TECHNICAL PAPER

Corrosion Under Insulation

Corrosion assessment for ArmaGel™ HT insulation systems tested according to NACE TG516 procedure.

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ABSTRACT

Corrosion Under Insulation (CUI) continues to be a major issue for process industries in oil, gas, chemical and power generation sectors. It is estimated that up to 10% of annual maintenance costs in these industries are caused by CUI[i, ii, iii]. Severe cases of CUI may put the safety of personnel, operation processes, environment, and reputation at risk.

The choice of insulation system is a critical factor for effective mitigation of CUI. The National Association of Corrosion Engineers (NACE) TG516 test protocol allows you to assess the performance of thermal insulation systems for industrial pipes when subjected to water ingress at defined time intervals and under constant (low) and cyclic (low/high) operating temperatures. The test of aerogel blanket insulation, ArmaGel™ HT, was conducted at Southwest Research Institute for 6 months from March until September 2019.

This paper will give a detailed insight into the applied simulation methodology and the assessment of the tested aerogel blanket insulation system and of the pipe material exposed to corrosive conditions. It will also present how the obtained results may be compared to those for conventional insulation products obtained in similar CUI test conditions and show that aerogel insulation materials offer effective resistance to water ingress which helps minimise the onset and spread of CUI.

Test conducted by:
Southwest Research Institute (SwRI)
6220 Culebra Road
San Antonio, Texas 78238, USA

INTRODUCTION

Armacell Energy offers two different kinds of industrial insulation materials which are applied directly to the pipe surface or equipment in industrial projects:

- ArmaFlex®, 'Industrial' type, Flexible Elastomeric Foam (FEF), based on synthetic rubber, with foamed closed cell structure.
- ArmaGel™, aerogel (AG) blanket, hydrophobic, with fibrous open structure, high maximum service temperature and low thermal conductivity.

For both ArmaFlex Industrial and ArmaGel products there are many technical, CUI-related parameters defined and published which are monitored for manufactured goods at regular intervals. For reference please see another Technical Paper published by Armacell Energy "Corrosion Under Insulation. A holistic approach to insulation system design to reduce risk of CUI on industrial piping." as well as the Technical Data Sheets of each product.

ArmaFlex Industrial and ArmaGel have been tested in respect to their CUI mitigation properties in salt-water spray and high humidity tests by TNO/Endures and InnCoa institutes, respectively.

The test results and findings have been presented in Technical Papers published by Armacell Energy 'Corrosion Under Insulation. Mitigating Corrosion Under Insulation (CUI): *Spread of corrosion assessment on ArmaFlex insulation systems in a continuous salt-water spray environment. A test conducted by TNO/Endures.'* and *'Corrosion Under Insulation. Spread of corrosion assessment for insulation systems in a high humidity environment with cyclic process temperatures. A test conducted by the world-renowned corrosion institute InnCoa [1].'*

1 See for reference https://local.armacell.com/en/energy/problems-we-solve/corrosion-under-insulation-cui/

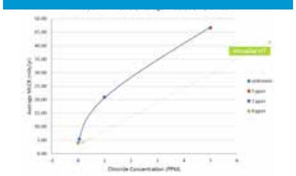
ARMAGEL™ HT INSULATION MATERIAL

The tested insulation material – ArmaGel HT is a flexible aerogel blanket designed for thermal and acoustic insulation of industrial pipes and equipment. The main features of ArmaGel HT are (see Fig.1):

- Very low thermal conductivity
- High flexibility across thickness range of 5, 10, 15 and 20 mm
- Long-term thermal stability
- Hydrophobic properties
- Low leachable chlorides, meeting criteria of 'Acceptable Analysis' in ASTM C795
- Low stress corrosion cracking (no coupons cracked) acc. to ASTM C692 for austenitic stainless steels
- Low Mass Loss Corrosion Rate (MLCR) which is comparable to distilled water acc. to ASTM C1617 for unprotected carbon steel

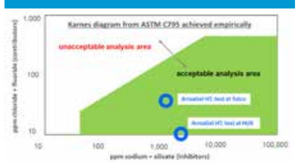
Due to its flexibility ArmaGel HT can be applied tightly even on small bore pipes leaving very little or no annular space. Linear seams between blanket sections can also be tightly fit making the whole system highly resistant to water ingress.

Corrosivity ≈ distilled water



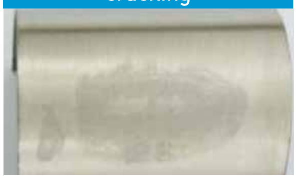
Corrosivity comparable to distilled water. ASTM C1617

Low leachable chlorides



ASTM C871 & C795

Low stress corrosion cracking



No coupons cracked. ASTM C692

Low thermal conductivity

Thermal conductivity curve

Long term thermal stability

Layer interface temperature values for ArmaGel HT on 12" pipe at 580 °C (1076 °F)

Hydrophobic material

Hydrophobic material with reduced water ingress

High flexibility

High flexibility at all thicknesses

Fig.1: ArmaGel HT - main technical features.

NACE TG516 TEST

NACE is widely considered to be a worldwide corrosion authority and provides a standardised test method "TG516" which is designed to test insulation materials and coatings applied to cylindrical surfaces. The design of the test method is based on an approach that simulates field conditions and replicates the conditions of a corrosive environment under insulation in an accelerated manner. The corrosive environments can be modelled (e.g., by the level of operating temperature) to represent specifically the requirements considered appropriate for the insulation material or system. TG516 provides strict guidance on how the test should be conducted. On the other hand, the test protocol allows for some test parameters to be established, e.g. the operating temperature in the pipe or configuration of the insulation layers, individually for each insulation system. A further requirement of the test is the application of a metallic jacketing without a liner on the inside surface which is installed over the insulation.

The principle of the test is to simulate insulation damage by drilling a small hole through the insulation thickness at the bottom of the pipe to promote water ingress through the system. The resulting breakdown of the insulation will lead to deterioration and corrosion of the insulated pipe made of unprotected carbon steel. The corrosion effect is hence expected during the 6-months test. The test methods aim to establish corrosion rates of the carbon steel in a CUI environment under a given insulation system. The CUI mitigation of different insulation materials and systems in the field can be compared to the corrosion results in the TG516 test under the same or similar conditions.

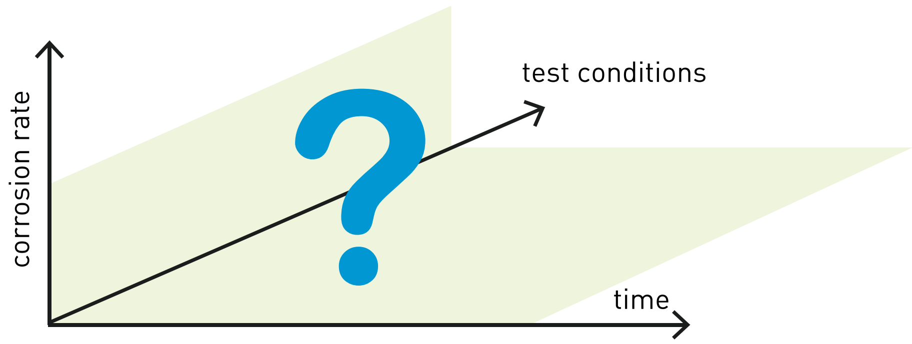


Fig.2: Purpose of TG516 test – corrosion rate in defined conditions and test time.

The purpose of the TG516 test is to:

- Establish corrosion rates of carbon steel in a CUI environment of wet insulation
- Observe the behaviour of the selected insulation and its ability to mitigate CUI
- Draw potential comparisons with other insulation materials and systems.

The test also allows for:

- Long term corrosion behaviour to be predicted
- Decisions regarding pipework/equipment design and coating to be made
- Select insulation material and system appropriate for particular project based on facts according to test results (see Fig. 2).

TEST METHODOLOGY

The minimum requirements and conditions of the TG516 test are defined in the following way:

- The tested object is a small-bore pipe with the length of 6 to 12 inch (152 to 305 mm), made of carbon steel (with optional anti-corrosion coating), insulated in accordance with the manufacturer's installation instructions and protected with metallic cladding
- The Insulation and the jacket are fitted tightly to the pipe surface and sealed with waterproof sealant at the terminations
- A small-bore opening of Ø6 mm (0.25 inch) is created to allow water ingress. The opening is made in the cladding at 6 o'clock (bottom) position, optionally extended into insulation up to the pipe surface
- The operating temperature range can be chosen as:
  - Continuous sweating test - constant, below the dew point (also known as 'condensation test'), see Fig. 3
  - High temperature cycle test - cycling above or below the dew point intermittently (in 24h period), see Fig. 4

  (No specific temperature values are given in the standard.)
- The insulated pipe is positioned inside a vessel (box or trough) which is filled with (salt) water in the morning of each day and then drained after 9 hours at regular intervals. During the weekend the vessel is kept dry. During these 9-hour periods the vessel is filled such that the insulated pipe is fully immersed in water. (Note: These timing intervals are recommended by the TG516 procedure but they may be adjusted for specific purposes). The salt solution concentration is not regulated. A C5 corrosivity category environment (according to ISO 12944) suggested chloride concentration is from 300 $\mu g/m^3$ to 1500 $\mu g/m^3$ (0.3 to 1.5 ppm)
- Test duration: 6 months (minimum recommended)
- Recommended electrochemical measurements of corrosion rate during the test:
  - EIS = Electrochemical Impedance Spectroscopy
  - OCP = Open Circuit Potential
  - LPR = Linear Polarisation Resistance
- Recommended measurement method of corrosion rate after the test is UT = Ultrasonic Thickness measurement.

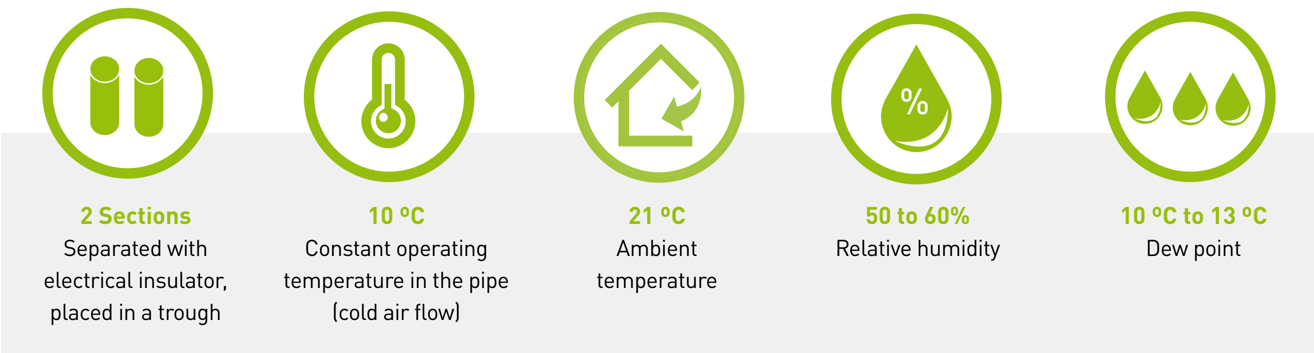


Fig.3: Conditions of continuous sweating (condensation) test.

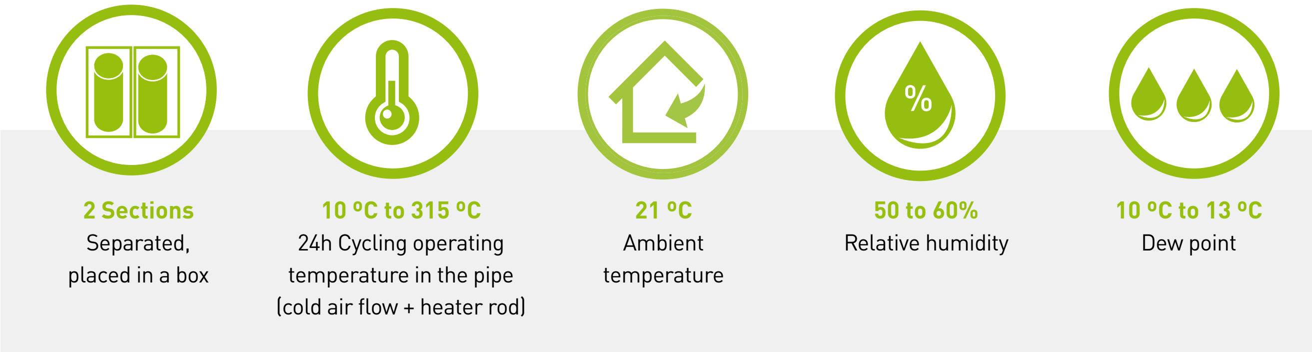


Fig.4: Conditions of high temperature cycle test.

In addition to the above listed requirements and recommendations of TG516, the following test details were set up for the test of ArmaGel HT at SwRI:

- Pipe: NPS 2 inch (50.8 mm inner diameter, 3.9 mm pipe wall thickness), length 12 inch (305 mm), carbon steel uncoated. Altogether four pipes were prepared: two for each temperature test scenario
- Insulation: 2 x 10 mm ArmaGel HT aerogel blanket fixed with wire
- Cladding: 316 stainless steel (austenitic) with 0.017 inch (0.34 mm) thickness. Unsealed overlap of 2 inch (50 mm). Secured with banding
- Insulation and cladding sealed tightly at terminations to eliminate water ingress there
- Opening: Ø6 mm opening in the cladding at 6 o'clock position for initial 40 days of the test, the opening was extended into insulation up to the pipe surface after 40 days
- Measurement: Three electrodes for electrochemical measurements
- Temperature test scenario:
  - » Continuous sweating test at operating temperature of the pipe 10 °C (50 °F)
  - » High temperature cycle test at operating temperature of the pipe 315 °C/10 °C (600 °F/50 °F) changing in 24h period

  The ambient temperature in each case was 21 °C (70 °F). Relative humidity was from 50% to 60% which yields the dew point at 10 °C (50 °F) to 13 °C (55.5 °F)
- The vessels in which the tested pipes were placed were filled with tap water for 9 hours each day from Monday to Friday and kept drained for 15 hours (in 24h cycles). For Saturday and Sunday, the vessels were left completely drained. After 30 days of test duration the tap water was replaced with 1500 ppm chloride solution.
- Three electrochemical measurements used to determine the corrosion rate during the test were applied:
  - » EIS = Electrochemical Impedance Spectroscopy
  - » OCP = Open Circuit Potential
  - » SCE = Saturated Calomel Electrode
- After the 6 months = 188 days corrosion rate was measured with UT = Ultrasonic Thickness technique
- Separately also the depth of pitting corrosion was measured
- Finally, the condition of insulation blankets was also evaluated
- For construction details of the tested pipe and insulation see Fig. 5.

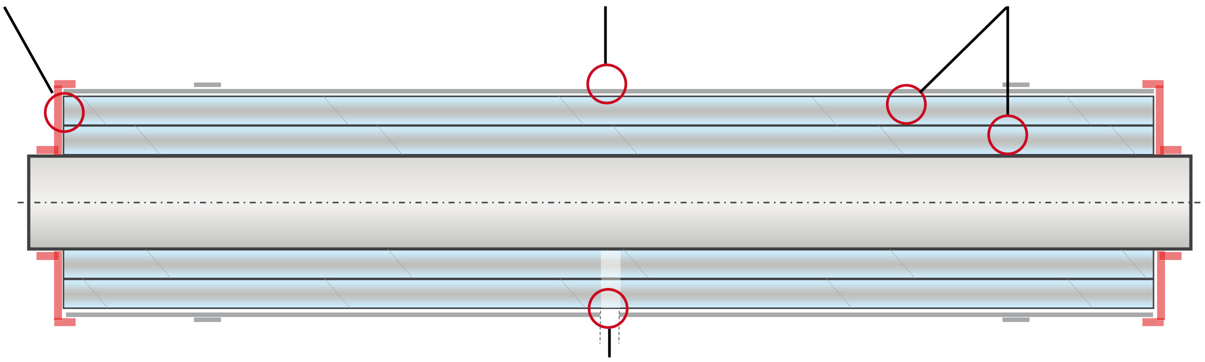


Fig.5: Set of the tested pipe and applied insulation system according to TG516.

CORROSION BEHAVIOUR DURING TEST

In order to assess both continuous sweating and high temperature cycles, two pairs of insulated pipes were subjected to two different patterns of wet/dry and temperature regimes.

For the continuous sweating (condensation) test at operating temperature of 10 °C (50 °F) and ambient temperature of 21 °C (70°F) the following corrosion behaviour patterns were present in each week (see Table 1 and Fig. 6.1):

Cycle	Operating Temperature	Description
5 x Fill (9h)	10 °C / 50 °F	Easy ingress of water. No evaporating process. **Slow corrosion rate**.
4 x Drain (15h)	10 °C / 50 °F	Slow drying process. **Slow corrosion rate.**
Weekend Drain (63h)	10 °C / 50 °F	Slow drying process. Long time during weekend. **Slow corrosion rate.**

Table 1: Corrosion behaviour patters of continuous sweating (condensation) test.

On the other hand, for the high temperature cycle test at operating temperature of 315 °C/10 °C (600 °F/50 °F) and ambient temperature of 21 °C (70 °F) the following corrosion behaviour patterns were present in each week (see Table 2 and Fig. 6.2):

Cycle	Operating Temperature	Description
3 x Fill (9h)	10 °C / 50 °F	Easy ingress of water. No evaporating process. **Slow corrosion rate.**
2 x Drain (15h)	10 °C / 50 °F	Slow drying process. **Slow corrosion rate.**
2 x Fill (9h)	315 °C / 600 °F	Ingress of water. Strong evaporating process. 85% (17 mm) of insulation thickness above 100°C. **High corrosion rate.**
2 x Drain (15h)	315 °C / 600 °F	Fast drying process. **High corrosion rate in initial phase** (until the insulation adjoining the pipe surface was fully dry).
Weekend drain (63h)	10 °C / 50 °F	Slow drying process. Long time during weekend. **Slow corrosion rate.**

Table 2: Corrosion behaviour patters of high temperature cycle test.

For the continuous sweating test, the corrosion process was notably slow throughout the entire test period. For the high temperature cycle test, high corrosion rates were observed during the filling and the early part of the draining period, even though this accounted for not more than 20% of the whole test duration. Moreover, the high corrosion rates which took place within this relatively short time period in the cycle (< 20%) resulted in notably higher overall corrosion than in the case of continuous sweating test with a slow but continuous corrosion process. The key factor for high corrosion rate clearly relates to the cyclic operating temperatures between the relatively low temperature of 10 °C (50 °F) (below the dew point) and very high temperature of 315 °C (600 °F).

Continuous sweating test

- Operating temperature of the pipe 10 °C
- Ambient temperature 21 °C

High temperature test

- Operating temperature of the pipe 315 °C / 10 °C
- Ambient temperature 21 °C

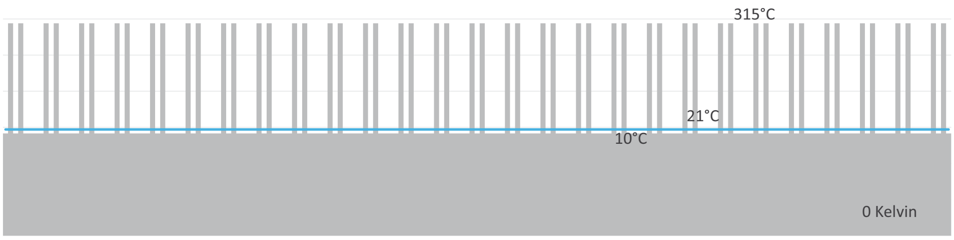


Fig.6.1 and 6.2: Cycling of the operating temperature during the test for 188 days.

RESULTS AFTER 188 DAYS

// Continuous sweating (condensation) test

Two pipes were tested under the continuous sweating (condensation) test. After 188 days (6 months) of the test the metallic cladding was removed. Next, both 10 mm layers of ArmaGel HT insulation blanket were carefully removed in turn. Both layers of ArmaGel HT blanket were noted to be in very good condition: they were easily removed, no obvious water absorption was found. There were identified isolated water droplets on top surface of both layers indicating that the hydrophobic properties of the insulation were maintained. Under the inner blanket "strings" of water droplets were found on pipe surface, within some of the insulation creases.

Regarding the pipe surface, isolated red and black corrosion deposits were found on the surface. There was superficial uniform corrosion on the surface in "strings" (or lines) directly under the insulation creases. The corrosion resulted led to an average measured loss of pipe wall thickness of 15.2 µm (after full 6 months). When converted to an annual value, the uniform corrosion rate was determined to be between 20 to 40 µm/year (see Fig. 7.1).

A small amount of pitting corrosion was observed at the end of the test with a few pits found with their depth up to max. 150 µm (i.e. 4% of the pipe thickness).

The pH value was measured as: 9.0 on the pipe surface, 8.0 to 9.0 in interface between the blankets and 7.0 to 8.0 on the outer insulation surface.

The corrosion rates for ArmaGel HT are comparable to those reported in previous investigations, using the TG516 method but slightly lower than those found in the literature at comparable temperatures.

Fig.7.1: Pipe surface of continuous sweating test after the test with traces of corrosion (after cleaning).

// High temperature cycle test

Two pipes were tested under high temperature cycle test (315°C/10°C or 600°F/50°F). After 188 days (6 months) of the test the metallic cladding was removed. Next, both 10 mm layers of ArmaGel HT insulation blanket were carefully removed in turn. Both layers of ArmaGel HT blanket were found to be in good condition. The outer layer was easily removable, but the inner layer was partly adhering to the pipe surface. There was no visual evidence of water absorption in either layer and isolated water droplets were identified on the top surface of both layers, which again indicated that the material maintained its hydrophobic properties for the duration of the test.

Regarding the pipe surface, red and black corrosion deposits were found over most of the surface. These deposits were deemed likely to be of oxide and magnetite oxide. According to the report of SwRI the presence of magnetite oxide film on the pipe surface is expected to help to impede corrosion rate and protect metal from further corrosion.

Overall, uniform corrosion was more pronounced than for the pipes tested under the continuous sweating condition. The average loss of pipe wall thickness was 22.9 µm (after 6 months). Converted to annual values, the uniform corrosion rate was determined to be from 32 to 54 µm/year (see Fig. 7.2).

Some pitting was also observed, with their depth reaching up to max. 180 µm (i.e. 5% of pipe wall thickness).

The pH value was measured as: 9.0 on the pipe surface and 8.0 in interface between the blankets.

The corrosion rates for ArmaGel HT are on the low end of the corrosion rates (≈ 40 to 100 µm/year) reported for similar test conditions using the TG516 method.

Fig.7.2: Pipe surface of high temperature cycle test after the test with traces of corrosion (after cleaning).

ELECTROCHEMICAL MEASUREMENTS

There were three electrochemical methods applied to measure corrosion rate during the test: EIS (Electrochemical Impedance Spectroscopy), OCP (Open Circuit Potential) and SCE (Saturated Calomel Electrode). The purpose of application of these corrosion rate measurement methods was to have the possibility to conduct ongoing measurements of corrosion rates during the 188 days test before the demount of the insulation material and to compare results with direct measurement of thickness of the pipe wall after the test (using ultrasonic technique).

Good correlation was found between the thickness measurement taken with the ultrasonic technique after the test and the three electrochemical methods. Findings of the OCP method concluded that in the continuous sweating test, the corrosion rate was decreasing and in high temperature cycle test it was rather steady and continuous.

Findings of the EIS results show that water reached the surface of the pipe only after 40 days when the opening at 6 o'clock bottom position which was initially only through the cladding, was extended through the whole insulation thickness. The fact that water did not reach the pipe for 40 days before the hole was extended demonstrates the reliable hydrophobicity of ArmaGel HT insulation material.

Figure 8 shows the corrosion rates measured for the continuous sweating (condensation) test and high temperature cycle test with ultrasonic thickness measurement after the test and with EIS method during the test.

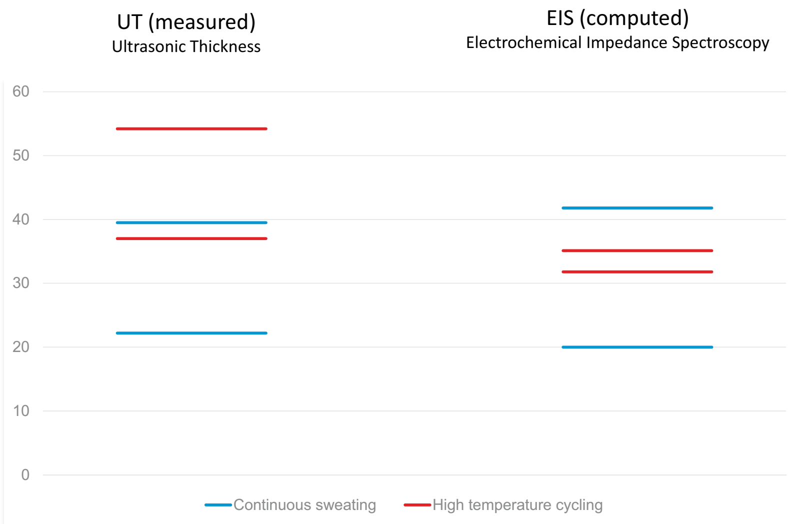


Fig.8: Annual corrosion rate of the tested pipe specimens.

The annual corrosion rate [μm/year] measured for ArmaGel HT aerogel insulation blanket during the test can be compared to the results obtained under similar conditions for other insulation materials. The published data can be found in NACE SP0198 ('Standard Practice. Control of Corrosion Under Thermal Insulation and Fireproofing Materials.'). Furthermore, some manufacturers of insulation materials have made their test results available to the public [iv, v].

When comparing available published test results, the corrosion rates of unprotected carbon steel under ArmaGel HT in wet conditions are observed to be significantly lower than the corrosion rates under other insulation materials, specifically:

- microporous insulation
- calcium silicate
- perlite

Figure 9 shows test results of ArmaGel HT according to NACE TG516 and comparable test results for other insulation materials. For many of the other insulation materials the corrosion rate is much higher.

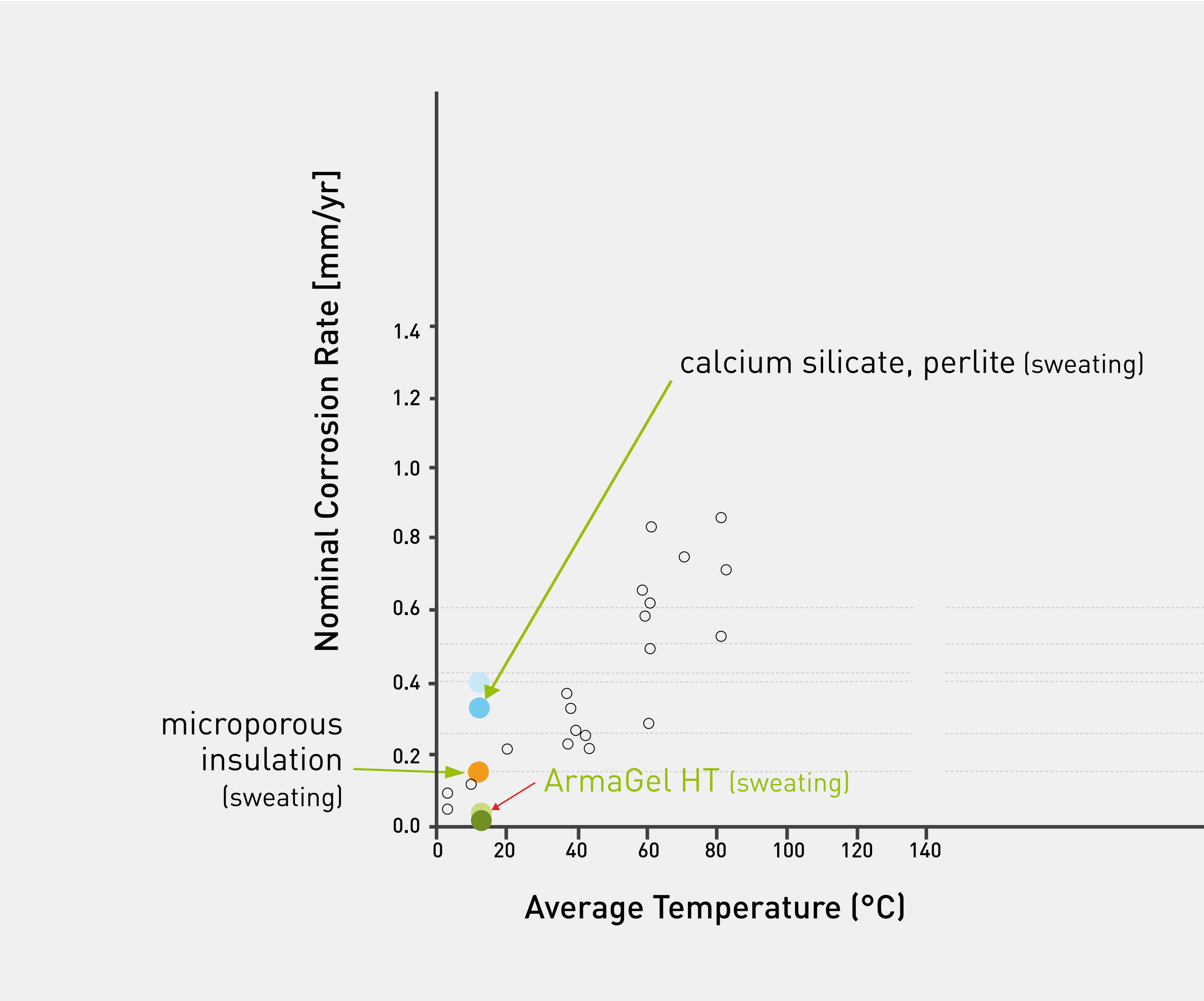
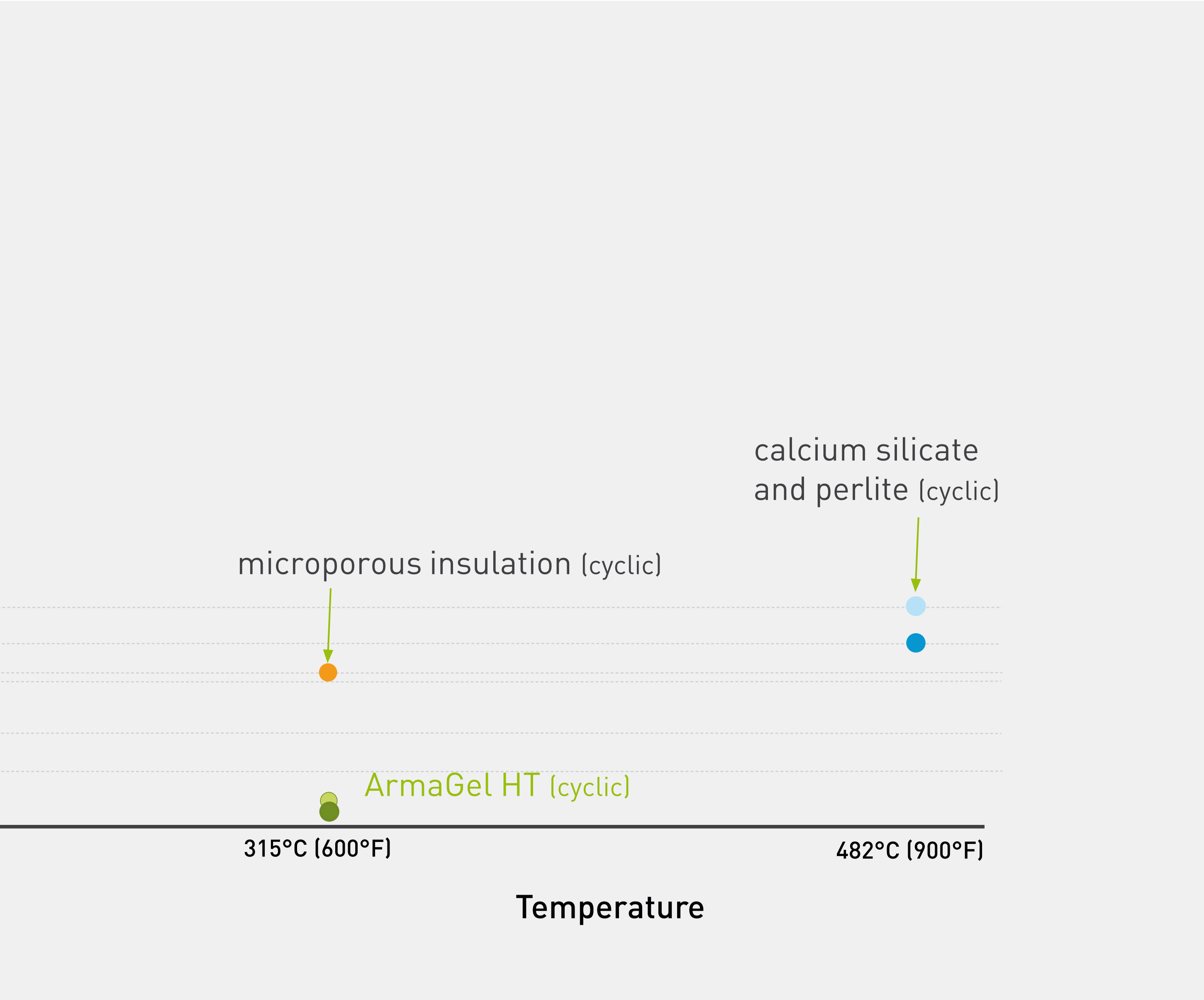


Fig.9: Comparison of the annual corrosion rate of various insulation materials tested in defined operating temperature conditions.



○ Examples of other insulation materials provided by NACE SP0198

KEY FINDINGS AND CONCLUSIONS

Based on visual, electrochemical, and ultrasonic thickness analysis, the morphology of bare carbon steel after 188 days of testing **ArmaGel HT** in wet conditions showed evidence of corrosion. The corrosion morphology was comparable among all the specimens tested with more significant corrosion found on specimens after high temperature cycling test. ArmaGel specimens after continuous sweating (condensation) test exhibited minimal corrosion with few shallow isolated pits.

Nominal average corrosion rates measured with electrochemical (EIS) technique for the continuous sweating and high temperature cyclic conditions were 30 µm/year (±15 µm/year) and 33 µm/year (±2 µm/year), respectively. These values are in good agreement with ultrasonic thickness (UT) measurements. See Table 3.

	Continuous sweating (condensation) test	**High temperature cycle test**
Bare carbon steel shows presence of corrosion after 188 days of testing. Corrosion morphology is comparable among all specimens tested.	Minimal corrosion with few isolated pits	More significant corrosion and shallow isolated pits
Nominal average corrosion rates measured with electrochemical (EIS) technique are in good agreement with ultrasonic thickness measurements.	**30 µm/y** (±15 µm/y)	**33 µm/y** (±2 µm/y)
Corrosion rates	**Comparable** to those reported in previous investigations but below those reported in the literature	**Below** those reported for similar test conditions

Table 3: Annual corrosion rate of the tested pipe specimens.

Corrosion rates for ArmaGel HT tested under continuous sweating conditions were comparable to those reported in previous investigations but lower than those reported in the literature for other insulation materials. For high temperature cycle case the corrosion rates for ArmaGel HT appeared to be on the low side of those reported for other insulation materials in similar test conditions.

Based on the test results the maximum corrosion rate may be approximately 50 µm/year for both sweating and cyclic conditions. This is equivalent to a corrosion rate of 1.25 mm over 25 years, which equates to ⅛ of the wall thickness for the pipe wall of 10 mm. This corrosion rate is considered by a number of major operators to be an acceptable design target considering that these results are based on a bare carbon steel pipe. Generally, it may be considered that a coating, providing additional protection, would normally be applied in the field. See Fig. 10. A further conclusion from the investigation is that ArmaGel HT Insulation showed high hydrophobicity. The hydrophobic performance (even at elevated temperatures) of the material under test was clearly a notable feature of the product. It was acknowledged that ArmaGel HT had a uniquely strong behaviour which was expected to offer significant advantages in the field.

The value of pH = 9 measured at the surface of the pipe is considered positive for CUI mitigation.

- Corrosion rates of 50 µm/y for both scenarios, would equate 1.25 mm per 25 years - which satisfies the design requirements of ⅛ to ⅙ of the wall thickness for a pipe wall of 10 mm (for uncoated condition)
- Insulation showed high hydrophobicity (even at high temperatures), which is believed to offer significant advantages in the field
- Value of pH = 9 measured at the pipe surface is considered favourable for CUI mitigation

Fig.10: Key findings and conclusions of TG516 test with ArmaGel HT. Corrosion rate in relation to the thickness of pipe wall, hydrophobicity and pH value.

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// Written by

Jarema Chmielarski
Technical Manager,
Armacell Engineered Systems
Targowa 2
55300 Środa Śląska
Poland

// In cooperation with

Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78238,
USA

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ABOUT ARMACELL

As the inventors of flexible foam for equipment insulation and a leading provider of engineered foams, Armacell develops innovative and safe thermal, acoustic and mechanical solutions that create sustainable value for its customers. Armacell's products significantly contribute to global energy efficiency making a difference around the world every day.
With 3,135 employees and 24 production plants in 16 countries, the company operates two main businesses, Advanced Insulation and Engineered Foams. Armacell focuses on insulation materials for technical equipment, high-performance foams for high-tech and lightweight applications and next generation aerogel blanket technology. For more information, please visit: www.armacell.com.

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