

# High performance polypropylene thermal insulation for high temperature and deep water applications

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## **ABSTRACT**

Flow assurance including thermal insulation are critical elements in the design and operation of flowlines and risers in deep waters due to a combination of high temperatures, high pressures and economic drivers for high availability. The stringent requirements put new challenges on insulation systems and the paper will discuss a suitable polypropylene insulation system that can meet these requirements. This paper addresses the development of material systems, manufacturing processes, qualification schemes and review design methodology to meet the requirements imposed on a wet insulation system for the most challenging deep water project to date. Associated discussion topics include coating of heavy wall pipes.

## **1 INTRODUCTION**

Over the past ten years, thermal insulation of subsea flowlines and risers has become increasingly important. With the advent of multi-phase flow in flowlines and risers from subsea completions, possibilities of wax and hydrate formation prevailed. Thermal insulation is used to prevent hydrate and wax formation during shutdowns and to maintain the fluid temperature inside the flowlines for easier fluid separation topsides or onshore.

For single pipe flowlines and risers, the mechanical loads as well as the thermal insulation requirements normally increase with deeper waters. Hence, the traditional thermal insulation foam technology used in shallow waters and the associated design and test methodology may not be applicable to deep-water projects.

The mechanical and thermal properties of polymer foams vary as a function of foam density. Higher density normally means better mechanical properties and reduced density improves insulation capacity. This is also true in the case of foams for subsea applications, where the increased hydrostatic head associated with deeper waters calls for higher compressive strength and better creep properties of the PP-foam. Higher compressive strength also improves creep characteristics and can be attributed to higher polymer stiffness and the final foam structure.

For deep-water thermal designs, this could lead to build up of excessively thick coatings that may cause manufacturing concerns as well as reducing installation vessel capacity. In addition, excessive coating thickness may reduce seabed stability for the flowline and increase drag forces on a steel catenary riser (SCR).

Combining a stiff linear copolymer polypropylene (PP) with a branched homopolymer PP, the benefits of high melt strength and high melt elongation result in excellent foam quality, characterised by evenly distributed bubbles with a closed cell bubble structure in the pipe foam layer. This leads to both higher compressive strength and improved creep resistance. At the same time, this novel combination of polypropylene technology retains tensile properties and impact resistance.

By combining the unique PP foam properties stemming from a combination of material characteristics and processing techniques with a strain based design methodology, this PP foam can be deployed in deep waters as will be described in this paper.

## **2 MATERIAL DEVELOPMENT AND CHARACTERISTICS**

### **2.1 Characteristics of High melt strength PP**

High melt strength combined with improved melt elongation are the main characteristics for the branched homopolymer called HMS-PP. A long-chain branched polymer is introduced into the PP, thus improving foaming conditions. Because of the polymer modifications, controlled bubble growth can be observed, leading to stable foam with a uniform closed-cell foam structure. Combining HMS with other PP grades and proper extrusion and mixing, considerably improved foam structures can be produced.

## 2.2 Characteristics of Stiff Polypropylene

A branched homopolymer will by chemical nature show more brittle behaviour than regular PP grades. For the overall mechanical properties to match all requirements during manufacturing, installation and operation, a high stiffness co-polymer PP is mixed with the HMS polymer. In general, the stiff PP shows the following properties compared to a regular grade (see Table 1).

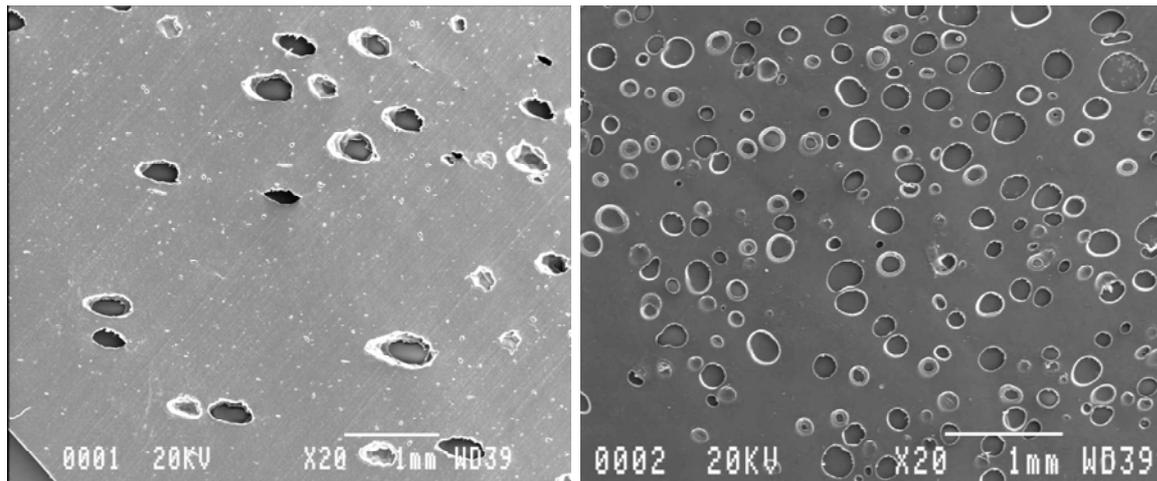
**Table 1 Typical Stiff PP Property Differences**

PROPERTIES	TYPICAL PP GRADE	NEW PP GRADE
Thermal Conductivity (W/m <sup>°K</sup> )	0,22	0,23
Tensile stress at yield (50 mm/min), MPa	28	31
Tensile strain at yield (50 mm/min), MPa	6	8
Flexural Modulus (2 mm/min), MPa	1300	1750

Therefore, combining the high stiffness PP and the branched PP, the mixture exhibits the following properties compared to traditional structural PP foam:

- High melt strength,
- High melt elongation
- Finer foam cell structure (see Figure 1)
- Higher stiffness and better creep resistance

These characteristics are also strongly linked to the extrusion process and subsequent die design and morphology. By discharging the polymer melt into an annulus the bubble growth and formation of foam cells can be better controlled than if the melt is applied onto the pipe by means of wrapping.



**Figure 1 Standard PP foam on left and improved foam on right**

The SEM photomicrographs in Figure 1 represent the same foam density; however, mechanical properties are improved. Use of the improved mechanical properties and strain

based design, makes it possible to deploy closed cell PP foam in water depths beyond 1500 meters.

**Table 2 Mechanical Properties Comparison**

PARAMETER	REFERENCE FOAM	NOVEL PP FOAM
Density (kg/m <sup>3</sup> )	820	650
Tensile Stress @ yield (MPa)	16	13
Tensile Strain @ break (%)	65	26
Young's Modulus (MPa)	800	830
Compression Modulus (MPa)	480	470
Thermal conductivity (W/m °K)	0,20	0,16

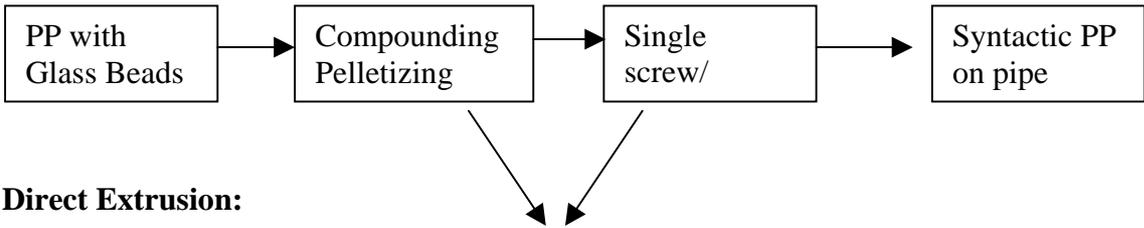
Durability is also an important feature. Creep is the dominant mechanism that governs the long-term properties. PP shows typical visco-elastic behaviour, where short-term deformation relates to the elastic behaviour of the foam (recoverable deformation) and long-term deformation relates to viscous behaviour (non-recoverable deformation). With improved elasticity in the novel foam, long-term creep resistance of the novel foam is better than the reference foam.

**2.2 Syntactic Polypropylene (SPP)**

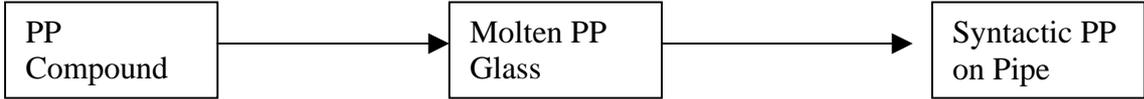
SPP is a filled compound where the filler is hollow glass microspheres. Syntactic polypropylene has been used in the offshore industry since 1995, when Shell selected this product for the Mars steel catenary riser (SCR) insulation. Up until approx. two years ago, all of the executed projects relied on applying ready made SPP.

However, the need to reduce thermal history (reduce material degradation) imposed on SPP compounds and drivers to reduce costs, led to development of a mobile turnkey compounding plant for this process (2).

**Extrusion from Pellets:**



**Direct Extrusion:**



**Figure 2 Schematic of Direct Extrusion vs. Pellets Extrusion**

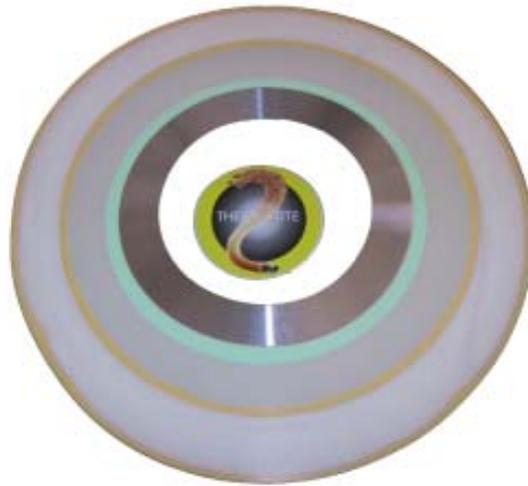
Main characteristics of the syntactic PP are compressive and creep behaviour similar to solid PP, lower k-value than solid PP reduces thickness (typical 22% less than solid PP), and SPP can be used as a thermal barrier.

Hollow glass microspheres are fragile and susceptible to point loads. Although the hydrostatic crush strength in many cases exceed the needs related to serviced water depths, broken

spheres as a result of loads in the process may deteriorate mechanical and thermal properties of the final compound. These loads include capillary pressure effects, shear, excessive glass loading rate, sinkers from microsphere production, and on-line change of melt behaviour.

## 2 MANUFACTURING PROCESSES

Schematically, Figure 3 shows a typical deep water insulation system build-up.



**Figure 3 Multi-Layer PP Insulation System**

Such a system relies on use of solid PP as thermal barrier, syntactic PP as thermal barrier and insulation and closed cell foamed PP as insulation system. Layer thickness will be determined by the thermal gradient through the coating thickness and subsequent exposure temperatures. As an example, this would typically expose the SPP to temperatures higher than 100°C at 1500 – 2500 meter water depth and the closed cell foam to maximum 40 – 60 °C. This will be closer discussed in the design section of this paper.

Such exposure temperatures in combination with external pressures in the actual service means that proper care has to be taken when selecting resin candidates and material combinations for both the SPP and the closed cell foam.

Table 3 shows the different parameters that distinguish and compare processing of the SPP and the closed cell PP foam.

**Table 3 Process Characteristics**

ITEM	SPP	CLOSED CELL FOAM
Melt strength	Poor	Good
Die Swell	Low	High
Die pressure	Medium	High
Melt Viscosity	High	Medium
Melt Temperature	High	Medium
Shear sensitivity	High	Medium

## 4 QUALIFICATION SCHEMES

In order to qualify the PP-foam for water depths down to 2000 metres, a rigorous qualification program was developed and performed to meet the defined performance criteria. The main objectives for the qualification program have been:

- ✓ To qualify the insulation system for subsea use
- ✓ To develop data for service life prediction (small scale and full scale)
- ✓ To use the generated data for design and engineering of thermal insulation systems for deep water service

The overall philosophy has been to execute the program so the loads reflecting the actual conditions on the insulation coating and establish acceptance criteria. Performed tests reflect loads during:

- ✓ Manufacturing,
- ✓ Storage (Stacking of Pipes),
- ✓ Installation (e.g. reeling), and
- ✓ Operation.

Framework for the qualification was existing international standards for polymers and foams as well as established procedures, requirements and specifications defined by operators and the manufacturer. In many instances, the InSpec Specifications and Recommended Practice form the basis for qualifying new products and systems.

### 4.1 Governing Deterioration

For the two distinct PP qualities described in this paper, it is extremely important to recognize the intrinsic properties that may reduce performance over time, and that needs to be compensated for in the design as described below.

#### 4.1.1 *Matrix Candidates for Syntactic PP*

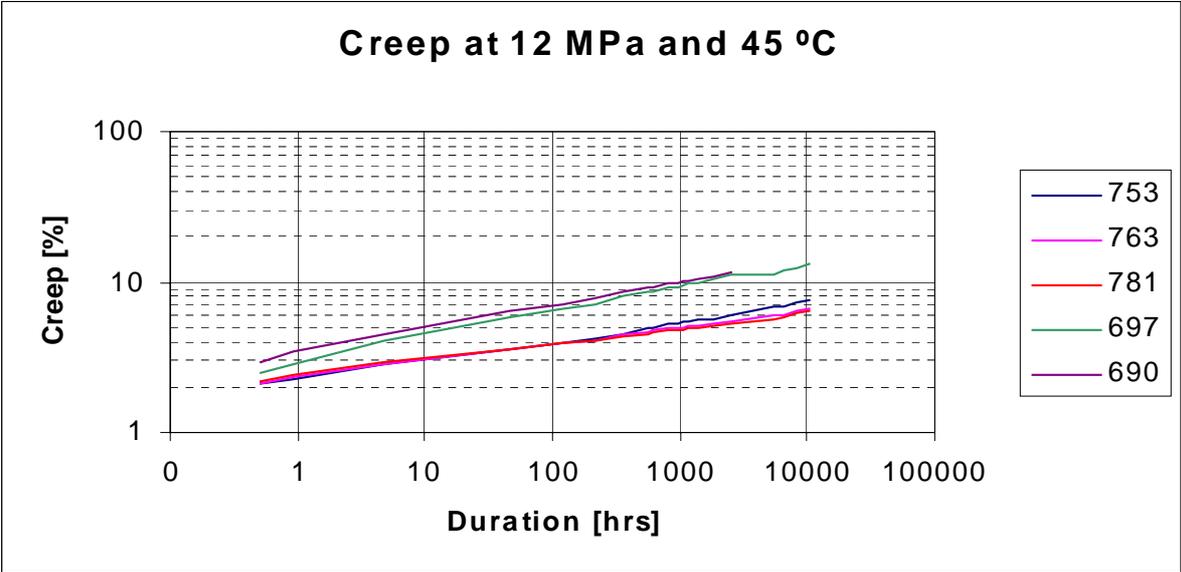
Although the SPP grades in many cases behave as solid materials (limited creep), there will be inherent capacity in different matrix PP materials that may limit the possibility use one single grade for all combinations of service temperature and water depth. As inclusion of hollow glass microspheres is not straight forward, resin modifications may be necessary. Such modifications may limit depth and/or temperature rating as modifying resins change mechanical and thermal properties. Applying the tri-axial creep test method and determine possible extrusion can screen such difference in properties.

#### 4.1.2 *Closed Cell PP-Foam*

The most critical parameter when designing with the visco-elastic behaviour of plastics is associated with creep. Creep in the foamed structures relates both to water depth (hydrostatic pressure) and the associated temperature gradient. The temperature gradient is dependent on layer thickness, thermal conductivity of each layer and internal and external fluid temperatures.

Creep is the most important long-term design consideration, as creep will result in changes of the insulation properties over time. Creep in foamed structures will produce an increase in density, which in turn will increase the thermal conductivity. Hence, it is important to understand the creep mechanisms in the foam and use these mechanisms in the design stages and compensate for this creep in the design.

Secondly, it is important to characterise the actual compressive load that the foam will experience during in-service conditions. On the pipe, the foam benefits from support axially and tangentially. Therefore, the creep will show as radial displacement of the PP-foam. Figure 4 shows results from a 10000 hour creep test. Such a long-term test will reveal any signs of secondary or tertiary creep and further document the long-term durability.



**Figure 4. Long Term Durability Tests**

As can be seen from these tests plotted above, general recommendations for deep waters (> 1000 meters), foam densities would typically be above 700 kg/m<sup>3</sup>.

**5 DESIGN METHODOLOGY**

System design of subsea thermal insulation systems with foamed materials requires detailed knowledge of the relationship between compressive strength and temperature, and the temperature dependency of creep. Although the initial compressive response of the system can conveniently be measured for a given set of operating conditions in a simulated service test, such testing is relatively short term, and does not provide reliable information concerning

creep. For this reason it has become now common practice within Bredero Shaw to perform long term (>5,000 hours) tri-axial compression and creep testing in addition to standard uniaxial tests when qualifying new products as well as a benchmark for durability.. Using this approach, the compressive creep rate is established under geometrically realistic conditions. Armed with such knowledge, and in combination with correctly calibrated FEA design tools it is possible to derive limit state system designs to meet both transient and steady state performance requirements at the end of the design field life. A good knowledge of the response of the system to hydrostatic loading at temperature also allows for the determination of layer thicknesses for individual materials in the system such as sPP and PP foam, such that reliability and system cost are optimised.

The thermal and hydrostatic aspects of insulation coating are designed using appropriate physical laws representing the conditions at the seabed, and using material geometries and thermophysical properties describing the start and modeled end of life conditions. Effects of possible degradation mechanisms on the thermophysical aspects of the system such as water ingress are factored into the design using appropriate functions, fitted to long-term experimental data. The mechanical response to temperature and pressure are inextricable from a design standpoint, and are in essence calculated simultaneously in an integrated mechanical / thermal FEA model.

The methodology used for simulating the mechanical response is to construct and discretise an initial multi-layer model, and to apply temperature dependent stress-strain and creep laws into each node. For each time step the combined effects of the hydrostatic and thermal loading are calculated and these effects translated into densification of the coating, changes in thermophysical properties and changes in geometry. A new through thickness temperature profile is calculated, and this is then used in the next time step. This process is repeated until the end of life situation is achieved. The mechanical calculation is subsequently verified against the results of triaxial compression and creep testing in order to ensure that a rational solution has been derived. It is important to use the temperature dependent moduli of materials, as their response is dependent not only on the absolute values of the internal and external temperature, but also the through thickness temperature profile.

The heat transfer equation is solved numerically using an implicit finite difference scheme. The following equation details the solution of the finite difference equation for a transient heat conduction problem in multidimensional directions.

$$C_i \frac{T_i^{k+1} - T_i^k}{\Delta t} = \sum_n \frac{T_n^{k+1} - T_i^{k+1}}{R_{ni}} + \dot{Q}_i \Delta V_i$$

Where

- T = Temperature,
- C<sub>i</sub> =Energy capacitance,
- R =Resistance,
- i =Volume element,
- n = number of dimensions,
- k = time step

The pipe geometry is discretised into a network of small finite volume elements. The above equation is applied to each of the element. Matrix-inversion is used to solve the system of implicit numerical equations that constitutes the pipe geometry.

A reciprocal U-value is found by adding all the subsequent layer resistances, for which the following formula applies:

$$U = \frac{1}{\pi \cdot OD \cdot R_{total}}$$

Where:

$R_{total}$  = Thermal serial resistance from the inside of the coating to the outside of the coating

$OD$  = Reference diameter for the U-value

$U_i$  = Heat transfer coefficient of the layer relative to the referenced surface.

It has formerly been practice within the subsea thermal insulation industry to use single figure thermal conductivities and heat capacities; however there has been a movement away from this practice in certain cases, including now the temperature dependence of these important factors. This allows for a more rigorous description of the thermal performance of the system. Transient state performance is calculated based on the end of life system, using the appropriately modified geometries and thermophysical properties.

## 6. CONCLUSIONS

1. The PP system described in this paper was selected for the most extreme combination of water depth and temperature (2200 meter/132 °C) as insulation material in the GoM.
2. With the use of closed cell foam and appropriate limit state design methodology, PP foam can be used down to water depths of around 2000 meters.
3. Careful consideration must be taken when selecting proper matrix candidates for syntactic PP.
4. The technology and design approach described herein can be further extended into shallow water applications.
5. Economics are attractive for a system composed of a syntactic and closed cell foam as described in this paper, relative to other systems.

## 7 REFERENCES

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