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DESIGN PARAMETERS FOR SINGLE PIPE THERMAL INSULATION SYSTEMS FOR OFFSHORE FLOW ASSURANCE

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Abstract

Limit state design of subsea thermal insulation systems has been shown to be feasible and robust. This requires careful implementation of extensive long-term laboratory data and property models into verified FEA / FDA tools. Such simulations allow for the determination of not only the steady state response, but also the transient response of the system as a function of temperature, hydrostatic loading, ageing, water ingress and time. This departure from the traditional use of monolithic thermal conductivities, heat capacities and water absorption values can allow in some cases for a reduction in the thickness of insulation, whilst simultaneously enabling control of conservatism. The current paper discusses the important influences affecting the performance of insulant systems and the results of verification testing along with design examples where the generally accepted design method is compared to the limit state approach.

1. Introduction

Client specifications for subsea insulation systems have been limited historically to a consideration of the heat loss per unit area of a given radiant surface (U-value). In many cases however it is not the steady state performance of the system that is the principal driver for insulation, rather the transient behaviour during heating / cooling cycles.

The three main determinants of transient system performance for each component in the system are:

- Thermal conductivity (k-value),
- Density (ρ)
- Specific heat capacity (Cp)

These are conveniently expressed through the thermal diffusivity (ψ) of the insulant.

$$\psi = \frac{K}{(C_P.\rho)} \tag{1}$$

In principle, ψ can be likened to the ratio of storage and loss of energy. The determinants of ψ are dependent on temperature, and thus of the temperature profile within the system at any time. It is important therefore that the design process for transient performance takes this into account, although it must also be remembered that temperature dependency of the k-value also has ramifications for the design of systems based on steady state considerations.

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Thermophysical properties of subsea thermal insulation systems vary with time under the combined effects of pressure, temperature and exposure to water. From the point of view of robust system design it is thus vital to have validated models pertaining to compression, creep and water absorption for those precise materials used in the system, and how the combined effect of these influence k-value, ρ and Cp.

2. Important Influences

2.1 K-value

Although conceptually simple to measure, the accuracy of typical k-value readings is ± 2.5%; this being due to a combination of sample preparation, calibration and measurement skill. Many thermal insulation materials have a k-value which lies in the range 0.11 – 0.25 W/m.K, however standard instrument calibration employs standards with k-values of 0.03 W/m.K and 0.37 W/m.K. Using the low k-value calibration material will bias the measured k-value downward, whilst using the high k-value standard will bias the value upward.

Bredero Shaw has developed calibration materials along with a sample preparation and measurement procedure which allows for the determination of k-values over a wide range of temperatures to an accuracy of ± 0.5% over the 0.1 to 0.25 W/m.K range.

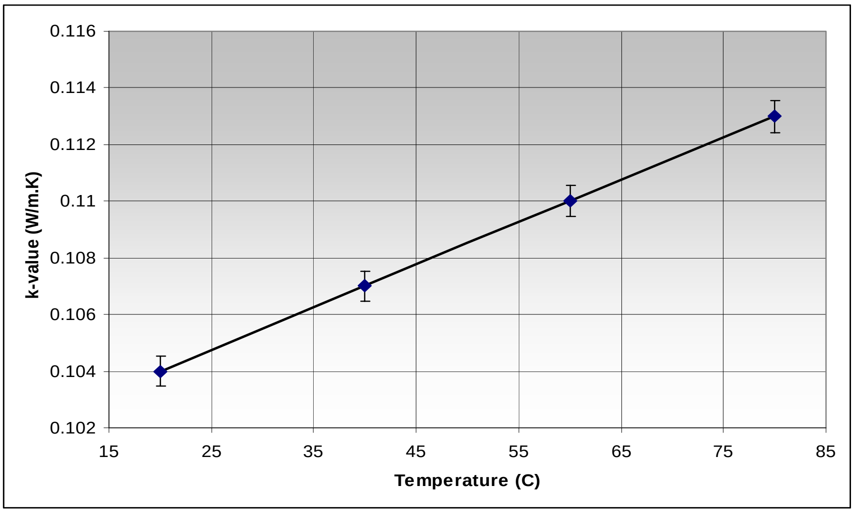

Figure 1. Temperature dependence of k-value for a model syntactic polyurethane

The values obtained from these measurements have been found to be in close agreement with theoretical values calculated from first principles using Bruggemann's and Maxwell's theories. K-values are not universal, and are affected by material chemistry, crystallinity, morphology etc. And must therefore be determined for each material.

2.2 Specific Heat Capacity (Cp)

The Cp of a material may be estimated from the raw materials using a simple linear mass fraction combination.

$$Cp = Cp_1.\gamma_1. + Cp_2.\gamma_2 + Cp_3.\gamma_3 \quad (2)$$

γi = mass fraction of component i
Cpi = Specific heat capacity of component i

Alternatively, the Cp may be determined as a function of temperature directly by the use of differential scanning calorimetry (DSC). The reader is made aware that there can be a significant difference between Cp values for materials within the same chemical family, and that there is a strong dependency of Cp on temperature.

2.3 Water Ingress

All insulation materials will absorb water over time to greater or lesser degrees. The equilibrium water concentration (Co) for a material is the amount of water that will be absorbed by the material at infinite time and the diffusion coefficient (Do) is the rate at which the fluid moves into the material. Both are given for combinations of material and temperature and to a lesser extent pressure. Given Co and Do data it is possible to calculate a water ingress profile at any given time, which reflects the concentration of water at each point in an insulation coating.

Water content has an effect on the k-value of insulation materials. Design must therefore take into account the water ingress profile at the end of the field life, and its effect on the k-value at all points. Water content has also a large effect in the Cp of the material, and corrections have also to be made for this in the case of transient simulations

2.4 Compression, Creep and Densification

During deployment and operation all single pipe insulants are exposed to a hydrostatic loading due either to clamps or the head of water. The response of the coating can be divided into two parts:

•The elastic response – which is recoverable
•The plastic response – which is not recoverable

Clearly it is important to develop models and supporting data in order to address the relative contributions of these two effects on the densification of the coating (and thus change in k-value) and the total thickness change over the life of the field. Bredero Shaw has developed the use of triaxial hydrostatic testing[1] to determine not only initial elastic compression, but also creep mechanisms as a function of temperature and pressure. This is used, together with standard compression and tensile testing to design and verify such changes for the life of the field.

2.5 Hydrostatic Loadings

Robust design of bonded insulation systems requires a firm understanding of the stresses arising within the coating and the response of the insulant material to the applied stress on the outer surface of the coating in terms of compression, creep and, in the case of syntactic materials, the ability of the inclusion to withstand the local stresses. A relationship exists between the thickness of the coating and the amplification of the applied hydrostatic field, effectively increasing the inner stress as the material thickness increases for a given hydrostatic load. Examples can be taken from blown polypropylene foams, solids or syntactic foams.

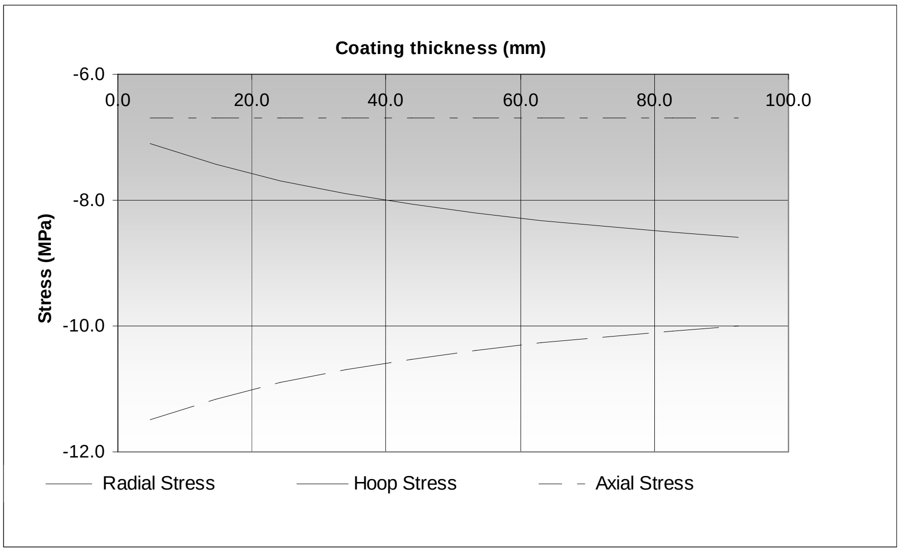

Figure 2: Internal stresses in a model PP foam at 10 MPa external loading.

As can be seen in Figure 2, the radial stress, which is the primary compressive component, increases toward the pipe. For visco-elastic materials robust system design requires a complete understanding of the compressive and creep mechanisms within the product and their stress and temperature dependency. An example of compression and creep mapping generally carried out on blown foams is shown in Figure 3 below.

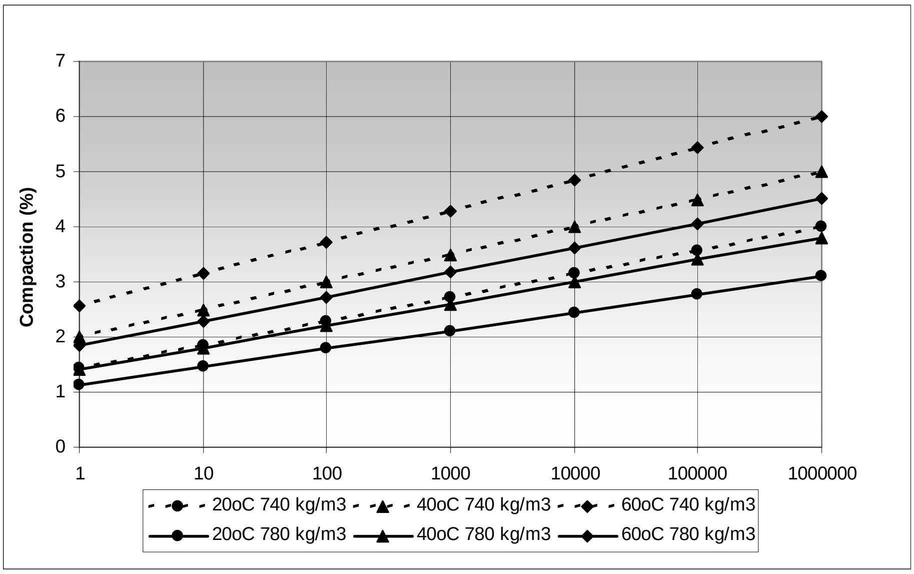

Figure 3: Initial compression and creep as function of temperature and density for a model PP foam

For syntactic materials this effect requires an understanding of the response of the syntactic inclusion (micro-balloon) to the applied stress. Considering the much used S32 micro-balloon, the compression and collapse behaviour for typical production places the 80 – 90% survival rate for the micro-balloons at 14 MPa, and the 70% survival rate as 18 MPa. 30% collapse of beads is of course associated with a significant compression of the material and a large rise in the k-value of the system. In order to design with a reliable product it is desirable to limit the degree of collapse to max. 10% of the microballoons, and as such the maximum allowable internal stress is 14 MPa. As can be seen in Figure 5, this places a thickness related limitation on the maximum allowable thickness for a given hydrostatic loading on the OD of the coating. The dependency of the thickness on max. sustainable hydrostatic loading is increasingly more noticeable for smaller diameter pipes, leading to significant limitations particularly in the case of pips in the 6.625" – 10.75" range, as usually used on subsea processing equipment, manifolds and trees (Figure 4).

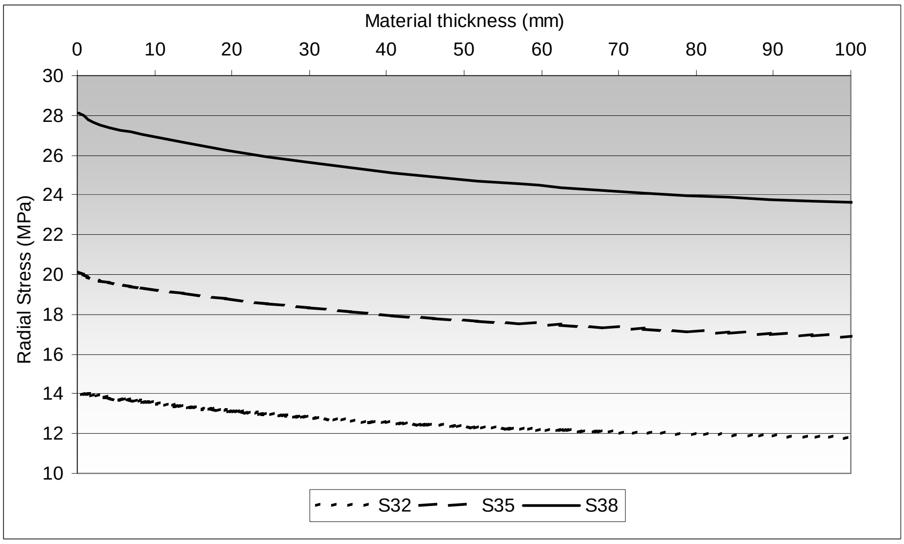

Figure 4: Design curve for S32, S35 and S38 micro-balloon in model PU matrix

This effect has been verified in the simulated service vessel in our own laboratories for an S32 based polyurethane coating at a thickness of 85 mm. Compressive creep was found to stabilise after a short time at pressures up to ca. 12 MPa (120 bar), however at pressures of 13 MPa the coating continued to compress, Figure 5. This is in keeping with the prediction in Figure 5.

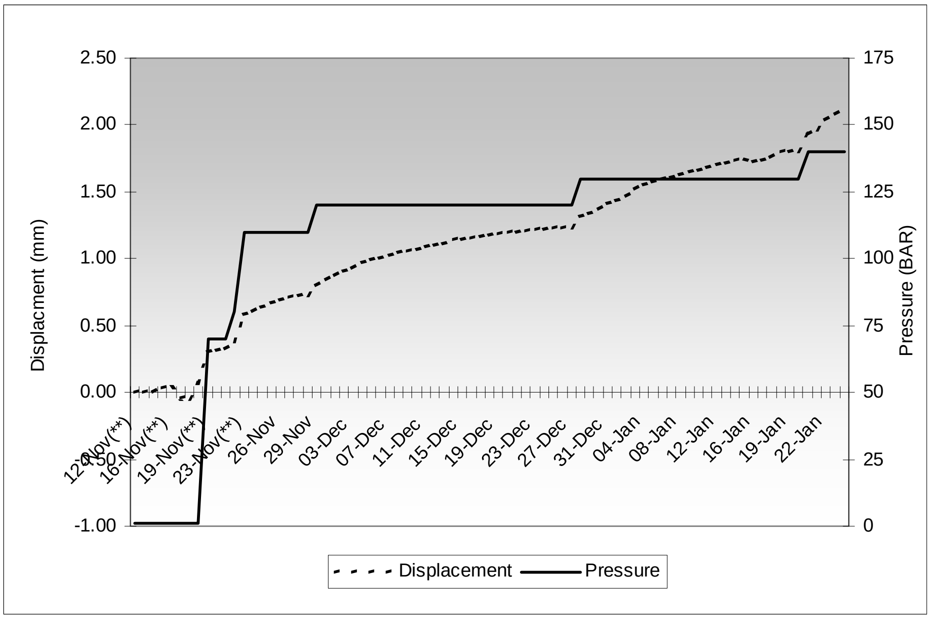

Figure 5: Effect of pressure on 85 mm coating when exposed to increasing pressures

Robust system design is critically dependent on the ability to predict all densification processes and their effect on the thickness and k-value of the system. Large-scale collapse of material is by its nature an unpredictable state, and any design process must ensure that a margin is kept between applied hydrostatic loadings and such states.

3.0 Limit State Design

A limit state is a set of performance criteria that must be met when the structure is loaded a particular way. For the case of single pipe insulation systems this refers to both the thermal and mechanical performance of the system. Design of single pipe thermal insulation systems has been historically quite primitive, and has referred to single values for k-value, Cp and density, and general compression and water uptake data. Moving to a limit state approach based on detailed thermophysical and physical data, and developing the design tool from the normal simple spreadsheet approach to dedicated FEA tools allows for design based on a true description of the system's response to temperature and pressure over time. This approach also allows for the controlled addition of conservatism, improved reliability of the design process, and in most cases a reduction in system costs. Many parallel trials with system design and system verification using "Simulated Service" testing have been performed, with a high level of agreement between theoretical and practical performance being demonstrated.

3.1 Design Example

A system is specified which should have the following performance characteristics.

- Pipe OD = 273.1 mm, wall thickness 20.6 mm
- UID= 2.8 W/m^{2}K
- Length 10 km
- Operation temperature = 85^{o}C
- Water depth = 1200m
- Sea water temperature = 4^{o}C
- Start temperature for cool down = 48^{o}C
- Minimum temperature = 22^{o}C
- Required cool down time = 12 hours
- Field life 20 years
- Fluid density = 17.5 kg/m^3, Cp = 2400 J/kg.K

3.1.1 Spreadsheet Design Method

For this example the system chosen is a generic glass syntactic polyurethane (GSPU) with the following characteristics:

- Single point ”dry” k-value = 0.15 W/m.K
- Single point Cp = 1700 J/kg.K
- Density = 800 kg/m^3
- Compression = 2%
- Water absorption 8%
- Wet k-value 0.165 W/m.K

U-value required 94 mm of coating
Cool down requires 100 mm

3.1.2 Limit State Method

- K-value = 0.145 to 0.2 W/m.K
- Cp = 1540 to 1751 J/kg.K
- Density = 800 to 833 kg/m^3
- Co = 8%, Do = 0.001mm^2/day
- Compression according to applied load (1.5% in this case)

U-value required 86 mm of coating
Cool down requires 92 mm

•If U-value is the driving force the thickness may be reduced by 8 mm (45 m^3 / 3.6 tons of material) using a limit state approach.
•If cool down is the driving force the thickness may be reduced by 8 mm (46 m^3 3.68 tons of material) using a limit state approach.

3.2 System Optimisation for Transient Performance.

As the U-value is not always the driving force for design, it is frequently of interest to optimise systems for transient performance. Using the limit state approach it is possible to derive systems with significantly improved performance. Considering an 10.75” OD pipe, 14.3 mm wall thickness. Cool down driven with a 12 hour requirement from 48°C – 18°C, 66 mm of an engineered proprietary multilayer polypropylene system is required, against 72 mm for a system designed using standard methods. In this case this is the difference between seabed stability and pipeline buoyancy, thus obviating the need for weight coatings.

4.0 Typical FEA Limit State Tool Output

Several plots are generated during the simulation process, including through thickness k-value in dry, compressed, and wet/ compressed states, compression and accumulated creep, cool down profile, water ingress profile, through thickness heat capacity profile etc. Some examples are shown below in Figures 6 to 8 below.

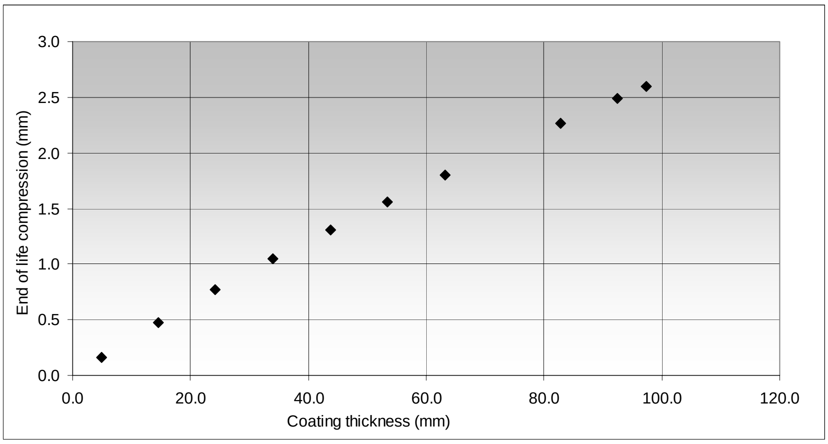

Figure 6: Compression & creep ogive.

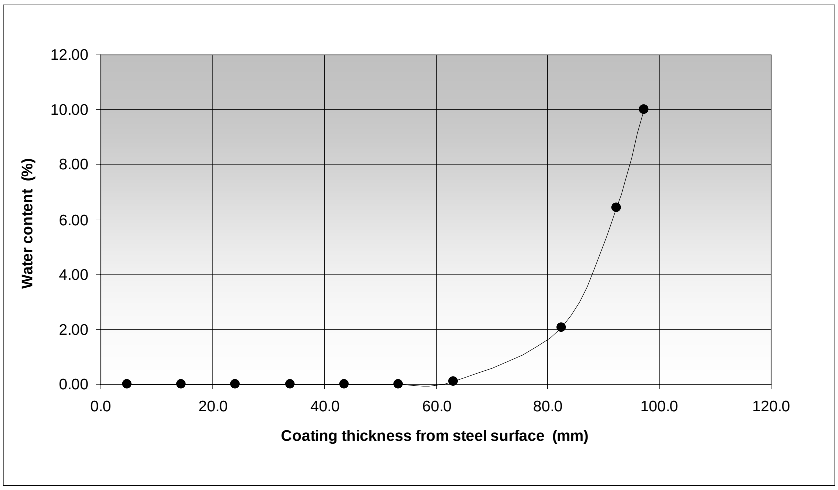

Figure 7: Water absorption after 20 years.

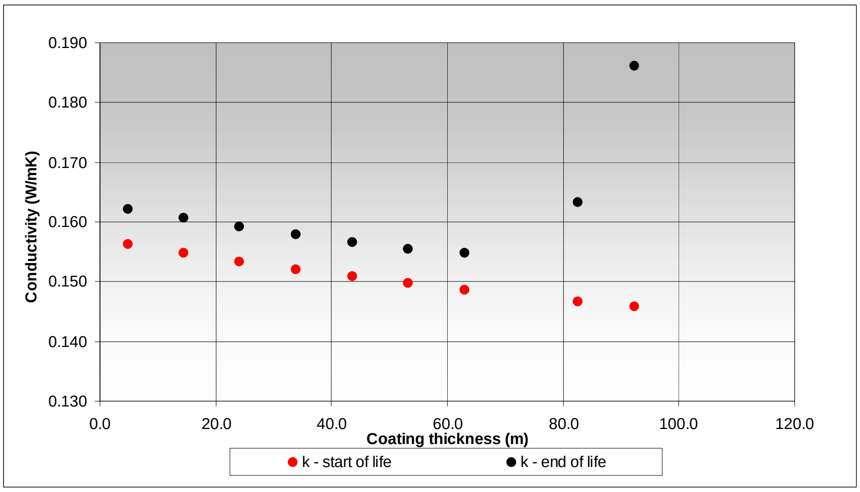

Figure 8: k-value uncompressed and dry, and compressed and wet

5.0 From Theory To Practice

The efficacy of the limit state design basis is demonstrated by the excellent agreement of systems modelled from first principles, based on laboratory data for the raw materials, and the results of Simulated Service testing. Considering a generic GSPU material based on S32 glass, with a 45 vol% fraction of beads, the theoretical temperature dependence of the insulant k-value is as shown in Figure 9.

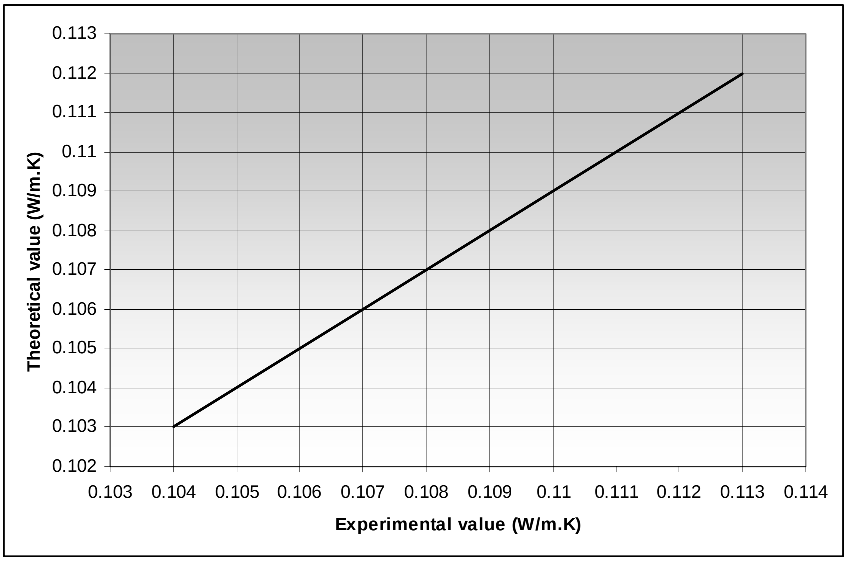

Figure 9: Theoretically determined k-values for a generic GSPU.

Based on the limit state approach 50 mm of GSPU on the OD of a 10.75" pipe would yield a U_{OD}-value of 3.64 W/m^2K for the initial period of pipeline operation with an internal temperature of 85^oC and an external temperature of 11^oC at 120 bar. Simulated service tests, performed on 50 mm of insulant under identical conditions indicate a normal heat flux from the surface of the pipe of -232 W, corresponding to a U-value of 3.66 W/m^2K**.**

The agreement between theory and practice is close, especially given the inherent inaccuracy of simulated service testing.

6.0 Advantages Of The Limit State Approach

- Extensive laboratory testing data for materials and systems,
- Models describing the response of the material's and system's thermophysical properties to applied thermal and hydrostatic loads.
- Ability to introduce controlled conservatism
- Verified FEA model where material response models are combined and allow for a determination of the thermophysical parameters at all points in the system.
- Ability to understand the thermal dynamic in different scenaria.
- Stable transparent and auditable design rationale.
- Utilising the potential in the system, rather than just the insulant
- Potential to reduce material usage and save cost
- Ability to create optimised thermal systems at a high level of confidence.

7.0 Acknowledgement

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8.0 References

[1] BOYE-HANSEN, A. AND FRIBERG, R. Thermal Insulation Of Non-Jacketed Deep-Water Flowlines And Risers Based On Mobile Manufacturing Units, Rio Oil & Gas Expo and Conference, Rio de Janeiro October 2000.