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VALIDATION OF THE PERFORMANCE OF OFFSHORE, DEEP WATER INSULATION

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ABSTRACT

Insulation is commonly applied to offshore pipelines to ensure the flow of hydrocarbons at elevated temperatures. The thermal properties of the insulation can be readily modeled; however, the performance of the insulation needs to be verified under conditions similar to those encountered in deepwater service. Autoclave testing of individual materials can be conducted but this is not representative of the conditions that the materials see in service. The insulation is typically present in layers, and not every layer is exposed to the same environment. Simulated service testing, where a full size pipe is exposed to a water pressure equivalent to that it will see in deepwater service load, is typically used to verify the performance of the insulation.

This paper presents the unique combination of a process control discipline with the data measurement capability of a new Simulated Service Vessel (SSV) to ensure accurate determination of U value for insulation systems in a deepwater environment. Three deep water tests have now been completed in the SSV.

INTRODUCTION

During the development and qualification of insulation systems for subsea oil and gas pipelines it is important to understand and quantify the behavior of the insulation under service conditions experienced in subsea environments. ShawCor's Simulated Service Vessel (SSV) is a key part of a new state of the art facility built to do just this.

This pressure vessel simulates service conditions experienced by insulated subsea systems such as linepipe, field joints and, flexible pipe by applying pressure to water surrounding these systems while controlling the temperature inside the pipe. By measuring the heat flow, thermal conductivity and compressive creep of the insulating material, both the thermal efficiency and depth rating capabilities of the insulation can be confirmed. This data is used to verify design of the system.

NOMENCLATURE

- α – *Thermal expansion coefficient*
- c_p - Heat capacity
- E – Young's modulus
- h - *Convection* heat transfer coefficient
- k – Thermal conductivity
- ε - Strain
- ν - Poisson's Ratio

σ – Stress
r - Radius
r_i – Inner radius
r_o – Outer radius
R - Radius
t – time
T – Temperature
T_{op} – Operation temperature
$T_{condition}$ – Temperature condition
u – Radial displacement
U – U value
w – Axial displacement
r, θ, z – coordinates

BACKGROUND

From both performance and safety aspects, the need for a precise understanding and determination of the service capability of insulated oil and gas subsea pipelines is essential. The increasingly high pressure and temperature performance demanded by the industry due to deeper drilling and deployment makes it ever more important that the performance limitations of insulated subsea pipelines are fully known.

EXISTING TECHNOLOGY

ShawCor has a SSV installed in Calgary, Canada that was designed based on similar systems used in the late 1990s but is no longer adequate for today's large diameter requirements. This SSV is limited to a pipe length of 1.83 m (6'), with outside pipe diameter including insulation of 356 mm (14") and minimum inside diameter of 125 mm (4.9"). The test pipe can be subjected to hydrostatic pressure of 280 bar with a maximum internal temperature of 160°C (320°F).

The Calgary vessel's oil heated system utilizes a closed loop internal cooling coil to control outside water temperature. The system uses two heat flux (HF) belts circumferentially mounted to measure heat flow through the insulation system with each belt containing three HF sensors and four temperature sensors at the surface of the insulation. Six Linear Variable Differential Transformers (LVDTs) are strategically located throughout the vessel to measure compressive creep during the simulated service test.

Due to the increasing demand for higher temperature, large diameter offshore pipelines, ShawCor has built a larger, state of the art, 82 tonne SSV, which has been built and commissioned in Toronto, Canada. The existing Calgary vessel will be used for long term material characterizations.

NEW SHAWCOR SSV

The new, much larger ShawCor SSV allows for an accurate assessment of the performance capability of an insulated pipe system under precisely controlled conditions of temperature and pressure. The SSV is fundamentally a large cylindrical autoclave which can accommodate a 6 meter (20') length of the insulated pipe or structure to be evaluated.

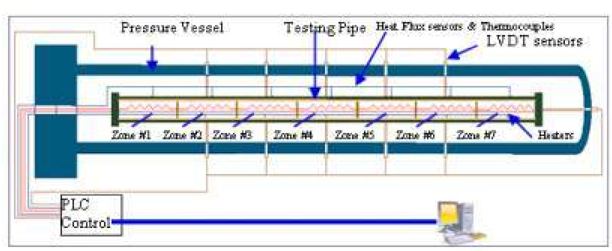
A thermally insulated sample is mounted in the vessel which is instrumented with the following: displacement transducers to measure diametrical change under hydrostatic load; thermal sensors for temperature measurement; and, heat flux sensors to determine the heat loss from the system. Once thermal equilibrium has been established, the vessel is pressurized and held at the required pressure for the duration of the test. The pressure is increased in specific increments to assess the immediate and long term response of insulation properties to changes in pressure at a specific operating temperature which is set by internally heating the test pipe.

Changes in compressive creep and heat flow are measured over time. U-value of the system can be calculated and compared with the design assumptions for the given pressure and temperature field.

INSTRUMENTATION SYSTEM

To obtain the desired measurements, the measurement and control systems in the new SSV facility are built to have features as shown in the following schematic. The steel pipe is heated with a seven-zone electrical heater, controlled by thermocouples in each zone. The following parameters are monitored:

- water temperature
- temperature of the insulation coating surface
- heat flux - up to 3 radial locations in 7 axial zones
- internal pipe temperature - at locations precisely matched radially and axially to the external heat flux sensors
- radial displacement using LVDT sensors
- power consumption in each of seven heating zones



The system continuously monitors and records the measurements during the test period. The multi-zone controls and multi-point measurements of this system provide integrity testing of the insulation coating performance under the defined testing conditions.

UNIQUE TESTING CAPABILITIES

To accommodate market requirements trending towards deep and ultra deep development opportunities and higher oil transportation temperatures, the new ShawCor SSV has been designed to test to an equivalent water depth up to 3,000 m (9,842') at an internal pipe temperature of up to 180°C (356°F).

Capability/Property of SSV	Specification
Minimum Test Pressure	25 bar (± 2)
Maximum Test Pressure	300 bar (± 5)
Chilled Water Temperature Inside Pressure Vessel	4°C (± 2)
Internal Temperature	20°C – 180°C (68°F – 356°F)
Sample Length	6 m max (18')
Vessel ID	1.2 m (48'")
Pipe Inside Diameter	95 mm - 660 mm (4" - 26")
Pipe Outside Diameter (includes insulation)	145 mm - 810 mm (6" - 32")
Overall Heat Transfer Coefficient (U)	< 6 W/m^2 K

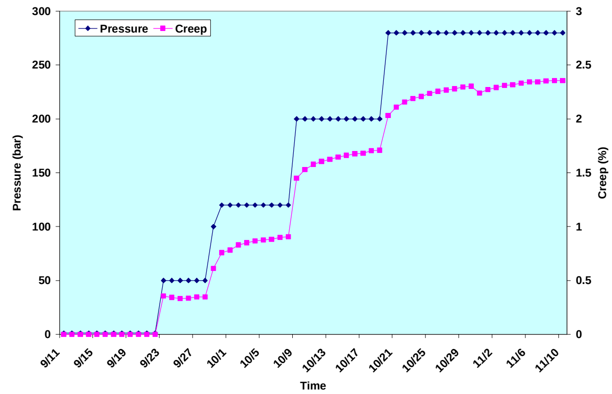
Testing is designed to accommodate the exact dimensions of the pipe (up to 26 "ID) that will be put into service so that clients will accurately know the true representative thermal performance of their installed pipe. The vessel also has the ability to test both the field joint and the main line insulation. As well, the SSV has the capability to compare the performance of three insulation coatings simultaneously, with multiple measurements for each coating.

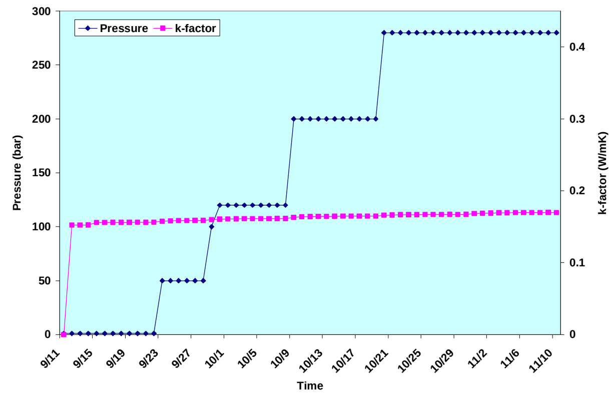
Furthermore, the SSV can test for cool down time and provide accurate, real time measurements of creep to evaluate long term reliability of the insulation. The heating system provides precise temperature control to ensure accuracy and a high capacity chiller provides a water temperature of 4 – 6°C (40 - 43°F).

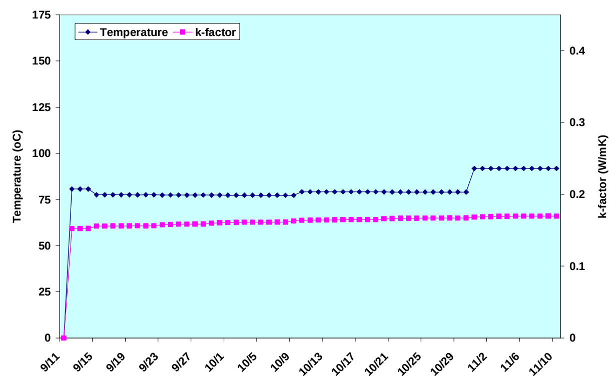
The testing schedule can be adjusted to accommodate customer requirements. Qualified technical staff will be on-site and third party inspectors will validate test results for clients.

DATA FROM SSV TESTING

The figures below illustrate typical responses of an insulated pipe system during simulated service testing. The data displayed below are from the Calgary SSV test facility. The system included a 273 mm (10") OD steel pipe of wall thickness 16 mm (0.63") coated with 50 mm (2") of ShawCor's new Thermotite® ULTRATM insulation coating.







Creep is mechanical deformation resulting from the composite effects of time, temperature and mechanical load. Initial performance and creep response are significantly affected by initial compositional properties such as crystallinity in crystalline polymer and foam structure where applicable. These properties are heavily dependant on initial processing conditions.

The compressive creep curves generated over time are important for computer modeling and thermal design of solid, foamed and syntactic insulation systems for various water depths and temperatures. The increase in pressure (blue line) is planned in steps to show the elastic (immediate) and the inelastic (long term) responses of the system to the pressure changes. This allows for construction of the design model. The typical response for foam is that the material compresses over time. For a solid polymer, the material shows an immediate response that reaches a plateau after about one week.

EVALUATING CREEP AND COMPRESSION

SSV testing is performed to evaluate the long term creep properties of thermal insulation systems and to estimate the service life of the coating. The initial performance is defined by the thickness of the material, the compressive modulus and the thermal conductivity. These values are readily determined in laboratory tests, and the initial U Value is calculated for any given geometry and material composition, as follows:

$$U = \frac{1}{A \times R \times \sum_{i=1}^{n} \frac{\ln(R_{i+1} / R_i)}{k_i}} \qquad (1)$$

Under operating conditions, the coating is placed under a thermo/mechanical load which alters the coating's thickness, resistance to compression, and therefore its thermal conductivity. For thick coatings (>25.4 mm or 1"), there is a substantial temperature gradient through the coating thickness (hottest on the inside and coldest on the outside) which produces a corresponding gradient of compressive strengths and thermal conductivities. These are best modeled using laboratory data for compressive strength and thermal conductivity as a function of temperature, and resolved with Finite Element Analysis (FEA) techniques.

In FEA modeling, the temperature profile in the system is described using the following heat transfer equations:

$$\begin{cases} \rho c_p \dfrac{\partial T}{\partial t} = -k \nabla^2 T \\ T(0, r) = T_0 \ (r_i < r < r_o) \\ T\big|_{r=r_i} = T_{op}, \ \dfrac{\partial T}{\partial r}\Big|_{r=r_o} = h(T - T_{condition}) / k \end{cases} \qquad (2)$$

The strain and stress distribution due to hydraulic pressure and the thermal stress when the pipe is tested can be simulated using the governing equations:

$$\begin{cases} \dfrac{\partial \sigma_r}{\partial r} + \dfrac{\partial \sigma_{rz}}{\partial z} + \dfrac{\sigma_r}{r} = 0 \\ \dfrac{\partial \sigma_{rz}}{\partial r} + \dfrac{\partial \sigma_z}{\partial z} + \dfrac{\sigma_{rz}}{r} = 0 \\ \varepsilon_r = \dfrac{\partial u}{\partial r}, \varepsilon_\theta = \dfrac{u}{r}, \varepsilon_z = \dfrac{\partial w}{\partial z}, \varepsilon_{rz} = \dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial r} \\ \varepsilon_i = \dfrac{1}{E}(\sigma_i - \nu \sigma_j - \nu \sigma_k) + \alpha \Delta T, \end{cases} \qquad (3)$$

Creep can be measured for homogenous materials in a triaxial creep test, which determines the specific material dependant deformation as a function of time, temperature and pressure; however, these samples are not representative of insulation comprising multiple materials and layers. Measurements are not additive since their relative thermal and mechanical properties are interdependent.

The creep characteristics are determined by the creep test and described as:

$$\varepsilon_c = A \sigma^m t^n \qquad (4)$$

The above relationship will be further verified by the SSV test and applied to the FEA modeling.

Creep performance of a full scale, insulated pipe cannot be accurately predicted from FEA models alone. The best estimate of creep behaviour is the result of comparing FEA models with the actual performance of a full scale installed pipe from an SSV test. The difference between the FEA model and SSV estimates provides a measure of uncertainty (variance), which can then be used to generate predictive confidence limits around the service life of the pipe.

From laboratory test data, an FEA model can be generated that predicts thermal and mechanical properties of the insulation based on coating thickness. Triaxial creep tests can be used to predict changes in thickness as a function of time, temperature and pressure. The combination of the triaxial data with the FEA model will then generate a second FEA model which can predict long term changes in thermal and mechanical properties due to creep. Confidence limits around these predictions are caused by variances in:

- laboratory data
- triaxial creep tests
- SSV test data

The FEA model will then be compared to the SSV test data collected on commercial size insulated pipe. Consideration of the pipe to pipe variance will be established using process capability studies and quality control (QC) data gathered during product development. This pipe to pipe variance, combined with the deviations between FEA predicted results and SSV test data will establish confidence intervals around the performance of all pipes manufactured under the specified production conditions.

VALIDATION OF THE U VALUE OF APPLIED INSULATION

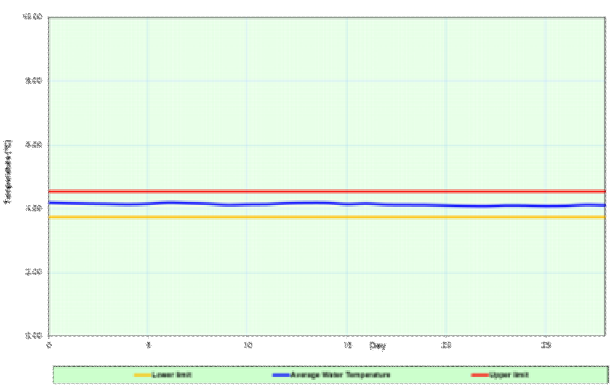
For the new, ShawCor SSV, U value is calculated according to the following equation:

$$U_i = -\frac{Q}{A \cdot \Delta T} = -\frac{2\pi r_o l q}{2\pi r_i l (T_{steel} - T_{water})} = -\frac{r_o q}{r_i (T_{steel} - T_{water})} \quad (5)$$

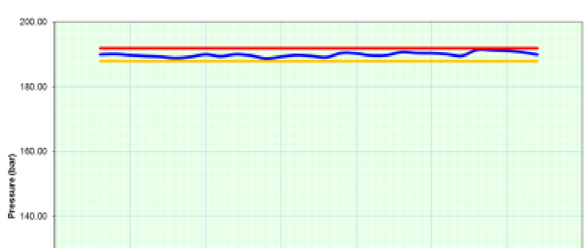
R_o is based on the original uncompressed outer diameter of the insulated pipe. R_i is the internal steel wall diameter, measured at the outset of the test. Q, T_{steel} and T_{water} are monitored continuously at 15 discrete locations, each with a dedicated thermocouple and heatflux sensor at a specific radial and axial location.

To ensure that accurate data is obtained from testing of the insulation value (U) of the coating, the temperature and pressure conditions are precisely controlled. This is illustrated in the control charts below where limited data variation is observed for both water temperature and pressure observed during a test run.

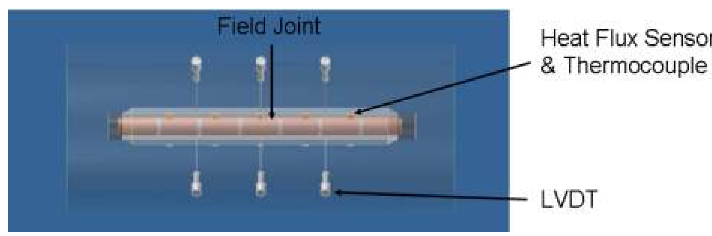
Water Temperature during Test in new SSV



Water Pressure during Test in new SSV



The vessel was meticulously designed to ensure data measurement capability along the length of the pipe so that reliable U value calculations are provided. U value is determined in 15 locations, at three locations in each of the 5 middle heating zones. The U value is calculated at each point using heat flux sensors and temperature sensors that are aligned at the same location on the pipe. Using these 15 data points, U is determined, along with the variation and confidence interval for the U value.



Since the measurement of U value involves a complex equation and a large number of individual sensors, a propagation of errors estimate is carried out for each test to generate confidence limits. The propagation of errors equation for this function and arrangement of sensors is as follows:

$$\sqrt{\left(\frac{\partial U}{\partial r_o}\right)^2 \times \Delta r_o^2 + \left(\frac{\partial U}{\partial q}\right)^2 \times \Delta q^2 + \left(\frac{\partial U}{\partial r_{so}}\right)^2 \times \Delta r_{so}^2 + \left(\frac{\partial U}{\partial \Delta T}\right)^2 \times \Delta\Delta T^2} \quad (6)$$

where:

$$\left(\frac{\partial U}{\partial r_o}\right) = -\frac{q}{r_{si} \times \Delta T} \quad (7)$$

$$\left(\frac{\partial U}{\partial q}\right) = -\frac{r_o}{r_{si} \times \Delta T} \quad (8)$$

$$\left(\frac{\partial U}{\partial r_{so}}\right) = -\frac{r_o \times q}{r_{si}^2 \times \Delta T} \quad (9)$$

$$\left(\frac{\partial U}{\partial \Delta T}\right) = -\frac{r_o \times q}{r_{si} \times \Delta T^2} \quad (10)$$

The delta values are obtained from the variance observed in the sensor readings, and the variables themselves are the typical readings during any given test.

With 15 independent sets of data for any individual test, the combined standard error, including propagated error, is typically less than 3% of the U value at the 95% confidence interval.

The high precision of the individual sensors combined with the elimination of assumptions of power loss due to axial heat-flux provide extremely reliable and reproducible results.

CONCLUSION

ShawCor is uniquely positioned to both analyze data and validate performance of insulation systems, with this new SSV facility. The precise measurement capabilities and capacity of the vessel allow detailed characterization of initial performance and promise accurate real time measures of continuous creep and thermal conductivity. Validation of insulation systems for clients can be done with a high degree of confidence. In addition, the close proximity of the SSV facility to ShawCor's research and development laboratories provides direct access to laboratory testing according to specific requirements. Finally, access to global production records and QC data permits much broader interpretation of results, especially as SSV data is collected over time.

In the short term, the combination of SSV test data, laboratory material testing and the analytical methodology described above will allow ShawCor to establish the most reliable predictors of long term performance available in the market. This is particularly important for finding novel material and design solutions for challenging deep sea environments, and demanding performance validations from our customers.

The long term objective is to discover and exploit synergies between material and design properties which will significantly improve the performance of subsea products.

ACKNOWLEDGMENTS

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