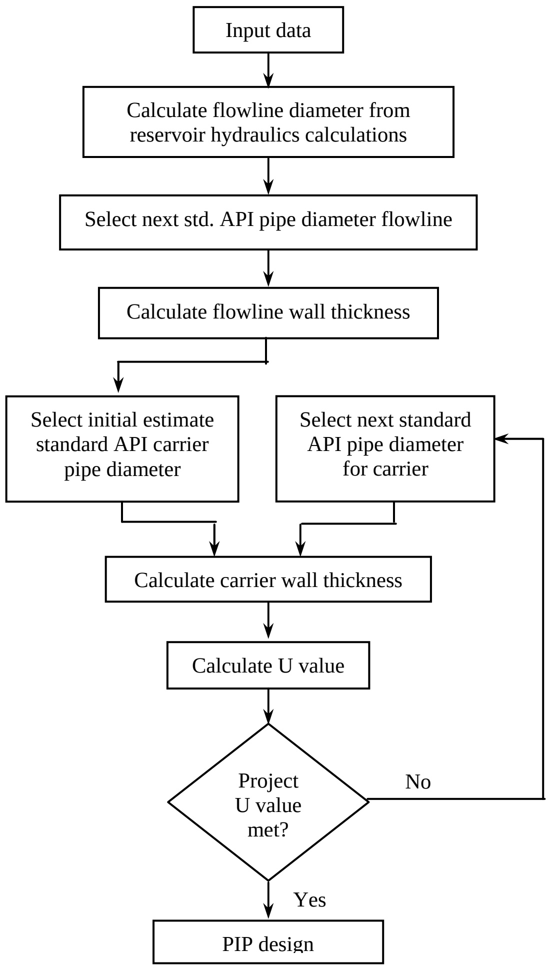
TABLE 6—SCR LENGTH FOR RESPECTIVE WATER DEPTH

	Water Depth (m)				
	1000	1500	2000	2500	3000
SCR length (m)	1234	1857	2479	3102	3725

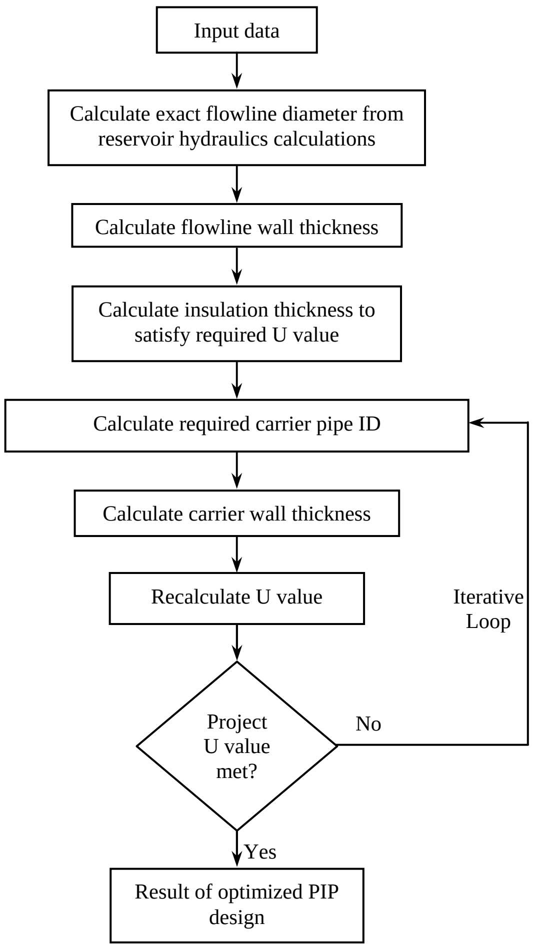
TABLE 7—TOTAL-COST COMPARISON

	Case Number				
	1	2	3	4	5
Total Cost (\$ million)	18.7	17.4	16.3	17.0	18.2
Difference (\$ million)	—	1.3	2.5	1.8	0.5
% Difference	—	7	14	11	3

Flow Diagrams



Flow Diagram 1



Flow Diagram 2

Figures

Figure 1: Cost Comparison for Typical WA development

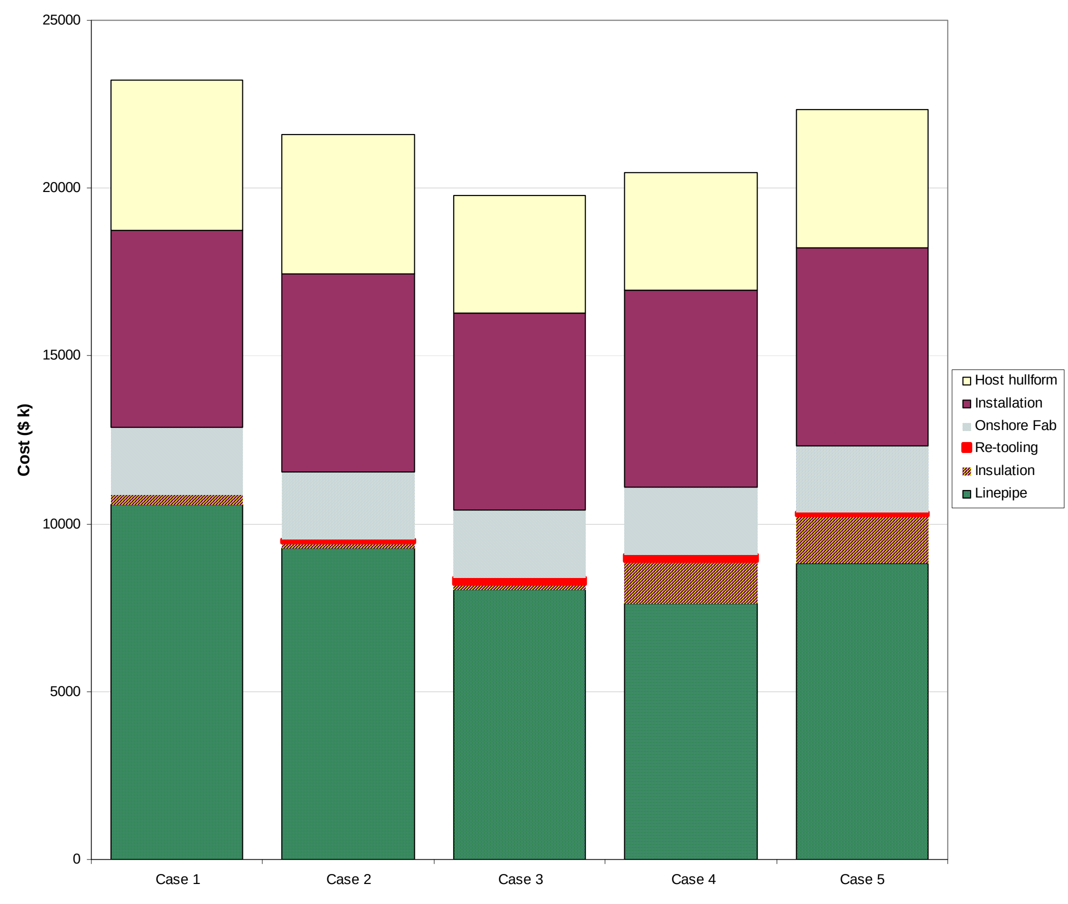
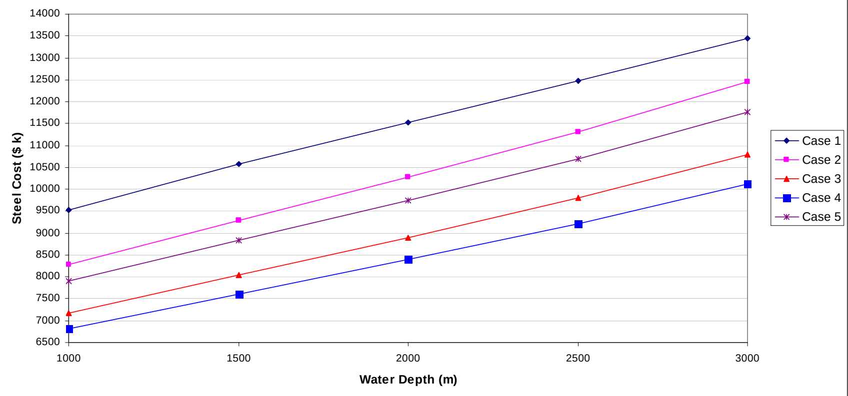


Figure 2: Steel Cost vs Water depth
(U = 1.5 W/m²K, Pipe length = 40000m)



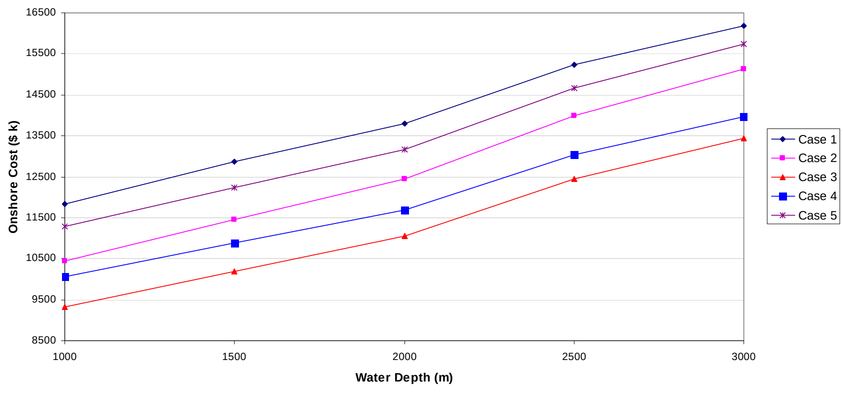


Figure 3: Onshore Cost vs Water depth
(U = 1.5 W/m²K, Pipe length = 40000m)

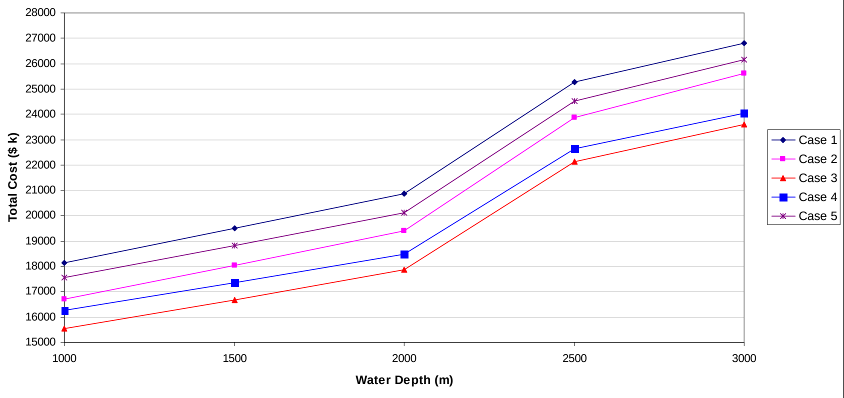


Figure 4: Total Cost vs Water depth
(U = 1.5 W/m²K, Pipe length = 40000m)

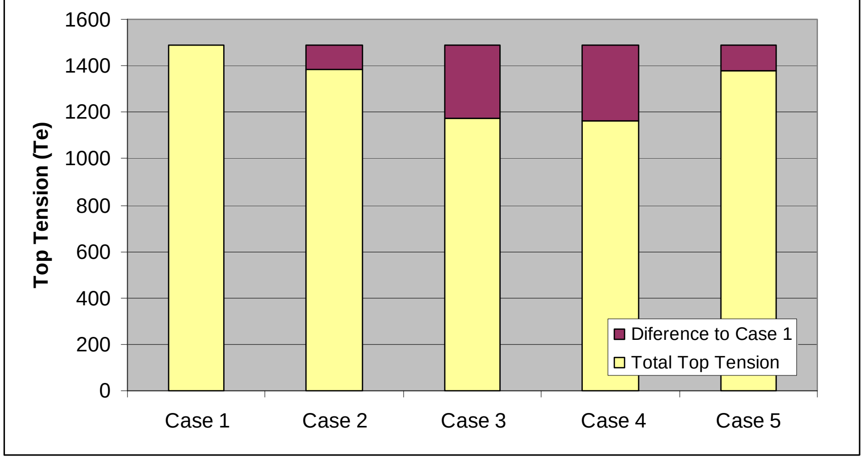


Figure 5: Top Tension for 6 Risers
(U=1.5 Wm^{2}K, water depth 1500m)

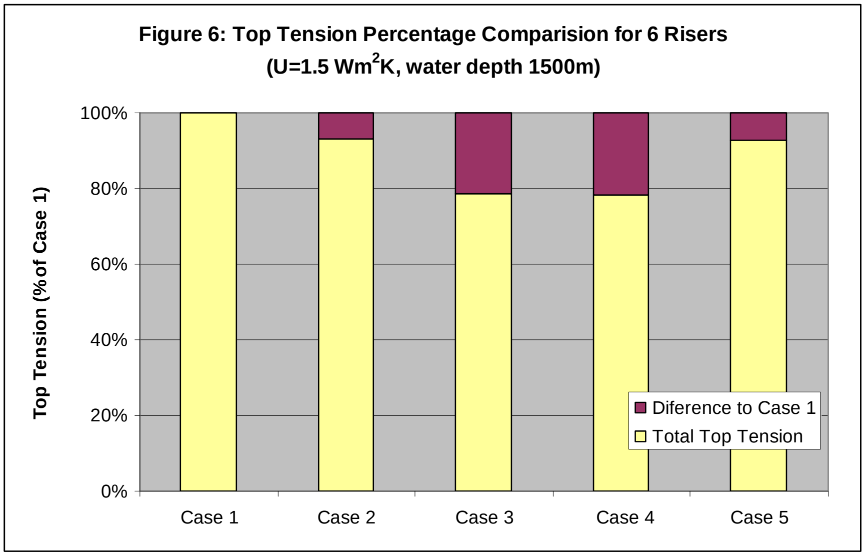


Figure 6: Top Tension Percentage Comparision for 6 Risers (U=1.5 Wm^{2}K, water depth 1500m)

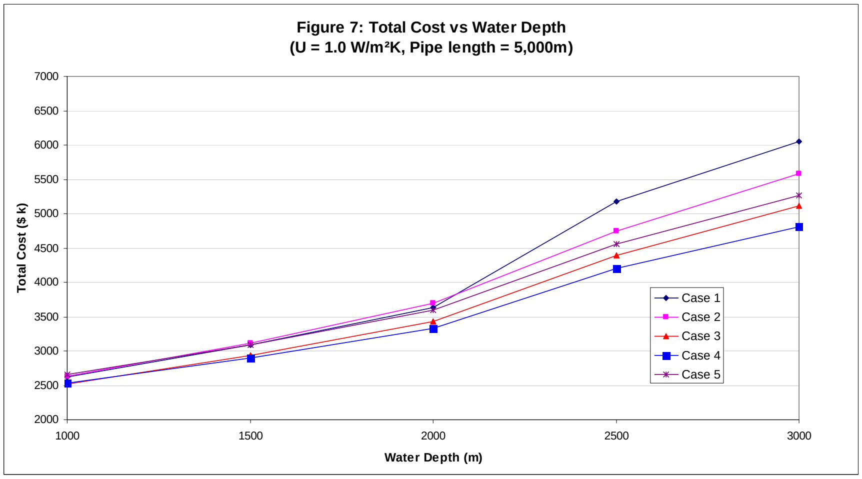


Figure 7: Total Cost vs Water Depth (U = 1.0 W/m²K, Pipe length = 5,000m)

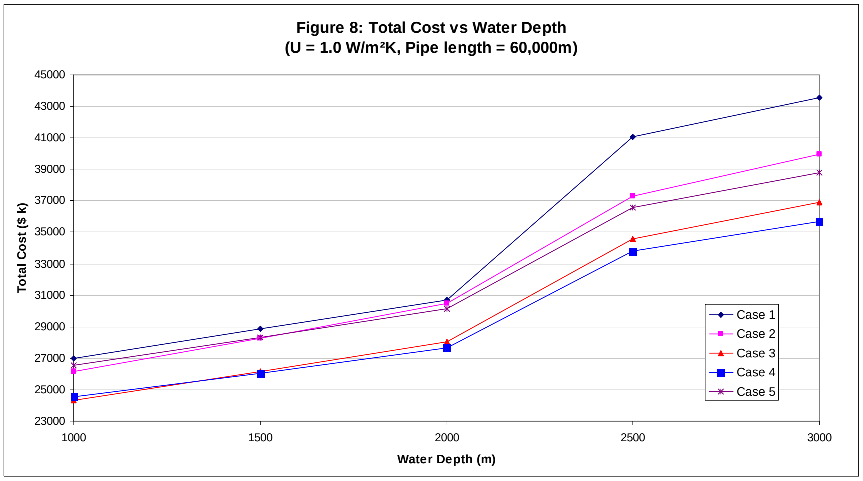


Figure 8: Total Cost vs Water Depth (U = 1.0 W/m²K, Pipe length = 60,000m)

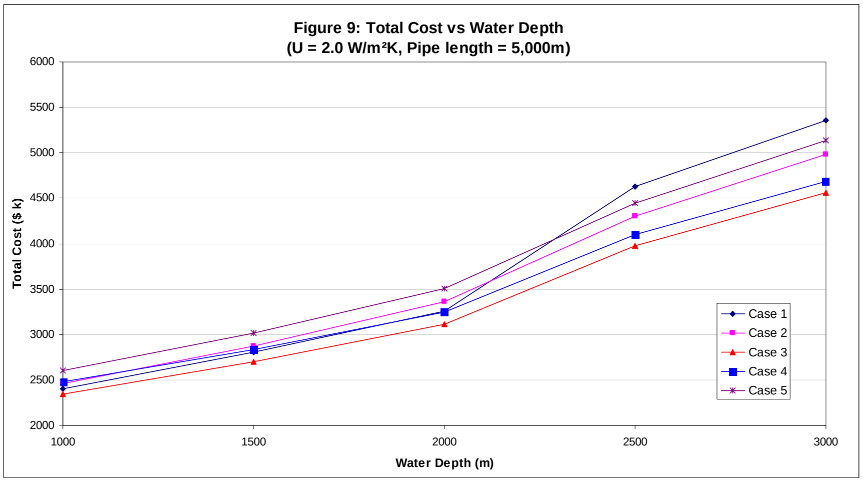


Figure 9: Total Cost vs Water Depth
(U = 2.0 W/m²K, Pipe length = 5,000m)
Total Cost ($ k)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1000
1500
2000
2500
3000
Water Depth (m)
Case 1
Case 2
Case 3
Case 4
Case 5

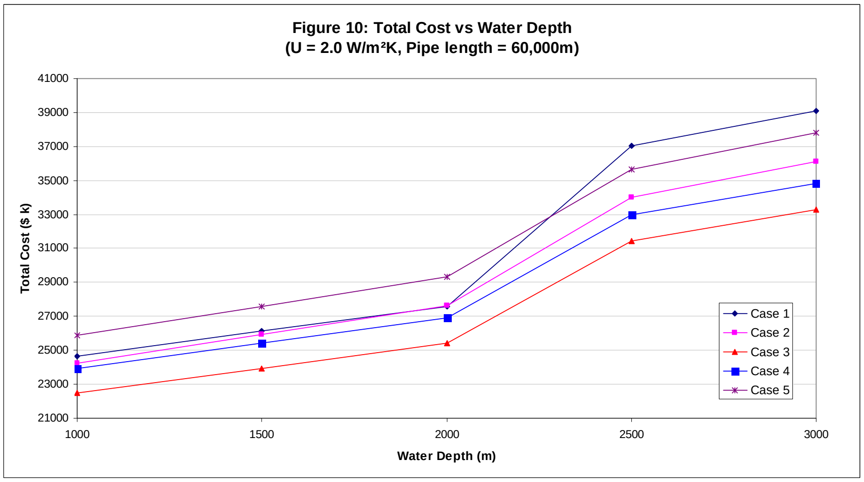


Figure 10: Total Cost vs Water Depth
(U = 2.0 W/m²K, Pipe length = 60,000m)
Total Cost ($ k)
41000
39000
37000
35000
33000
31000
29000
27000
25000
23000
21000
1000
1500
2000
2500
3000
Water Depth (m)
Case 1
Case 2
Case 3
Case 4
Case 5