OTC 14121

# Development and Qualification of Novel Thermal Insulation Systems for Deepwater Flowlines and Risers based on Polypropylene

Allan Boye Hansen/Bredero Price Norway (Thermotite) and Cecilia Rydin/Borealis AB



This paper was prepared for presentation at the 2002 Offshore Technology Conference held in Houston, Texas U.S.A., 6–9 May 2002.



## 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 low 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 insulation system that can meet these requirements.

## 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[1].

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.

Polymer foams change mechanical and thermal properties as a function of foam density. Higher density normally means better mechanical properties and reduced density improves insulation capacity. 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 on a steel catenary riser (SCR).

The paper will describe the development and qualification related to a novel deep water thermal insulation system for single pipe flowlines and risers based on polypropylene (PP). Included items are materials development, design methodology and test methods, qualification tests and a brief description of the first installation of this system in the Gulf of Mexico. Figure 1 shows a typical build-up of such a thermal insulation system.

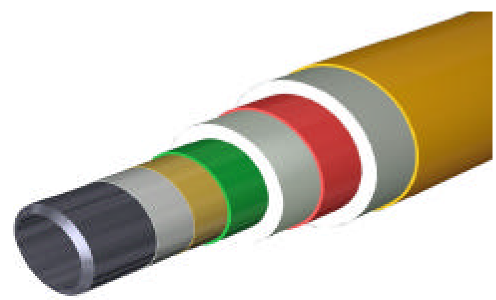

**Figure 1. Thermal Insulation System for Single Flowline**

**Performance Requirements**

The development program defined a set of performance criteria for the insulation coating. These requirements are shown in Table 1. Relevant aspects related to the different load scenarios for installation and operation were defined in the functional requirements. Reeling produces the highest stress and strain in the coating during installation, especially below 0°C and this was the selected installation method for qualification.

## Materials Development

As described in the introduction, the foaming process of polymers generally lead to a trade-off between mechanical properties and thermal insulation properties. The increased hydrostatic head associated with deeper waters calls for higher compressive strength of the PP-foam. Higher compressive strength also improves creep characteristics and can generally be attributed to higher polymer stiffness and the final foam structure.

**Polypropylene Block Copolymers**

The new generation PP materials are based on a unique balance between stiffness, toughness and good long-term creep resistance. This heterophasic PP material is a highly crystalline material with a finely distributed and dispersed ethylene- polypropylene rubber phase. Good mechanical properties are shown over a wide temperature range, in addition to high abrasion and good chemical resistance.[2]

**High Melt Strength Polypropylene polymers (HMS-PP)**

High strength combined with improved melt elongation are the main characteristics for 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. Because of the loads introduced by extrusion, improving melt strength and melt elongation considerably improves foam make-up.[3]

By combining a stiff linear copolymer polypropylene with an HMS-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 compression strength and improved creep resistance.[4]

**Foam Structure and SEM Characterization**

A foam based on the material combination of stiff PP and HMS-PP contains bubbles that are smaller and more evenly distributed in the foam layer. High melt elongation effects both foam stability and foam structure, seen as even bubble size and distribution throughout the pipe insulation layer.

The difference in foam structure is illustrated in Figures 2a and 2b, where foam from a reference PP copolymer is compared to the novel PP, in a scanning electron microscope (SEM) photography of a foamed cross-section. High melt strength allows improved stability and foaming closer to the outer surface of the pipe. This is seen in the SEM photograph, where the lower left-hand corner corresponds to the outer surface of the pipe.

The foam structure is directly correlated to the mechanical strength of the foam and is therefore a valuable tool when evaluating the mechanical properties.

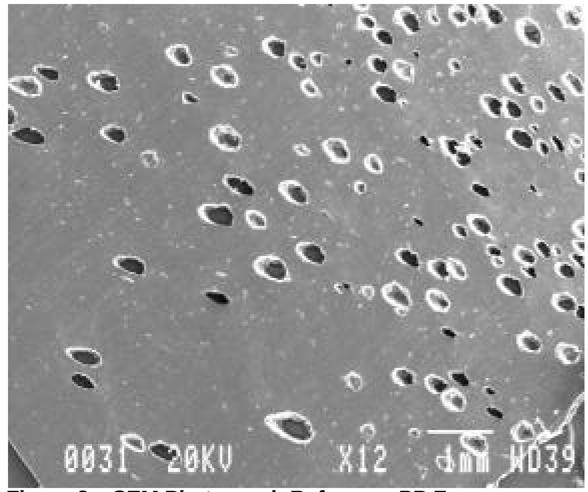


**Figure 2a. SEM Photograph Reference PP Foam**

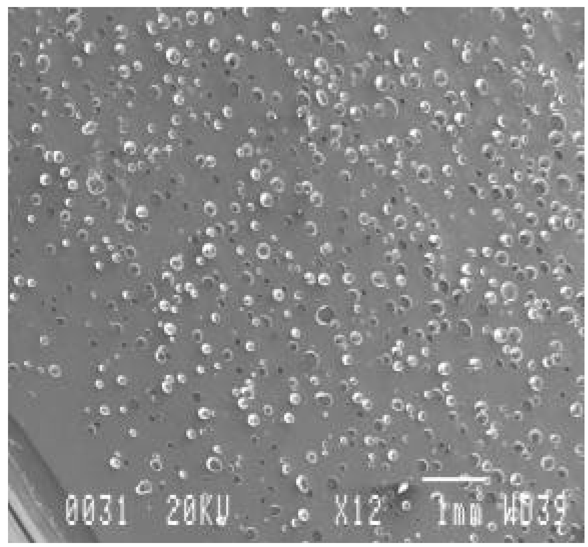


**Figure 2b. SEM Photograph Novel PP Foam**

## Test and Design Methodology

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.

The current standard in the industry calls for determining the compressive strength of at 5% strain, e.g. ASTM D695M.

Use of this standard encompasses testing of rods machined from the PP-foamed structure. These rods are then exposed to a compressive load unsupported. Hence, the rods will displace the load axially, radially and tangentially. This will produce extremely conservative results and does not produce valid data regarding actual behaviour on a pipe.

Also, there exist test methods that calls for hydrostatic compression of small-scale samples. In most cases, this introduce full hydrostatic loads in all three directions on the sample and again not providing actual means for introducing stresses and strains equivalent to actual applications.

Therefore, a new tri-axial test methodology is developed in close collaboration with SINTEF (Center for Industrial and Technical Research). Below is a summary of this development.

By using the Finite Element program ANSYS, the stresses in a submerged flowline have been studied. Figure 3 shows the principal stress direction and the calculated average stress values in the foam for a submerged pipe at 2000 meter water depth. Also, the figures compare the calculated stress levels for three typical small-scale test methods. The stress levels are shown for (A), which is equivalent to the uni-axial compressive strength test method as described in ASTM D695, (B) represents the stress for the tri-axial creep test and (C) shows the stress levels for a hydrostatic test case.

Tri-axial creep test provides conservative results compared to a simulated service test as the test is carried out on cylindrical specimen, machined to tight tolerances to fit into the autoclaves. Differences in test results between the tri-axial creep test and a full scale simulated service test can be attributed to the coating hoop stiffness and the wedge effect (decrease in coating diameter towards steel pipe).

The tri-axial cylinder creep test seems to be the small-scale test that provides the most correct state of stress and at the same time a conservative compression estimate.

**Test Method Description**

A photography of the tri-axial creep test method developed in this project is shown in Figure 4. A lubricating mixture of silicon grease and water entrapped along the specimen surface ensures a low friction between the cylinder wall and the PP-foam test specimen. Friction is easily controlled and held at a minimum by rotating the cylinder wall relative to the test specimen.[5]

**Limit State Design**

Commonly used design practice in the industry would allow the use of safety factors as has been applied to steel pipe design in the past. As an example, the use of a uni-axial compressive strength test according to ASTM D695 and a safety factor of two would normally mean that PP foam would not be deployed deeper than approximately 600 meter water depth. However, this design approach does not reflect the visco-elastic behaviour of PP foam, nor does it reflect on-pipe behaviour, or shows performance changes with time, pressure and temperature.

As creep is the major criterion when designing with the PP systems, the use of limit state design is most applicable when performing a design with the PP system. Although this approach requires a detailed understanding of the foam behaviour as a function of foam density, hydrostatic pressure, temperature and time, this design philosophy reflect the structural response to an actual load scenario and will not produce overly conservative designs.

With the limit state design philosophy, PP foam are currently used in water depths down to 1450 meters in the Gulf of Mexico.

## Qualification Program and Test Results

In order to qualify the PP-foam for water depths down to 2000 metres, a rigourous 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
- Establish operator acceptance and deploy the first commercial installation

The overall philosophy has been to execute the program so those loads reflect 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. Because of the novelty in the product, the manufacturer also developed special test equipment and test procedures to perform the creep tests as described in earlier sections of the paper.

Most qualification tests were executed in close collaboration with third party institutes such as Heriot-Watt University, DnV, and SINTEF.

The raw material supplier also performed several qualification tests related to materials characterization.

### Ageing Tests

All polymeric products experience degradation reactions in the presence of oxygen. The main factors to influencing polymer degradation are concentration of oxygen and exposure to heat and light. To be able to use polymers in an application over years of service, it is very important to understand the degradation mechanism and its prevention.

To prevent degradation the polymer must be stabilised so it is effectively protected during processing, transport, storage, installation and operation. An advanced stabilisation package has therefore been developed to meet both short-term and long-term thermal stability requirements for offshore pipeline applications.

Long-term thermal stability of PP coating materials have been evaluated through a series of oven ageing tests. Degradation of PP because of thermal stability is a key issue when elevated temperatures are combined with presence of oxygen. Thermal insulation coatings on flowlines and risers have limited exposure to oxygen; therefore, degradation slows down in such an environment. To simulate the environment for these subsea flowlines, oven tests have been carried out in an inert atmosphere (circulated nitrogen). In parallell oven ageing tests in circulated air have been performed according to standard methods, shown in Table 2.[6]

### Mechanical Tests

The mechanical strength of the foamed pipe coating for the newly developed PP materials compared to the reference PP foam is summarised in Table 3. The increased stiffness of the new PP materials clearly reflects the mechanical properties of the foam. By increasing the stiffness (tensile modulus) by 40% the compression strength increase from 13 to 19 MPa, measured by uniaxial compression of 5% according to ASTM D695. This improvement in compression strength is valid although the density for the novel PP foam is lower than the reference foam. This means that both compression strength and thermal insulation capacity is improved for the novel foam. With equivalent densities, the novel foam has an improved compression strength of 80% compared to the reference foam, shown in Figure 5.

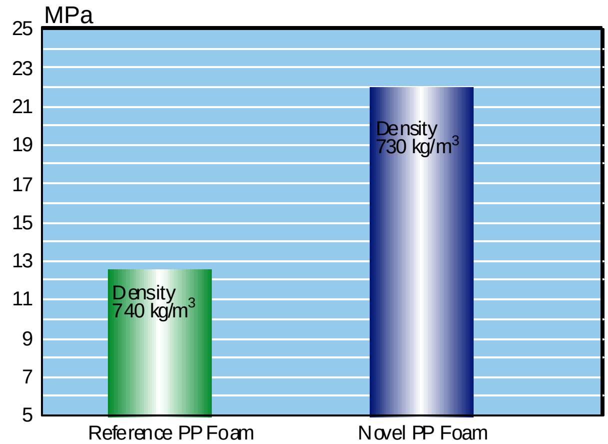

**Figure 5. Compressive Strength @ 5% Strain Comparison**

The improved creep resistance can be attributed to the increase in both the tensile and compression modulus, as seen in Table 3. Long-term creep tests with the tri-axial method are currently ongoing. An extrapolation of the results in Figure 6 indicates that the total compression and creep at 12 MPa (1200 meters water depth) at 20 °C will be 7,7 % after 20 years.

The homogeneity of the foam structure is of main importance to reach an even insulation layer and thereby optimal mechanical properties of the pipe coating. The most important factors to reach a uniform foam structure are the material selection in combination with optimal process parameters during pipe coating manufacturing.

### Thermal Conductivity

Thermal conductivity represents a key property for insulation foams. Lower k-values mean improved insulation and reduced layer thickness and costs. Although the base polymer for the novel PP insulation system has slightly higher thermal conductivity than the original PP (0,23 W/m °K versus 0,22 W/m °K), the improved mechanical properties of the novel foam improve also improve the insualtion properties in deep water. Figure 7 is a plot of thermal conductivity (k-value) vs. uni-axial compressive strength for the novel PP foam and the reference PP-foam.

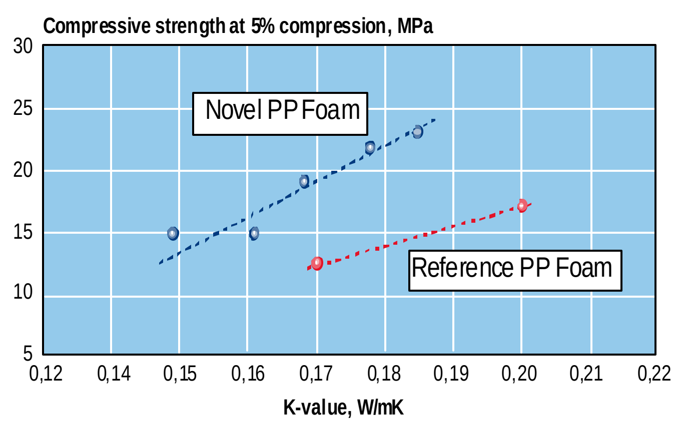

**Figure 7. Thermal Conductivity vs, Compressive Strength**

**Bending Tests**

Bending tests were performed to determine suitability for two different conditions:

- Suitability for reeling (static bending test)
- Suitability for use on steel catenary risers (dynamic bending test)

Tests include field joints and results show that the PP insulation system is well suited for reeling and for use on SCRs.[7]

**Simulated Service Tests**

This test comprises of inserting a coated section of pipe in an autoclave and pressurising the system to the working hydraulic pressure. The pipe then has hot oil passed through the bore and the external pressurised water is kept at a steady low temperature in line with seabed temperatures. Sensors are attached to the coating to monitor the heat flux and the compression of the coating. Through a number of these tests it has been established that the coating stabilises between 2-3 days.

**Design Example**

Based on the results from small-scale testing and the simulated service tests, logarithmic creep curves can be plotted. These creep curves are important when designing a PP insulation system for various water depths and temperatures. Below is a design example of a typical deep water case study. The functional requirements for this case is water depth of 2000 meters (20 MPa), a wellhead temperature of 60 °C and a OHTC requirement of 5,3 $W/m^2$ °K.

When using creep resistant foam for deepwater fields it is important to reduce the exposure temperature on the foam. A load case of 20 MPa is close to the yield strength of the material and it is necessary to derive a design that would reduce the creep rate as a result of temperature. These effects are known for all plastics that show visco-elastic behaviour.

From the creep tests and the full-scale simulated service test, it is important to reduce the temperature to $\leq$40 °C. Figure 8 shows a typical build-up of a multi-layer PP temperature gradient through the layer thickness.

## Manufacturing and Installation

Manufacturing of the novel PP insulation systems is executed by cross-head extrusion. This method provides opportunity for building multi-layer structures where foam properties can be tailor-made by varying process parameters. Such a method can also be made mobile and transported to varous sites to improve logistics and reduce costs. Use of the cross-head extrusion process has a seven year track record in the Gulf of Mexico both releatd to insulation of risers and flowlines.

Installation of these systems has been performed by J-lay and reeling and field joint coating is made both onshore and offshore. In 2001, the novel thermal insulation technology described in this paper was manufactured and deployed in the Gulf of Mexico.

## Conclusions

Based on the development and qualifiaction program for the novel thermal insulation system, conclusions are:

1. The new generation of PP materials shows potential for use in deeper waters and improved thermal insulation capacity.
2. Creep resistant foam can be used in deep waters and may contribute to reduced volume and fewer trips during installation of the pipes.
3. Development of the tri-axial creep method provides the opportunity to predict long-term behaviour by small scale tests.
4. The small-scale test methodology and the full-scale testing show good correlation and small-scale tests may be used for demonstrating performance of foamed structures over a wide range of temperatures and pressures.

## Acknowledgements

The authors would like to thank Bredero Price Norway (Thermotite) and Borealis for permission to publish this paper. We also take the opportunity to thank those individuals within the two companies who have contributed considerably and our collaboration partners at SINTEF.

## References

1.Pattee, F.M. and F. Kopp: “Impact of Electrically-Heated Systems on The Operation of Deep Water Subsea Oil Flowlines”, OTC 11894, Offshore Technology Conference, Houston, TX 1-4 May 2000.

2. Ek, C.-G: “The new generation Polypropylene block copolymer for non-pressure pipe applications”, paper at Plastics Pipes XI conference, Munich, September 3-6, 2001.

3.Panzer, U., Rätzsch, M.: “Novel High Melt Strength Polypropylene“, SPO 1998

4.Rydin, C., Sjöberg, L.: “Polypropylene thermal insulation systems for offshore pipeline applications “, 14th Pipeline Protection Conference, Barcelona, 29-31 October 2001

5.Boye Hansen, Allan and Friberg, Reidar: “Thermal Insulation of Non-Jacketed Deep-Water Flowlines and Risers Based on Mobile Manufacturing Units”, Rio Oil & Gas Expo, 16-19 October 2000.

6.Hartviksen, G., Melve, B., Rydin, C.: ”Full scale testing of Åsgard flowline PP insulation at 140°C- ageing and long-term performance” Oilfield Engineering with polymers conference, London , 28-29 November 2001.

7.Boye Hansen, A., Duncan, J., and Simonsen, E.: “Polypropylene Deepwater Insulation Experience to Date and Future Trends in Combination with Direct Heating Flow Control Systems”, 2nd Workshop on Subsea Pipelines, 26-27 April 1999, Rio de Janeiro

*Table 1.  Insulation System Performance Requirements*

| PARAMETER DESCRIPTION | CRITERIA |
|---|---|
| Reeling Radius | 7 – 10 meters |
| Thermal Stability (Operating Temperature) | 4 – 140 °C |
| Thermal Conductivity | 0,13 – 0,23 W/ m°K |
| Creep resistance | <8% overall, 100 – 2000 meters* |
| Service Life | 10 – 20 years |

*) Some individual layers may experience higher creep as a result of higher exposure temperature

*Table 2.  Ageing Test Results*

| Standard | Requirement | Performace |
|---|---|---|
| DIN 30678 | 140°C/ 2400 hours, No cracks | Passed |
| NFA 49-711 | 150°C/ 1000 hours, Delta MFR ≤ ± 50%) | Passed |

*Table 3.  Mechanical Property Tests Summary*

| Property | Novel PP Foam | Reference PP Foam Typical value | Test method |
|---|---|---|---|
| **Density (kg/m3)** | **690** | **760** | **ASTM D792** |
| **K-value (W/mK)** | **0,169** | **0,185** | **ASTM C-177** |
| **Tensile Modulus (MPa)** | **1260** | **900** | **ISO 6259** |
| **Tensile Strength (MPa)** | **18** | **16** | **ISO 6259** |
| **Elongation at break ( %)** | **46** | **80** | **ISO 6259** |
| **Compression Modulus (MPa)** | **680** | **480** | **ASTM D695** |
| **Compression strength at 5% compression (MPa) Uni-axial** | **19** | **13** | **ASTM D695** |
| **Total Creep after 20 years 12 MPa / 20°C** | **7,7 %** | **16%** | **Tri-axial Test Method** |

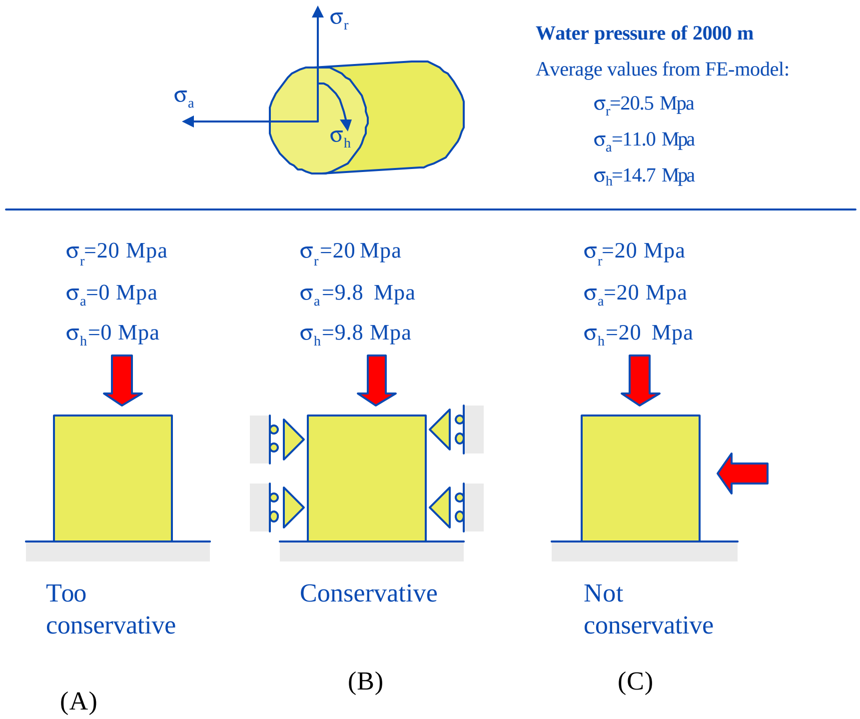


**Figure 3. Stress Analysis for Submerged Insulated Flowline and Three Corresponding Test Methods**

**Figure 4. Photography of the Tri-Axial Test Method Set-Up**

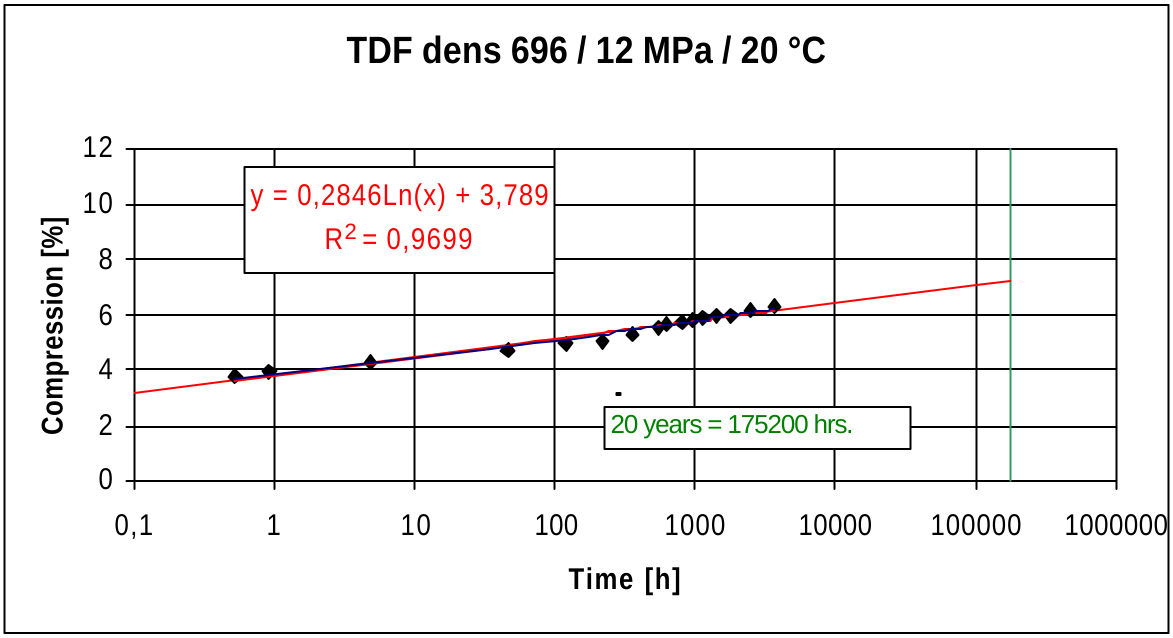


Figure 6. Creep Curve, 3712 hours for Novel PP foam

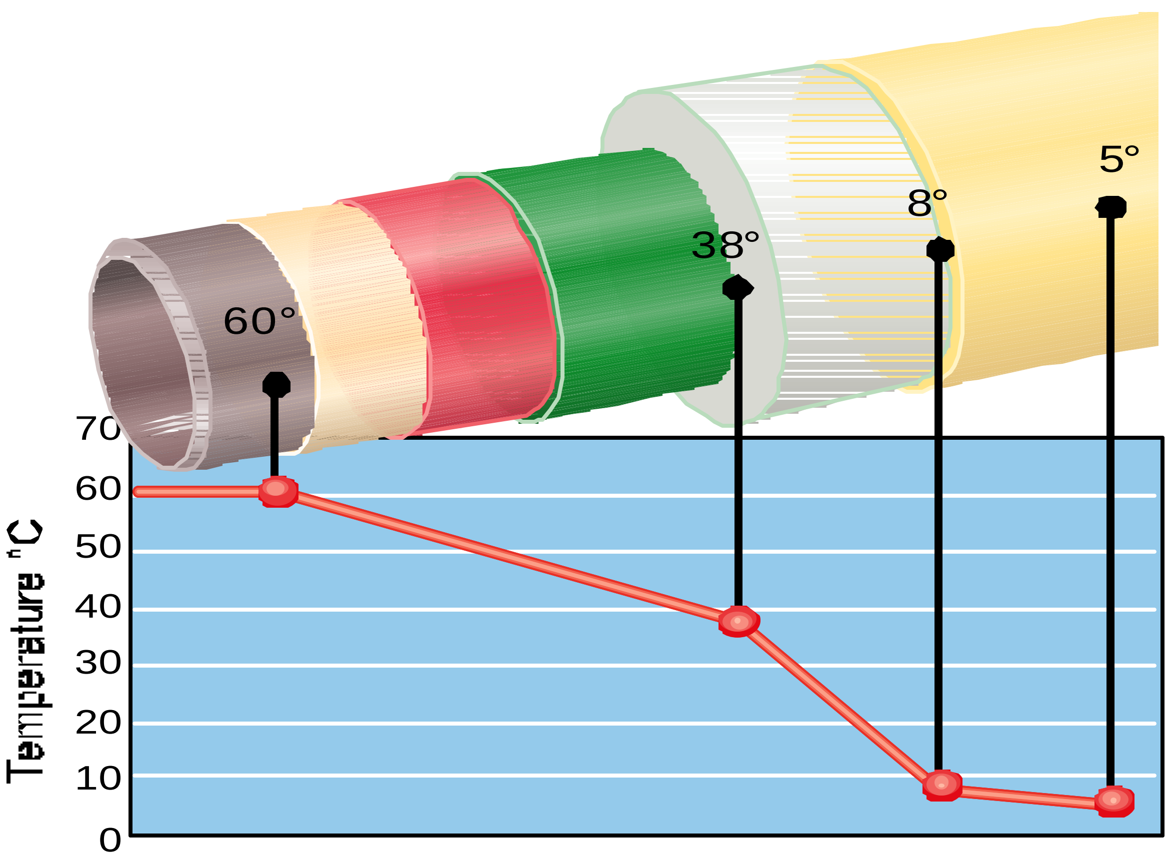


Figure 8. Temperature Profile Through layers for a Deep Water Design