CUI Testing of Mineral Wool with a Corrosion Inhibitor to Stringent Industry Standards

White paper by Farhan Qadir and Ricky Seto,
ROCKWOOL Technical Insulation

Introduction

In industrial facilities, unseen threats are often the most dangerous — and few are as harmful as corrosion under insulation (CUI). Responsible for a significant proportion of piping and equipment failures, CUI silently progresses beneath insulation systems, where trapped moisture and elevated temperatures accelerate metal loss. Despite billions of dollars spent annually on maintenance and repairs, CUI remains a significant contributor to unplanned outages, safety incidents, and reduced asset life across the oil and gas, petrochemical, and other heavy industrial sectors. By some estimates, CUI accounts for up to 60% of pipeline maintenance costs [1].

How CUI Occurs

CUI develops when water in the form of rain, condensation, or process leakages penetrates the protective cladding/jacketing, becomes trapped within the insulation system, and migrates to contact the metal pipe surface. Factors such as damaged jacketing or poor joint sealing can allow moisture ingress. Industry standards, including NACE SP0198 and API RP583, state that the riskiest temperature range for CUI on metal pipes and equipment made from carbon steel is 50–175°C (122–347°F) [2]. Thermal cycling from operations can accelerate oxidation and extend the CUI temperature range to processes operating as low as -12°C (10°F). Over time, this hidden attack compromises wall thickness, weakening the asset until leaks or failures occur. Because the insulation system conceals the damage, CUI often progresses unnoticed until significant deterioration has already occurred.

Industries have relied on mineral wool insulation for decades due to its thermal efficiency, fire resistance, and ease of installation. However, mineral wool's vulnerability to moisture ingress has made it a focus in the fight against CUI. Recent advancements — particularly the integration of corrosion inhibitors directly into mineral wool — aim to slow or prevent the initiation of corrosion on insulated pipelines, especially in high-risk process environments.

Evaluating how insulation systems perform in CUI-prone conditions depends critically on the test standards applied. Since the early 2000s, the go-to laboratory test for determining CUI performance has been ASTM G189, *Standard Guide for Laboratory Simulation of Corrosion Under Insulation* [3]. The ASTM G189 test simulates a CUI environment by cycling specimens between wet and dry conditions over insulated steel to assess corrosion behavior.

A recently introduced testing standard, the TM21549 method (*Test Method for Assessing the Impact of an Insulation Material on the Corrosion of Austenitic and Ferritic Steels under Laboratory Conditions*), also incorporates wet and dry cycles over insulated pipe sections [4].

While both test methods are similar at a high level, they differ in critical ways. This paper compares the ASTM G189 and TM21549 CUI test methods, assessing their differences and similarities. The paper also presents results from mineral wool and alternative insulation types tested to both standards and analyzes them to reveal how evolving methodologies influence performance assessments. By understanding these differences, industry professionals can make more informed decisions about material selection and CUI mitigation strategies in the decades ahead.

Experimental Procedure

ASTM G189 Test Methodology

ASTM G189 provides a framework for replicating the wet/dry thermal cycling that drives CUI in industrial service. The method is primarily used as a comparative testing tool to evaluate insulation materials, coatings, and corrosion-inhibitor technologies before introducing them to the field. ASTM G189 is not a pass/fail standard but instead enables users to simulate specific service conditions and their effects on the corrosion of pipe segments.

Test Setup Requirements. While the method is suitable for testing pipe specimens of any material, carbon steel is the material most commonly tested. The test requires at least three pipe specimens, insulated from each other by a non-porous and non-conductive ring. A spacer is used between the rings to allow for two separate test measurements. The pipe specimens are prepared from a 2-inch nominal-diameter pipe material with a thickness of 3/16 inch (4.75 mm) and a width of 1/4 inch (6.35 mm). Before testing, specimens are cleaned, degreased, and weighed to facilitate the calculation of material loss after testing. The selected insulation material is then fitted around the specimen, with aluminum or stainless-steel jacketing applied to replicate field installations.

An immersion heater located inside maintains the temperature of the pipe sections, and temperatures are monitored during testing using a thermocouple.

Water is introduced into the test cell through holes drilled into the jacketing and insulation. A metering pump delivers the water directly to the pipe surface through tubing installed in the test cell holes. Two holes on the bottom of the pipe test cell allow water to drain out.

Electrochemical testing is an optional feature of the tests, allowing for the measurement of instantaneous corrosion rates during testing.

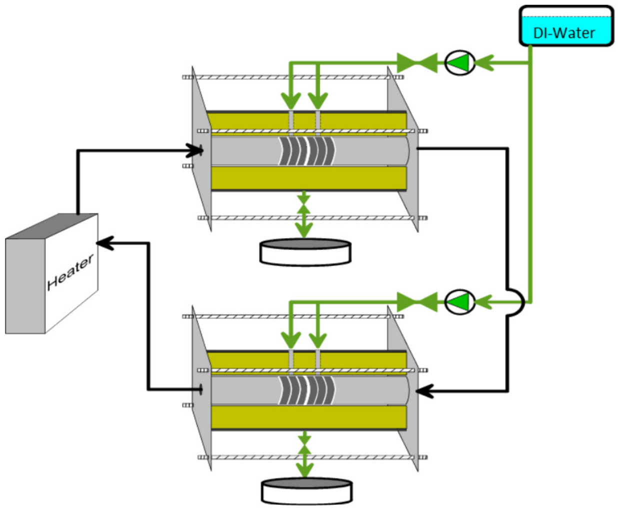

Figure 1. Schematic of the customized test setup for ASTM G189.

Test Cycling Procedure. Insulated specimens are placed in a controlled environmental chamber, where they undergo repetitive, cyclic wet/dry conditions representative of field conditions. Users can select their own cyclic conditions, thereby mimicking the criteria they are most concerned with. However, the test does provide some guidelines for testing conditions, as shown in Table 1.

A typical 24-hour cycle begins with a wetting phase lasting 20 hours, during which the pipe sections are wetted by pumping the test electrolyte (deionized water) at a boosted flow rate to fully wet the test cell, followed by a maintenance flow rate and under a fixed temperature (for example, 60°C [140°F]) and a defined flow rate. The wetting phase is followed by a 4-hour drying phase, during which the electrolyte pump is turned off, and the test cell is typically exposed to a higher temperature (e.g., 150°C [302°F]).

The tester can decide the temperatures of the specimens during the wetting and drying stages. However, it is generally recommended to set the temperature within the range where CUI is prevalent. The user can determine the chemistry of the pumped electrolyte, such as distilled water or a specific chloride concentration.

Test Duration and Evaluation. The test does not provide specific recommendations on the duration or number of cycles. Standard testing durations typically range from 10 to 30 cycles for preliminary comparisons, with extended studies exceeding 60 cycles to produce advanced corrosion morphologies.

Upon completion, the insulation materials are carefully removed, and the test specimens are weighed before cleaning. The specimens are then cleaned in accordance with ASTM G1 [5] and weighed again. Post-test evaluation includes weight-loss measurements to determine the average corrosion rate, as well as a visual examination for general corrosion, pitting, and under-deposit attack.

This paper provides ASTM G189 test results performed with the following materials:

- Mineral Wool without inhibitor
- Mineral Wool with inhibitor
- Perlite
- Aerogel

Cyclic testing was conducted with the following conditions (Table 1):

Table 1. Cyclic Watering Procedure

Step	Wet	Ramp up	Dry	Ramp down
Temperature [°C] (°F)	60 (140)	60 to 150 (140 to 302)	150 (302)	150 to 60 (302 to 140)
Duration [hr]	18	1	4	1
Water injection	40 ml/10 min. +2.5 ml/hr	No	No	No

The test lasted 21 days, and deionized water was used as the test fluid to assess the insulation's impact.
The test coupons were made from 2-inch nominal diameter carbon steel pipes (ASTM A106 Grade B) with a width of 14.3 mm.

TM 21549 Test Methodology

The AMPP TM21549-2024 standard outlines a comprehensive method for evaluating the influence of insulation materials on CUI of bare metal substrates. Designed for use across various industries, the method provides a *relative performance assessment* under simulated and accelerated field conditions, rather than relying on simple pass/fail criteria. Like ASTM G189, this test involves various CUI temperature conditions and realistic wet/dry and hot/cold cycles that promote corrosion development.

Test Setup Requirements. The **test setup** in AMPP TM21549-2024 is designed to realistically simulate CUI conditions across a range of temperatures. The standard describes two main apparatus configurations — one for low-to-moderate temperature testing ranging from 10°C to 175°C (50°F to 347°F), and another for high-temperature testing above 175°C (347°F). This separation ensures that corrosion behavior can be accurately captured under the specific thermal and mechanical stresses generated by each condition.

In the **low-temperature configuration**, inline spools are connected using electrically isolating couplings that ensure each spool acts as its own independent electrochemical system, preventing galvanic interaction between specimens. The spools are equipped with thermocouples to precisely monitor surface temperature and are sealed to prevent leakage at connection points. The spools are wrapped in the test insulation material, jacketed, and then placed in an immersion environment containing the test solution. The entire assembly is designed to enable accurate control of wetting and drying cycles, ensuring consistent exposure and drying times.

For the **high-temperature configuration**, each spool is housed in its own independent vessel, rather than forming a connected inline system. This design accommodates higher thermal expansion and contraction without damaging seals or insulation integrity. Compression rings are used to maintain a secure fit while allowing for expansion and contraction during heating and cooling cycles. Heating is achieved using internal electric heater rods or similar thermal control devices. This configuration helps replicate the more extreme operating environments found in industries such as high-temperature steam systems and refinery units.

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In both low- and high-temperature configurations, carbon steel pipe sections of specific dimensions are used as the test specimens. The test standard recommends a spool size of 12 in (30 cm), while no recommendation is provided for pipe diameter. Each spool features four equally spaced, 6.35-mm (¼-inch) diameter holes drilled radially through the jacketing and insulation to facilitate water ingress to the outer pipe surface beneath the insulation. These holes are crucial for ensuring moisture can reach the metal surface during wet cycles, thereby accelerating the CUI phenomenon under study.

Once prepared, the spools are wrapped with insulation per the manufacturer's installation guidelines and then covered with protective jacketing. Care is taken to ensure that the external setup mimics field application as closely as possible. This realistic application method is critical in observing how insulation and jacketing configurations influence the rate and severity of corrosion development during CUI testing.

Test Cycling Procedure. The cycling procedure follows a standard schedule of five wet/dry cycles each work week, starting with wetting at 8 am and drying at 5 pm for five days, followed by two days of drying. The cycles are alternated between low- and high-temperature conditions on alternate days, as per the recommended weekly profile. The first four weeks use deionized water as the wetting solution, followed by a 1,500-ppm chloride solution for the remaining eight weeks, with fresh solution added for each wet cycle. Appendix A of the standard also provides recommended temperature profiles, allowing for customization based on user requirements.

Test Duration and Evaluation. The minimum test duration is three months, although longer periods may be used depending on the objectives. At the end of the test, a detailed visual inspection is performed, and, as in ASTM G189, weight-loss measurements are obtained after cleaning the spools in accordance with ASTM G1. Metallurgical analysis is performed to assess pit depth and overall metal loss using techniques such as ultrasonic testing or microscopy for more detailed corrosion characterization. Additional pH measurements at the pipe surface beneath the insulation are also recommended to provide further insight into conditions that developed during testing.

Electrochemical measurements are optional in this standard.

This paper provides TM 21549 test results with the following materials:

- Mineral Wool without inhibitor
- Aerogel
- Control without insulation

The following cycling, as per test method TM21549, was used (Table 2):

Figure 2. Representative pictures of the test specimens.
Top: uninsulated control specimens, Bottom: Mineral wool with inhibitor insulation.

Table 2. TM 21549 Cyclic Conditions

Day/Time		Wet/Dry Condition	Heater Temperature, °F (°C)
Monday	7:00 am	Fill (wet)	70 (21)
	4:00 pm	Drain (dry)	
Tuesday	7:00 am	Fill (wet)	300 (149)
	4:00 pm	Drain (dry)	
Wednesday	7:00 am	Fill (wet)	70 (21)
	4:00 pm	Drain (dry)	
Thursday	7:00 am	Fill (wet)	300 (149)
	4:00 pm	Drain (dry)	
Friday	7:00 am	Fill (wet)	70 (21)
	4:00 pm	Drain (dry)	

During weekends, the specimens were left in dry, 70 °F temperature conditions.

The specimens tested were made from nine uncoated, 2-inch nominal-diameter, Schedule 40, low-grade A500 carbon steel pipe spools. Three pipe spools were then insulated with aerogel insulation and cladding per the manufacturer’s installation guidelines. Three other specimens were insulated with mineral wool with inhibitor technology and cladding in accordance with the manufacturer’s standard installation requirements.

Results

ASTM G189-21 Test Results

After completing the test cycles, the test specimens were cleaned and weighed to determine the amount of weight loss. Figure 3 shows the weight loss resulting from the cyclic wet/dry conditions on the pipe samples. An average uniform corrosion rate was also calculated (indicated by the dashed lines in Figure 3).

Table 3 presents the localized corrosion results (as measured by pit depth) for each sample, while Figures 4-7 display the appearance of the top and bottom of the test specimens before and after cleaning.

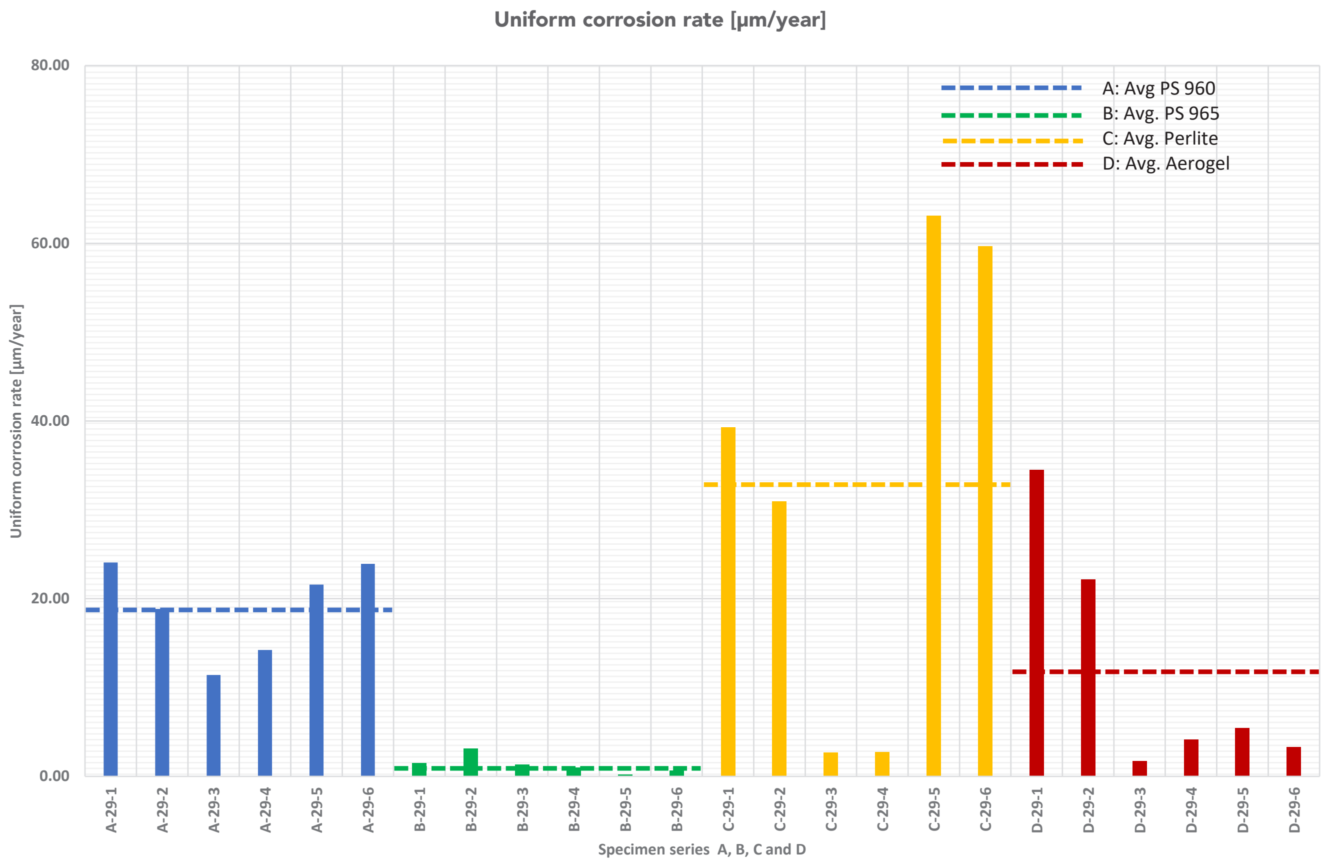
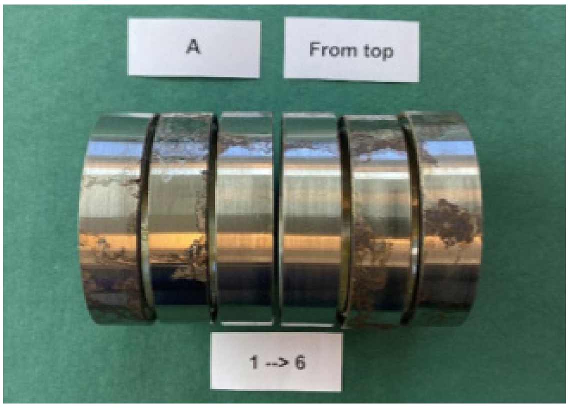


Figure 3. Corrosion rate results for each test specimen per ASTM G189-21 test.

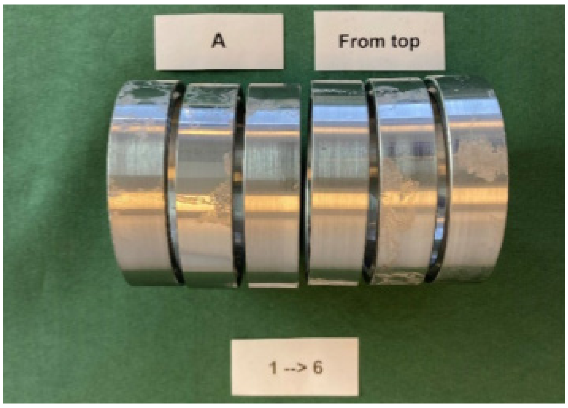
Table 3. Localized Corrosion Results for each specimen

Calculated Pit Depth (μm)																								
	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
Deepest pit depth	20	159	42	48	57	78	30	32	17	15	9	19	79	110	16	25	67	68	102	90	36	79	10	10
Average pit depth	28	82	35	53	62	64	26	36	34	13	16	44	98	114	25	33	71	87	98	97	38	64	8	8

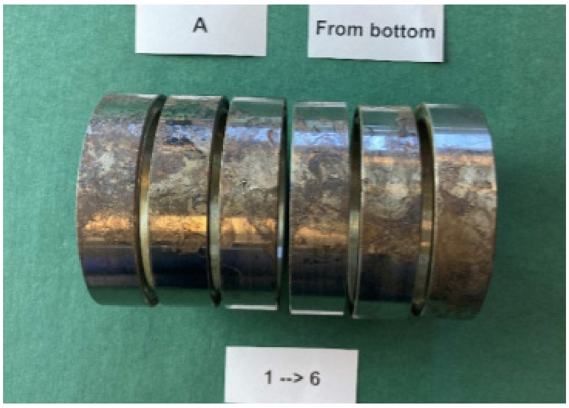
Figure 4. Pictures of Mineral Wool w/o Inhibitor Samples After Test



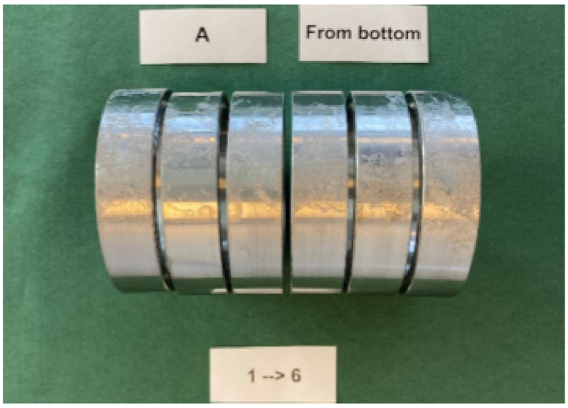
Sample A. After test, before cleaning. Top view.



Sample A. After cleaning. Top view.

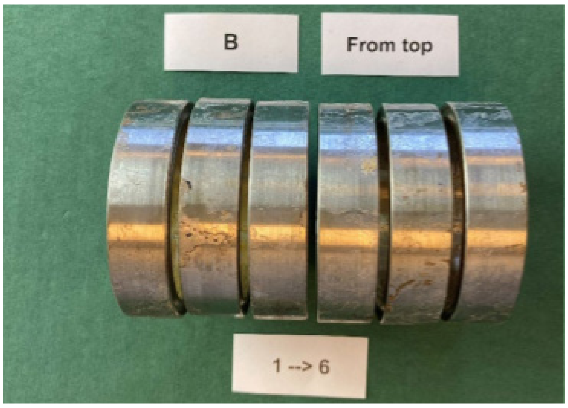


Sample A. After test, before cleaning. Bottom view.

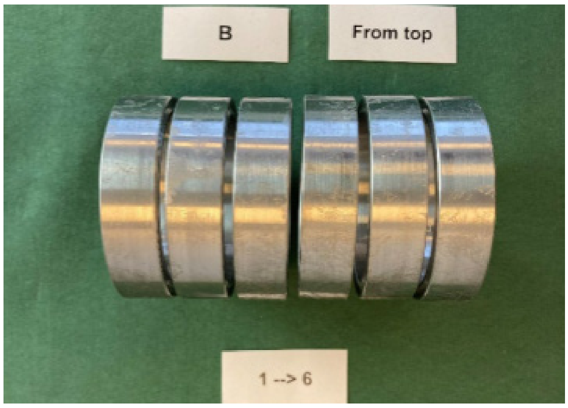


Sample A. After cleaning. Bottom view.

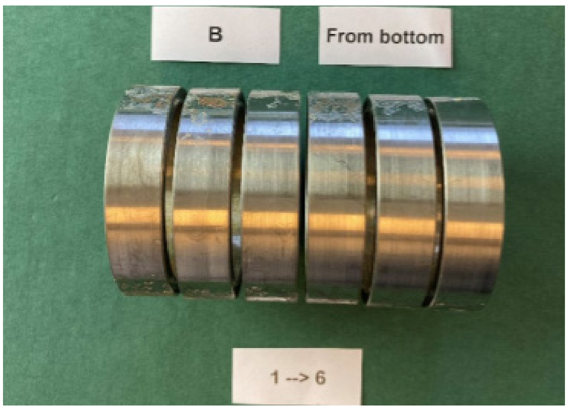
Figure 5. Pictures of Mineral Wool with Inhibitor Samples After Test



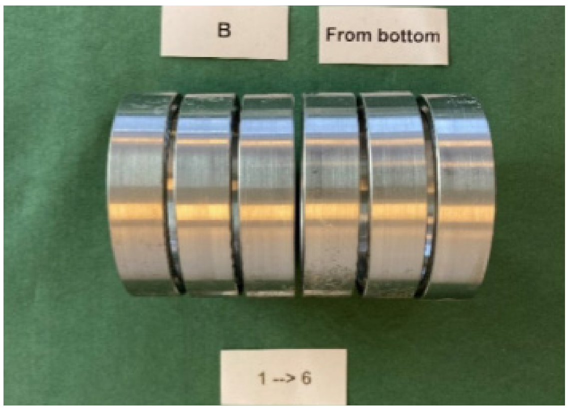
Sample B. After test, before cleaning. Top view.



Sample B. After cleaning. Top view.

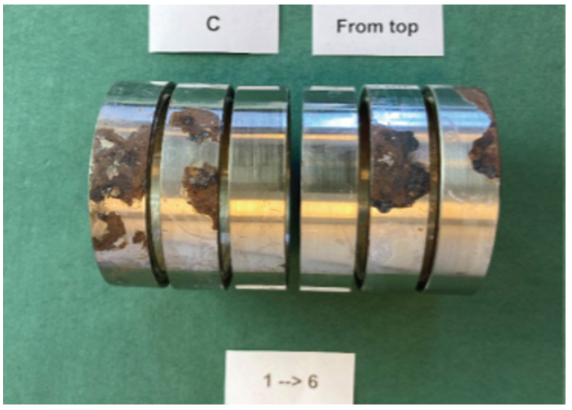


Sample B. After test, before cleaning. Bottom view.

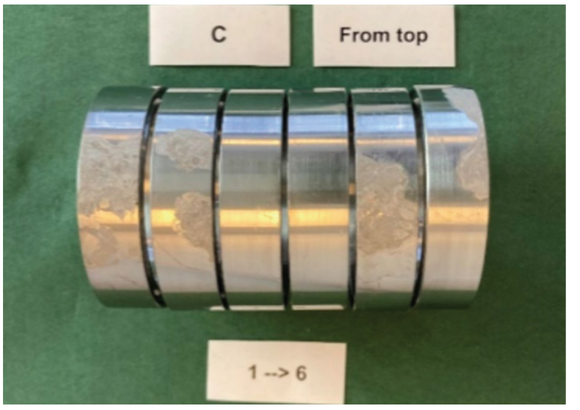


Sample B. After cleaning. Bottom view.

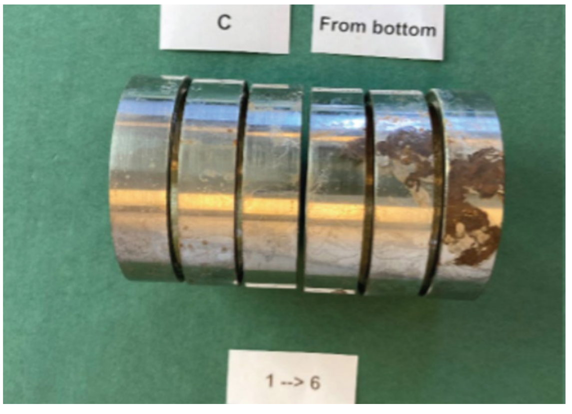
Figure 6. Pictures of Perlite Samples After Test



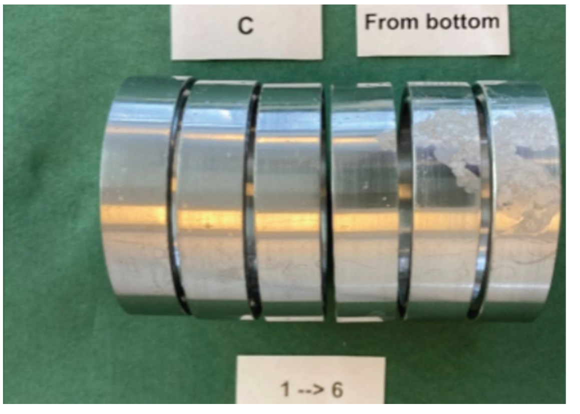
Sample C. After test, before cleaning. Top view.



Sample C. After cleaning. Top view.

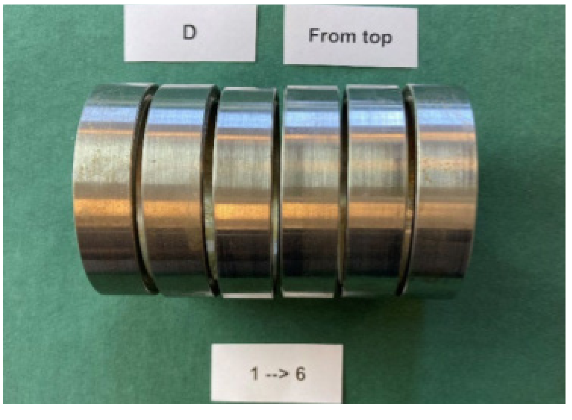


Sample C. After test, before cleaning. Bottom view.

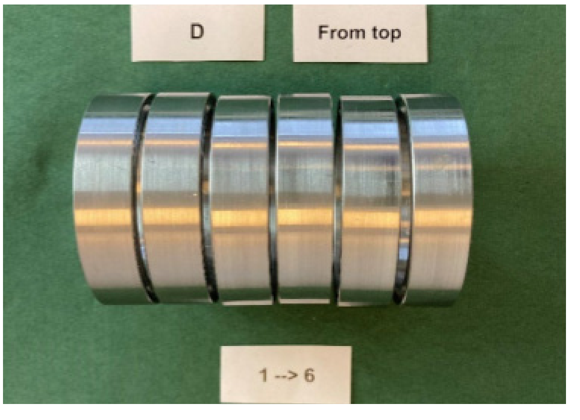


Sample C. After cleaning. Bottom view.

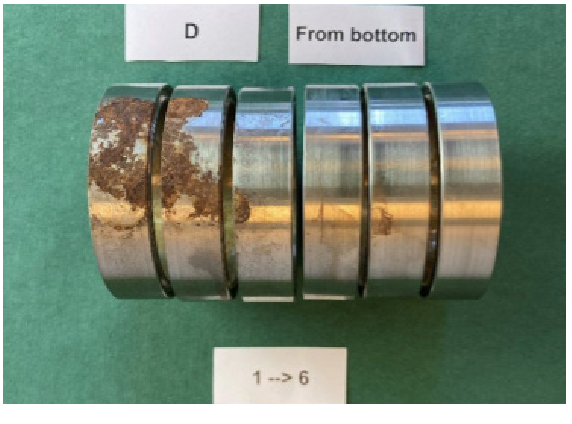
Figure 7. Pictures of Aerogel Samples After Test



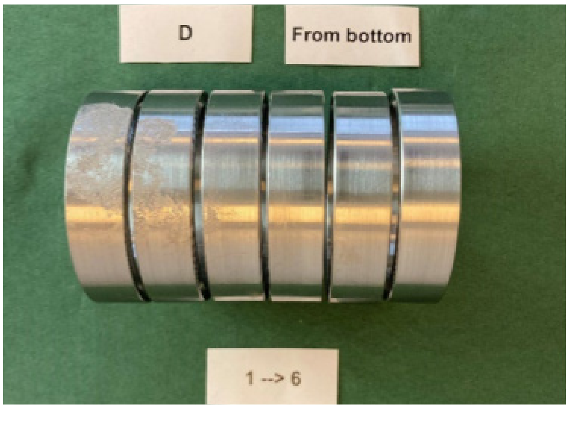
Sample D. After test, before cleaning. Top view.



Sample D. After cleaning. Top view.



Sample D. After test, before cleaning. Bottom view.



Sample D. After cleaning. Bottom view.

ASTM TM21549-24 Test Results

After completing the test cycles, the pipe sections were analyzed to determine the impact of the wet/dry cycling. Table 4 displays the results of a localized corrosion analysis, commonly referred to as pitting, and Table 5 shows the weight-loss analysis that predicts overall corrosion rates. Figures 8-10 show the test samples (top and bottom) after cleaning.

Table 4. Localized Corrosion Analysis Results after the Test as per ASTM G46 Standard

Specimen ID	Insulation Type	Pit Depth (μm)	Pit Density	Measured Pit Depth (μm)
1A	Mineral Wool with Inhibitor	C1	A3	50
2A		C1	A3	100
3A		C1	A3	10
4B	Aerogel Blanket	C1	A4	300
5B		C1	A4	240
6B		C1	A3	200
7	Control (no insulation)	C1	A2	5
8		C1	A2	20
9		C1	A2	15

Table 5. Results of Weight Measurements and Computed Corrosion Rates

Specimen ID	Insulation Type	Pre-Weight (g)	Post-Weight (g)	Δm (g)	CR (mm/y)	$CR_{Avg.}$ (mm/y)	$CR_{Std. Dev}$ (mm/y)
1A	Mineral Wool with Inhibitor	1,559.47	1,548.59	10.88	0.124	0.14	0.03
2A		1,572.40	1,557.51	14.89	0.170		
3A		1,563.85	1,553.27	10.58	0.121		
4B	Aerogel Blanket	1,544.05	1,527.57	16.48	0.188	0.16	0.02
5B		1,528.54	1,514.66	13.88	0.158		
6B		1,580.03	1,567.23	12.80	0.146		
7	Control (no insulation)	1,533.40	1,530.19	3.21	0.037	0.03	0.01
8		1,613.40	1,611.74	1.66	0.019		
9		1,627.90	1,625.25	2.65	0.030		

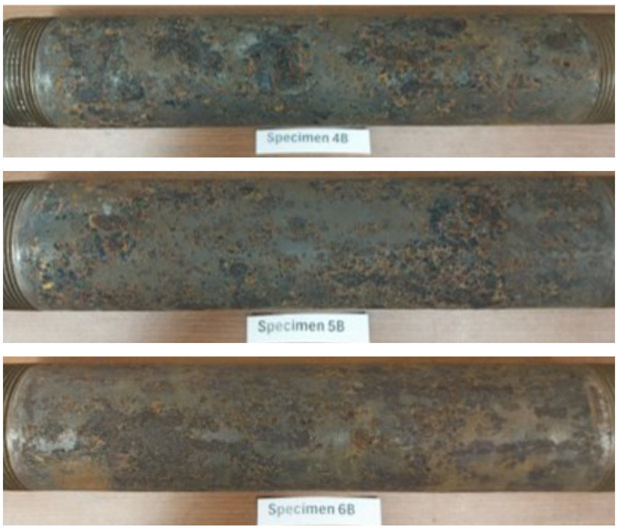
Figure 8. Pictures of Mineral Wool with Inhibitor Samples After Cleaning

Top.

Bottom.

Figure 9. Pictures of Aerogel Samples After Cleaning

Top.



Bottom.

Figure 10. Pictures of Control Sample with No Insulation

Top.

Bottom.

Discussion

While their setups differ, ASTM G189-21 and AMPP TM21549-2024 possess several similarities.

- Both tests aim to provide reproducible, comparative data to understand how materials perform under CUI conditions.
- Both use laboratory-based test methods to evaluate CUI by simulating service-like conditions involving wet/dry cycling, temperature control, and insulated specimens.
- Both tests introduce water to the pipe surface through holes drilled through the insulation to the pipe.
- Each standard allows for the assessment of various materials, coatings, and insulation systems, and includes detailed procedures for sample preparation, environmental condition control, and post-test corrosion measurements, such as mass loss, pitting analysis (ASTM G46), and wall-thickness evaluation.
- Ultimately, the results from both tests support informed material selection and protection strategies.

Key differences also exist between the tests, which impact test outcomes.

Guide versus Prescriptive Test

ASTM G189 is intentionally designed to allow the user to tailor the test to mimic the field conditions being studied. For example, the test provides some example test parameters for cycles and fluid chloride content, but it does not provide any prescriptive guidelines. While the TM21549 can be used to study various conditions, it also provides more prescriptive, defined wet/dry cycle conditions, as well as chloride content, as standard test conditions.

Both tests have advantages and disadvantages. ASTM G189's more open test design allows for broader study, providing users with the flexibility to develop their own scenarios. However, this also makes it more difficult to compare results across tests unless the same conditions are used. Although the more prescriptive TM21549 test yields a more standardized comparison of test results, these results may not be suitable for all conditions.

Overall, the results between the tests are similar. For example, the mineral wool with inhibitor and aerogel performed well in both tests regarding average uniform corrosion rates. The average corrosion rates were higher in the TM21549 test, which could be attributed to the chloride content in that test (only deionized water was used in the ASTM G189 test).

Specimen Size

ASTM G189 requires smaller, 14.3-mm (0.56-in) wide samples, as compared to the longer 305mm (12-in) samples needed for the TM 21549 test. Smaller samples have the advantage of a smaller test assembly for each sample. Six different samples can be simultaneously tested in ASTM G189 in a relatively small space.

Conversely, the TM21549 test samples create space limitations that usually limit testing to three samples at a time. However, the larger samples allow for a better visual representation of the pipe sections and how corrosion progresses over longer sections.

The smaller samples provide a more accurate calculation of corrosion loss, as the weight loss occurs on a smaller base than in the larger sample. Without significant weight loss, it becomes more challenging to detect losses in a larger sample.

Pumped Fluid versus Submerged in Fluid

One of the most significant differences between the tests is the method used to introduce the water. In ASTM G189, the water is pumped to the pipe surface, whereas in TM21549, the pipe sections are submerged under water. Both methods are good ways to study CUI, given that it is widely accepted that water will find its way through the insulation system one way or another in the real world. However, ASTM G189's pumping method removes any advantage the insulation's water repellency would have on the corrosion rate. In contrast, the TM21549 method enables water-repellent insulation to perform its function and minimize water ingress to the pipe surface.

Results Comparison

In both tests, the mineral wool with inhibitor and the aerogel resulted in generally low corrosion rates on the test specimens, with the mineral wool with inhibitor having an advantage. While not studied in the TM21549 test, the mineral wool with inhibitor performs significantly better than the mineral wool without inhibitor in the ASTM G189 test. While the uniform corrosion rates were similar for aerogel insulation and mineral wool, a significant difference in localized corrosion rates was observed between the aerogel and mineral wool samples with inhibitors in both tests. This can be attributed to the vapor-open structure of mineral wool, which allows water in the insulation to evaporate out more easily. The closed structure of aerogel traps water that gets in, leading to higher localized corrosion.

Conclusion

Both ASTM G189-21 and AMPP TM21549-2024 effectively replicate corrosion under insulation (CUI) conditions, providing valuable comparative data on material performance. While similar in objective and general approach, they differ in flexibility, specimen size, and the method of water introduction—factors that can influence test outcomes. ASTM G189 offers greater flexibility for tailoring conditions to specific scenarios, but it can limit direct comparability across studies. In contrast, TM21549's prescriptive parameters enable more standardized comparisons but may not capture all field conditions.

Smaller specimen sizes in ASTM G189 enable more efficient use of space and greater sensitivity to weight loss, while TM21549's larger specimens better represent real pipe sections. Differences in water delivery—pumped in accordance with ASTM G189 versus submersion in accordance with TM21549—can affect the role of insulation water repellency on corrosion rates. Despite these variations, both tests show consistent trends: mineral wool containing inhibitors outperforms aerogel in localized corrosion resistance, and both insulation types show generally similar overall uniform corrosion rates. It is also observed that mineral wool with an inhibitor significantly outperforms mineral wool without an inhibitor in terms of CUI mitigation.

References

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