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Energy Report
Method for Qualification of Coatings Applied to Wet Surfaces

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Method for Qualification of Coatings Applied to Wet Surfaces	DNV COLUMBUS, INC. Materials & Corrosion Technology Center 5777 Frantz Road Dublin, OH 43017-1386, United States Tel: (614) 761-1214 Fax: (614) 761-1633 http://www.dnv.com http://www.dnvcolumbus.com
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Prepared by:	*Name and Position* Feng Gui Senior Engineer	*Signature*
Verified by	*Name and Position* C. Sean Brossia Director – Program Development	*Signature*
Approved by:	*Name and Position* C. Sean Brossia Director – Program Development	*Signature*

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EXECUTIVE SUMMARY

The field application of a pipeline repair or rehabilitation coating usually cannot wait until ambient conditions become optimal. In a humid environment, water can condense on the pipe surface because the pipe surface is usually cooler than the ambient air. For buried pipelines, the surface temperature is typically 40-60^{o}F, which easily facilitates condensation on the pipe surface. In such situations, although the surfaces are not perfect for coating application, they have to be coated due to the need to backfill the excavation the site and rebury the pipe.

To meet the requirements of applying coatings on wet surfaces, several coating manufacturers are producing "wet surface tolerant" products. The wet surface tolerance claim is based on the coating's ability to displace small amounts of water on the surface during application. This does not address the fundamental problem that the coating must be able to cure, adhere, and maintain integrity when applied to a non-ideal substrate. Evaluation of suitable products by end-users is extremely difficult because it requires complete control of the steel surface during application and cure.

The objectives of this work, therefore, were first to develop a testing rig that can simulate the conditions encountered in the field when conducting coating repairs. Coatings were then applied to pipe spool pieces in this testing rig for performance evaluation both in the lab and in the field. Secondly, a methodology was developed to screen and evaluate coating candidates for a specific application. Through this development process, critical parameters that can be used to evaluate the coating performance were identified.

Based on the results, the key findings include:

- A testing rig was developed and constructed to enable the simulation of water condensation encountered in the field; it was found that water continuously condensed on the pipe surface and thus it better simulates the field condition than forming wet surfaces by misting (water spraying);

- Coatings should be applied under humid conditions created properly in the lab to conduct valid evaluation of the coating performance;

- The tested coatings were able to achieve relatively uniform performance at different o'clock positions on the pipes tested in the lab. When applied in the field, however, extra effort might be necessary to facilitate water displacement since the pipes are typically larger than those used in the lab;

- Relative humidity level had significant impact on the coating performance. Therefore, it might be necessary to consider (if possible) conducting coating repair under conditions where the lowest relative humidity can be achieved (dry season or avoid raining days);

- The wet coating products were ranked initially by the adhesion strength, which was the same as the performance ranking obtained in the long term lab testing by cathodic disbondment, EIS and water soaking tests;

- The performance ranking obtained in the one year field testing was consistent with that observed in the lab testing. The difference in the performance between coatings (two evaluated) was smaller in the field than in the lab (that is there was greater separation in the relative performance of the coatings tested in the lab than in the field);

- The post-cure adhesion strength could be used as an initial screening parameter to select coatings for wet surface application assuming the wet condition was created properly. However, relatively longer term evaluation is also necessary to further evaluate the coating performance so that properties, such as water permeability, should be considered as well in selecting the best product for application; other properties, such as impact resistance and bend resistance should also be considered in evaluating a coating product.

1 INTRODUCTION

The field application of a pipeline repair or rehabilitation coating usually cannot wait until ambient conditions become optimal. In a humid environment, water can condense on the pipe surface because the pipe surface is usually cooler than the ambient air. For buried pipelines, the surface temperature is typically 40-60^{o}F, which easily facilitates condensation on the pipe surface. In such situations, although the surfaces are not perfect for coating application, they have to be coated due to the need to backfill the excavation site and rebury the pipe.

To meet the requirements of applying coatings on wet surfaces, several coating manufacturers are producing “wet surface tolerant” products. The wet surface tolerance claim is based on the coating’s ability to displace small amounts of water on the surface during application. This does not address the fundamental problem that the coating must be able to cure, adhere, and maintain integrity when applied to a non-ideal substrate. Evaluation of suitable products by end-users is extremely difficult because it requires complete control of the steel surface during application and cure.

Because coating formulations are trade secrets, it is not possible to determine if a product has been formulated to actually be suitable for wet surfaces. During a field repair, some wet surface tolerant coating products failed immediately after application as reported by an undisclosed gas transmission company. Clearly, the in-house development and qualification testing by the manufacturer for this product did not measure the critical properties for continued performance or the conditions at which the coating products were evaluated did not closely simulate conditions that could be encountered in the field. Currently, there are no standards for testing the wet surface tolerance of any coatings, and field simulations or field trials are limited to the existing ambient conditions.

The objectives of this work, therefore, were first to develop a testing rig that can simulate the conditions encountered in the field when conducting coating repairs. Coatings were then applied to pipe spool pieces in this testing rig for performance evaluation both in the lab and in the field. Secondly, a methodology was developed to screen and evaluate coating candidates for a specific application. Through this development process, critical parameters that can be used to evaluate coating performance were identified.

2 EXPERIMENTAL

Materials

The five wet surface tolerant coating products used in this work are listed in Table 1. The coating products were applied to 8″ (OD) × 8″ (L) X42 pipe steel spool pieces. Prior to coating application, the pipe surface was abrasive blasted to near-white finish per NACE#2/SSPC-SP10[1]. The blasted and cleaned pipe was then wiped to remove any loose particles and debris with a wet paper towel.

Testing Rig

Figure 1 is the developed testing rig that was used to simulate the field conditions to form condensation on the tested pipes prior to coating application. The testing rig consists of a chamber constructed from plexglass that contains a humidity control unit, a temperature control unit, and two sets of gloves for accessing and coating the samples inside the chamber. A humidity sensor was also installed inside the chamber to feed the signal to the humidity control units. On the interior side of the chamber top, a misting device consisting of three nozzles was installed and it was also used to spray water onto the pipe samples.

Coating Application

Coatings were applied in the developed testing rig. The cleaned pipe was assembled with acrylic end caps, placed on metal stands, and installed in the coating application chamber, as shown in Figure 2. The pipe surface temperature was maintained at approximately 50°F during coating application in wet conditions by flowing chilled water through the pipe ID using a temperature-controlled water recirculation bath, while the dry "control" pipe was at room temperature. When condensation was observed on the pipe surface (Figure 3), usually within 1.5 hours after reaching the desired humidity (70% or 85%) and temperature level, the coating was applied to the pipe. Each coating product was applied with a roller following the specifications provided by the manufacturers to both wet and dry pipe surfaces in order to compare the resultant coating performance as a function of application environment. For coating under dry conditions, the coating was applied to the pipe after it was assembled with another stand under normal laboratory conditions. The room temperature and humidity were nominally 75°F and < 35% RH. In a few cases, the coatings were also applied in the humidity chamber with water sprayed onto the pipe surface to create wet surfaces. This was done to investigate whether the coating performance would be different on the wet surfaces created from two different methods.

Adhesion Testing

Coating adhesion was determined using the ASTM D4541-95 standard method to measure the pull-off strength of the coating[2]. The adhesive strength of the coating was assessed by measuring the greatest perpendicular force that an area can resist before the coating is detached from the substrate. The main advantage of this test method is that quantitative information can be obtained and compared. A pull-off adhesion tester that conforms to ASTM D4541 appendix A5 was used. The main components of the pull-off adhesion tester are a pressure source, a pressure gauge, and an actuator (Figure 4).

[1] "Near-white Metal Blast Cleaning", NACE No. 2/SSPC-SP10, NACE International (Houston, TX)
[2] "Standard Test Method for Pull-off Strength of Coatings Using Portable Adhesion Testers", ASTM D4541-95, ASTM International (1995)

During operation of the tester, the flat surface of an aluminum dolly was adhered to the coating to be evaluated using two-part epoxy. The strength of the dolly adhesive must exceed the strength of the pipe/coating bond to obtain an accurate measurement. The flat surface of the dollies was properly cleaned with an organic solvent and with an abrasive pad before each use. After allowing the bonding adhesive to properly cure, a coupling connector from the actuator was attached to the dolly (Figure 4)[3]. The test is performed by progressively increasing pressure in the actuator until the dolly pulls away from the surface. The pull-off strength, as indicated by the reading on the tester (in psi) was documented and compared for different coating products. The adhesion tests were performed at the 12, 3 and 6 o'clock positions for the pipes tested in the lab and 12, 3, 6 and 9 o'clock positions for the pipes tested in the field. The dollies were attached to the coating after it was cured (24 hours after application per manufacturer specifications) and the dolly adhesive was allowed to dry for another 24 hours. The coating pull-off strength was thus obtained 48 hours after initial coating application. The dollies used were of sufficiently small diameter to maintain total adhesion with the coating.

Contact Angle Measurement

A wet surface tolerant coating product needs to displace water from the pipe surface in order to adhere properly. In general, the water displacement ability of a liquid can be evaluated by the contact angle of the liquid against water on the surface of interest. In order for the liquid to repel water, a low contact angle is desired. With regard to wet surface tolerant coatings, the product must displace water during application by repelling water and establishing strong adhesion to the surface. To investigate whether the water displacement ability of the coating products had any appreciable impact on their adhesion, the contact angles of the coating droplets against water on a steel surface were measured on pipe steel samples. A droplet of the coating product was applied on a prepared steel surface (i.e., abrasive blasted and cleaned). The sample was then immersed in water and the contact angle of the coating droplet was measured. The contact angle measured using this method reflects the water displacement ability of the coating product. A lower contact angle indicates better water displacement ability.

Long Term Performance Evaluation in the Laboratory

The long term performance evaluation included water soak testing, cathodic disbondment (CD) testing, and Electrochemical Impedance Spectroscopy (EIS) testing of coated samples. The tests were primarily focused on the three wet surface tolerant coating products.

All long term performance evaluation testing was conducted on coated 4 ″× 4″ samples. The coating products were first applied on 8 ″ pipe spool sections and the coated pipe section then was cut into 4 ″× 4″ samples. For the water soak testing, the backside and the cut edge were coated with an epoxy coating for protection and to prevent edge effects. The samples then were

[3] DeFelsko Corporation product image

immersed in deionized (DI) water for 90 days. After 90 days of exposure, the samples were removed for adhesion evaluation. The water soak testing setup is shown in Figure 2.

CD testing was performed according to the instructions in ASTM G95[4]. To accomplish this, acrylic test cells were attached to the 4 in. x4 in. coated samples using silicone sealant. The test set up is shown in Figure 7. Replicates of each coating product applied under both wet and dry conditions were evaluated. Samples were removed after 30 and 90 days and the cathodically disbonded area was evaluated following the instructions in ASTM G95.

The test cell used for EIS testing was similar to that used for CD testing (Figure 8). The samples were exposed to 3.5% NaCl solution (by weight) and EIS was performed periodically over a total exposure time period of three months. Each EIS test was conducted from 100 kHz to 0.1 Hz with a potential magnitude of 100mV_{rms}. The impedance at 0.1 Hz was extracted and used to quantify coating performance.

Long Term Performance Evaluation in the Field

Pipes (8″ OD and 4′ length) were coated under dry and wet conditions for the performance evaluation in the field. The coatings used in the field evaluation were SPC SP 4888 and Tapecoat 7100 wet bond epoxy. The wet condition of the pipe surface was obtained in a small room with humidity controlled since the pipes were too long to fit in the humidity chamber. The coated pipes were allowed to cure for 48 hours then the adhesion strength at selected locations on the surfaces were measured to get the initial readings. These pipes were transported to Virginia and installed along a pipeline that is operated by the co-sponsor of this project. The soil at the installation site was sampled and the soil chemistry was analyzed. The soil chemistry data is shown in Table 2. The layout of the pipes at the installation site is shown in Figure 9. The installed pipes were connected to the cathodic protection system for the pipeline. The pipes were removed from the field after one year of exposure. Pull strength adhesion measurements were performed on 3 o'clock, 6 o'clock, 9 o'clock and 12 o'clock of the tested pipes to obtain the adhesion strength, which was then used to evaluate the coating performance.

3 RESULTS

Effect of O'clock Position

The adhesion strength of the coating at 12 o'clock, 3 o'clock and 6 o'clock positions were performed on the coated pipe samples. Since water tends to drip down along the pipe surface due

[4] "Standard Test Method for Cathodic Disbondment Test of Pipeline Coatings (Attached Cell Method)", ASTM G95, ASTM International (1998)

to gravity effects, it was suspected that this might change the amount of water present on different o'clock positions and thus lead to a difference in coating performance.

Figure 10 through Figure 13 are the adhesion strength of the coating applied under both dry and wet conditions as a function of the o'clock positions on the pipe section. In general, the adhesion strength is independent of the o'clock position. There is a slight difference between o'clock positions for a couple of coatings but the difference is not significant. Thus, although water was dripping down along the pipe surface, it did not have significant impact on coating adhesion. One possible reason might be that because water was formed on the pipe surface by condensation it was relatively uniform. In addition, the pipe sample used for the lab evaluation was relatively small in size (8″×8″). Consequently, it is feasible to apply more force to the coating when applying it to the pipe and thus help the coating displace water fairly uniformly over all o'clock positions.

Effect of Humidity

Two products were applied to the pipe samples at different relative humidity levels to investigate the effect of humidity on coating performance. The adhesion strength of the coatings as a function of relative humidity is compared in Figure 15 and Figure 16. Note that the lowest humidity level in these two figures represents the laboratory condition during that particular test. In general, the coatings had the highest adhesion strength when applied to a dry surface, which was also true for other coating products. When the humidity was controlled at 70%, the adhesion strength was reduced significantly. For example, in the case of SP 4888 the adhesion strength at 70% was only one third of that observed when applied on a dry surface. A similar reduction in the adhesion strength was also observed for Tapecoat applied at 70% relative humidity.

Coating adhesion strength further decreased when the relative humidity was increased to 85%. However, the magnitude of the decrease varied depending on the coating product being applied. As shown in Figure 15, the SP 4888 product did not exhibit a considerable reduction in the adhesion strength at 85% RH compared to 70% RH. However, for the Tapecoat product, the adhesion strength decreased by half compared to 70% RH.

Based on the discussion above, it seems that the humidity influences the coating adhesion strength and thus the overall protection performance quite significantly. More importantly, it has to be noted that the coating application could be a challenge in extremely humid environments where condensed water can form on the pipe surface continuously. In a couple of tests for this work, the coating products were applied to the pipe specimen at 100% RH. It was noted that higher force was needed during coating application to help the coating displace the water at this high relative humidity. If additional force was not used, even the wet surface tolerant coatings would peel off from the pipe sample surface during application. The same observation occurred at 85% RH as well although the coating application was not as difficult.

Two coating products were also applied to pipe steel surfaces that had water formed by misting instead of condensation. The objective of this was to investigate if one can achieve a viable wet surface by misting – a relatively simpler and easier process than condensation – for evaluating and screening wet surface tolerant coating products. The coating adhesion strength obtained on misted surface was compared to that on condensed surface in Figure 15 and Figure 16. One immediate observation is that the coating adhesion strength depended on the o'clock position to some extent, although the average strength magnitude was approximately the same as that obtained at 85% RH. Thus, the water amount may vary along the pipe surface due to dripping and water bead runoff. In fact, the coating at 12 o'clock looked similar to that applied under dry conditions. It seems that the very top of the pipe sample had less water as it dripped away after misting was stopped, as shown in Figure 14. Therefore, although misting might be simpler and easier in terms of getting a wet surface, this wet surface is non-uniform, is different from that obtained with condensation, and is very different from the wet surface obtained in the field where continuous, more or less uniform water generation under relatively high humidity is a common problem.

Longer Term Lab Performance

Figure 19 shows the results from CD testing for SP4888. The Tapecoat 7100 and Carboguard 635 coatings are shown in Figure 18 and Figure 19, respectively. The appearance of the disbonded area was significantly different and dependent on the coating type and the application condition (i.e., dry vs. wet). In general, for the same coating product, the sample coated under wet condition shows more severe disbondment compared to the same coating applied under dry conditions. Additionally, the disbonded area increased with exposure time (as is generally observed for all coatings). Note that all samples were inspected after 30 days and 90 days of exposure except for Carboguard 635 coated sample which was removed from testing after 70 days. Recall that Carboguard 635 coated samples also showed near-zero adhesion when applied under wet conditions. Testing of this specimen was terminated early because severe disbondment occurred which led to leaking of the solution from the test cell. Among the three tested products, specimens that have performed well in other tests showed the smallest disbonded area after both 30 days and 90 days. A small disbonded area indicates that coating adhesion is generally maintained except for what is near the defect area. The results from this test were consistent with other test methods presented in this work.

Figure 20 and Figure 21 are the coating impedance measured at 0.1 Hz for coated samples in 3.5% NaCl as a function of time for dry and wet application conditions, respectively. Independent of coating application condition, the impedance generally decreases over time, indicating the decay in the coating performance as a barrier to the corrosive environment (which is not unusual for most coatings). The samples coated under dry conditions showed much higher impedance than the coatings applied under wet conditions. Furthermore, the difference in the impedance between these samples (i.e., applied under dry conditions) was relatively small. The samples coated under wet conditions showed a much more appreciable decrease in the impedance during the exposure period. More importantly, a difference of approximately two orders of magnitude in the impedance was observed between different coating products when they were applied under wet conditions. This indicates that the coating products did perform differently when they were applied to dry vs. wet surfaces and this difference can be identified by EIS testing.

Figure 22 and Figure 23 show the adhesion strength of the coating before immersion and after immersion in DI water for 90 days. Generally, the adhesion strength of the samples decreased after water immersion with the exception of the specimens coated by Tapecoat 7100. For this sample, the adhesion strength remained roughly the same after water immersion. Carbogard 635 failed prematurely in cathodic disbondment tests, and had near zero adhesion when applied in wet conditions. Because of this, it was excluded from the immersion tests shown in Figure 23.

Long Term Field Performance

Figure 24 and Figure 25 show the adhesion comparison of the coatings on the pipes exposed in the field for one year. Only Tapecoat 7100 and SP 4888 were evaluated in the field testing since these two coatings performed better than others in the lab evaluation. Clearly, the coatings applied under dry conditions still showed higher adhesion strength than those applied under wet conditions. Similar to what was found in the lab evaluation, the coating performance did not seem to have significant difference at different o'clock positions.

The coating performance ranking seems to be consistent to that based on short term lab evaluation. Note that SP 4888 was found to perform better than Tapecoat 7100 in the lab testing. The field data showed the same trend although appreciable scattering on the data were observed. However, it should also be noted that the difference between the performances of these two coating products decreased for the samples tested in the field compared to those tested in the lab (Figure 10 and Figure 11). This is likely due to the difference in the time that was needed to fully cure the coatings.

It should be noted that even though the ranking of the coating performance of the samples tested in the field based on adhesion strength was generally consistent with that observed in the lab, there is a difference in the resistance to impact. As shown Figure 26, the SP 4888 became somewhat brittle after one year of aging in the field compared to Tapecoat 7100. This implied that the lab testing not only needed to consider the adhesion strength but also the resistance to impact since the third party damage is the biggest threat to pipelines.

4 DISSCUSION

In this work, the coating products listed in Table 1 were applied to dry surfaces, wet surfaces at various humidity levels, and wet surfaces obtained via misting. The adhesion strength for all tested coating products and application conditions is summarized in Figure 27 (applied on wet and dry surfaces) and Figure 28 (applied on wet surfaces).

Clearly, as shown in Figure 27, there was a difference in adhesion strength after curing between coating products and application conditions. In general, the coatings applied under dry conditions had higher adhesion strength compared to wet application conditions, which is consistent with the previous discussion on humidity effects. Furthermore, the tested coating products had different adhesion strengths even when the application conditions were the same. Thus, the comparison of adhesion strength upon coating curing allowed the differentiation of the coating performance in a relatively short time period.

The adhesion strength for all evaluated products applied on wet surface (including misting) is shown in Figure 28. In general, SP 4888 had the highest adhesion strength on wet surface compared to the other two products. Tapecoat 7100 Wetbond had the lowest adhesion strength. However, although Carboline Carboguard 635 showed an intermediate adhesion strength compared to other two products, in one case two weeks after application, the coating cracked and peeled off from the steel surface, as shown in Figure 29. SP 2888—a non wet surface tolerant coating product—had higher adhesion strength than some of the wet surface tolerant coating products. Therefore, in these two cases, the short term lab evaluation by measuring adhesion strength may not provide enough information with respect to coating selection. A longer observation period or evaluation in the lab may be needed to finalize the coating selection. In fact, in the long term lab evaluation, Tapecoat 7100 performed better than Carboguard 635, confirming the necessity to perform longer term confirmatory evaluations.

Figure 30 shows the contact angle of water against three wet surface coating products on pipe steel. As previously noted, the coating with smaller contact angle against water will have better water displacement ability and thus likely adhere to the wet metal substrate better. Therefore, specimens coated with product SP 4888 would be expected to have better water displacement ability on the pipe steel over than products Tapecoat 7100 and Carboguard 635 since SP4888 has the smallest contact angle among the three tested samples, which is consistent with previous observations.

Most coating products evaluated in this work are fairly viscous. It was found that extra efforts need to be taken to assist the coating products to repel water and establish strong adhesion on the pipe surface. That is, extra pressure and force needs to be applied by the applicator when using the roller. This is especially true when applying the coating products in extremely humid environments. Additionally, the pipe steel is not generally corrosion resistant and it relies on the coating to combat corrosion. Once water is generated from condensation, the pipe surface forms flash rust. Consequently, the resultant pipe surface may not be in a perfect condition for optimal coating adhesion. Thus, any wet surface tolerant coating product not only should have good water displacement ability but also needs to be capable of tolerating non-ideal surface conditions (e.g., the presence of corrosion products).

The short term evaluation by adhesion strength measurement, the long term evaluation using CD, EIS, and water soak testing, and the long term field evaluation provided the same performance ranking for the three wet surface tolerant coating products. That is, the coating products showed the highest adhesion strength 48 hours after application also performed the best during 90-day CD and water soak tests, during approximately 80 days of EIS monitoring and one year of field exposure. Therefore, the initial adhesion strength measurement seemed to be a viable method to assist screening the coating products for wet surface application though longer-term confirmatory tests were needed to refine the ranking. That is, the adhesion measured after 48 hours can provide a quick indication of viable and non-viable candidates on a pass/fail basis.

In a corrosive environment, coatings serve as the protective barrier by isolating the substrate from the environment. To achieve good corrosion protection, the coating products must establish strong adhesion with the substrate. The adhesion strength measurement is a reliable method to provide an initial indication of coating performance. It should be emphasized that the coating product selected after short term evaluation (i.e., adhesion strength measurement) should be evaluated in long term exposure tests, such as CD, EIS, and water soak to further verify and refine what its performance is. This is because other factors - such as the coating's permeability with respect to a corrosive electrolyte - also significantly affect the performance of the coatings. These factors are not reflected by short term adhesion strength measurements and thus a longer term test is needed to explore their effect on the coating performance. Additionally, the initial evaluation also needs to include techniques that can investigate the resistance of the candidate coating products to impact and bending since these properties are equally important in providing protection for pipelines in the field.

5 SUMMARY

- A testing rig was developed and constructed to enable the simulation of water condensation encountered in the field; it was found that water continuously condensed on the pipe surface and which better simulates field conditions than forming wet surfaces by misting (water spraying);

- Coatings should be applied under humid conditions created properly in the lab to conduct valid evaluation of coating performance;

- The tested coatings were able to achieve relatively uniform performance at different o'clock positions on the pipes tested in the lab. When applied in the field, however, extra effort might be necessary to facilitate the water replacement since the pipes are typically larger than those used in the lab;

- Relative humidity level had a significant impact on the coating performance. Therefore, it might be necessary to consider (if possible) conducting coating repair under conditions where the lowest relative humidity can be achieved (dry season or avoid raining days);

- The wet coating products were ranked initially by the adhesion strength, which was the same as the performance ranking obtained in the long term lab testing by cathodic disbondment, EIS and water soaking tests;

- The performance ranking obtained in the one year field testing was consistent with that observed in the lab testing. The difference in the performance between coatings (two evaluated) was smaller in the field than in the lab;

- The post-cure adhesion strength could be used as an initial screening parameter to select coatings for wet surface application assuming the wet condition was created properly. However, relatively longer term evaluation is also necessary to further evaluate the coating performance so that properties, such as water permeability, should be considered as well in selecting the best product for application; other properties, such as impact resistance and bend resistance should also be considered in evaluating a coating product.

6 TABLES

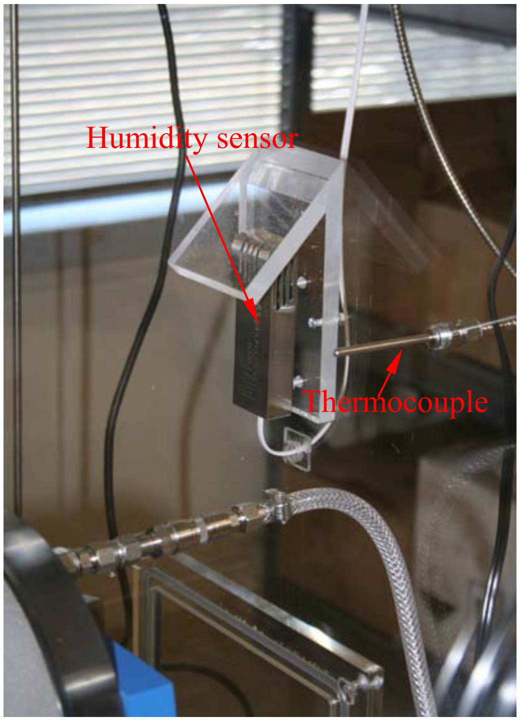
Table 1: The list of the coating products

Item#	Name	Coating type	Manufacture	Remarks
A	SPC SP4888	Epoxy	SPC	Wet-Surface tolerant
B	Tapecoat 7100 Wet Bond Epoxy	Epoxy	Tapecoat	
C	Carboline Carboguard 635	Epoxy	Carboline	
D	SPC SP2888	Epoxy/Urethane	SPC	standard coating
E	Denso Protal 7200	Epoxy	Denso	
F	Carboline Carboguard 890	Epoxy	Carboline	

Table 2: The soil chemistry at the pipe installation site in the field.

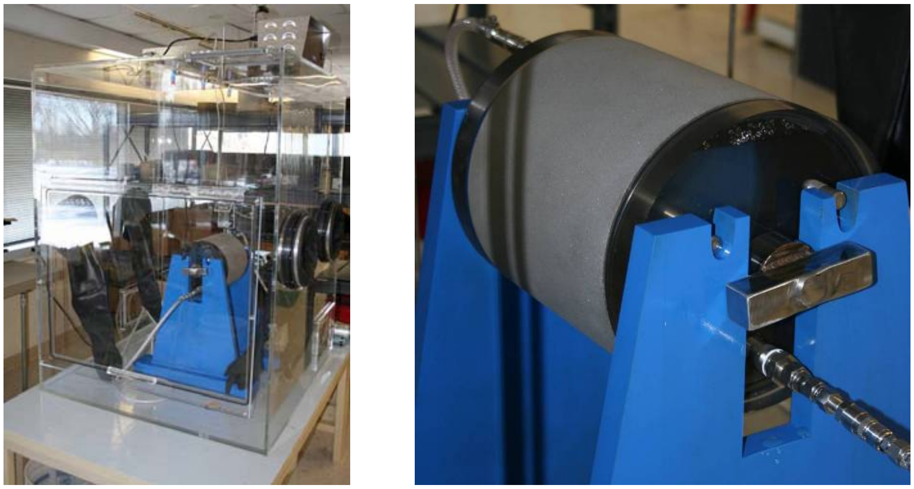
Field ID	Sample ID	Soluble cations mg/kg		Soluble anions, mg/kg							pH soil	Total acidity mg CaCO3/kg	Total alkalinity mg CaCO3/kg	Moisture content %	Resistivity Ohm-cm
		Ca^{2+}	Mg^{2+}	NO_2^-	NO_3^-	Cl^-	SO_4^-	S^{2-}	CO_3^{2-}	HCO_3^-					
#1 Upstream; Sampled 11-16-09	S09034-01	5.6	3.4	.078	10.368	2.1	<9.02	<24	16.8	34.2	5.02	0	28.1	28.71%	43000.0
#3 Downstream; Sampled 11-16-09	S09034-03	5.9	3.6	.046	18.539	1.5	<8.96	<23	17.6	35.8	5.02	29.3	29.3	31.83%	37000.0

7 FIGURES



(a) (b)

Figure 1: The testing rig. (a) The metal boxes sitting on the top of the chamber are the humidity and temperature control units. The gloves installed on the box on both the front and the back sides are used to keep access to the chamber and to apply coatings; (b) The humidity and temperature sensor installed inside the chamber.



(a) (b)

Figure 2: The chamber for coating application (a) and the stand to hold the pipe to be coated with a coating product (b).

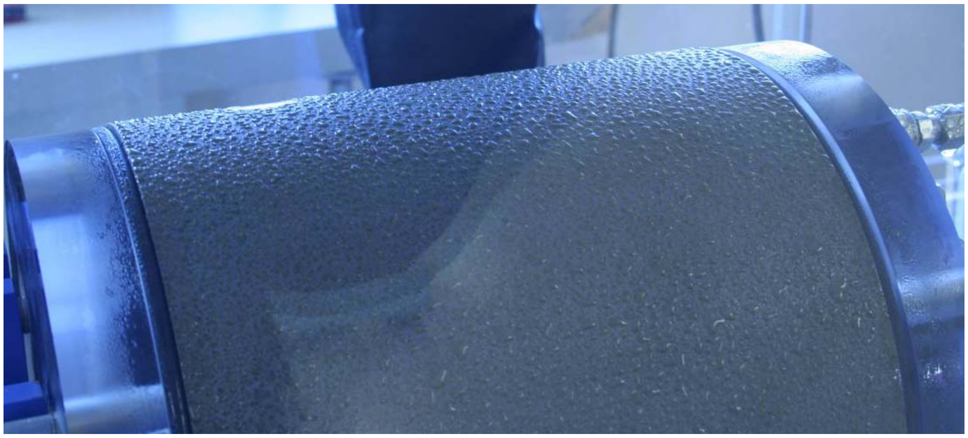


Figure 3: The water condensation accumulated on the pipe sample placed in the testing rig.

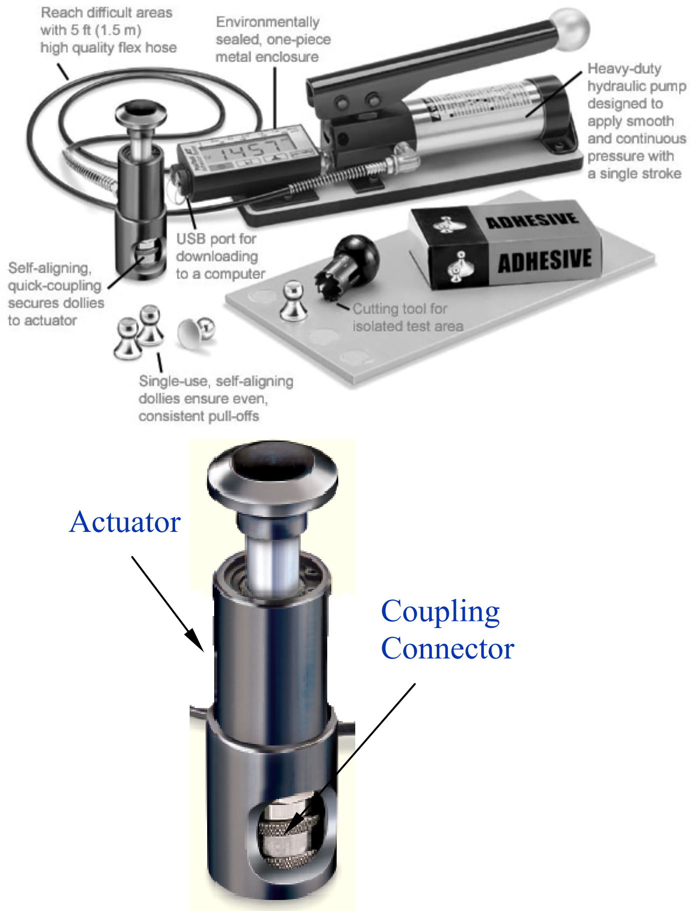


Figure 4: Adhesion tester and coupling connector and actuator attached to a disposable Al dolly.

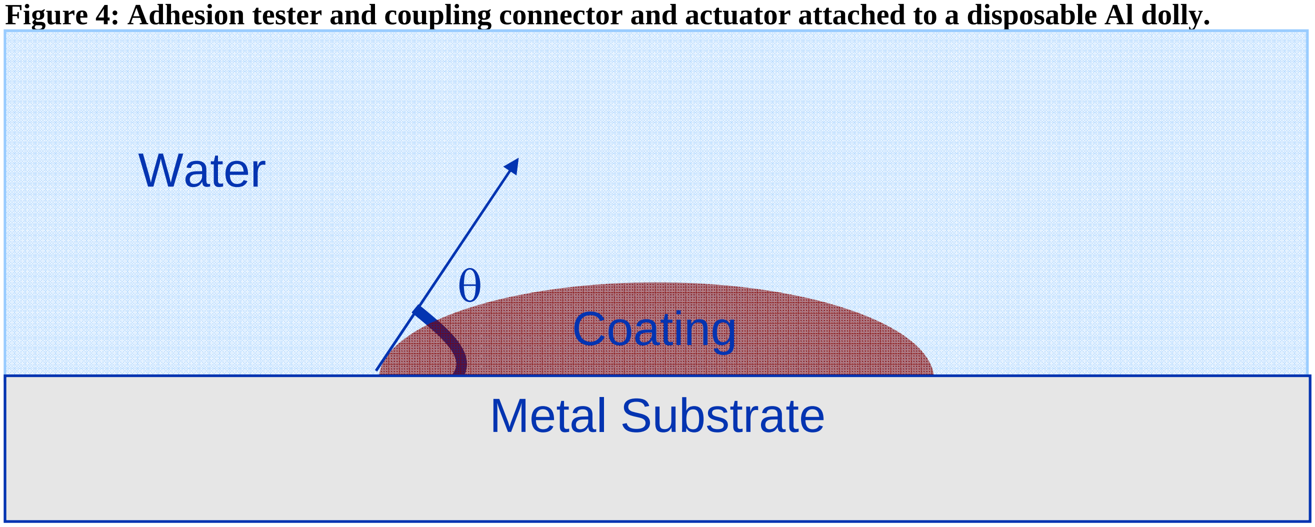
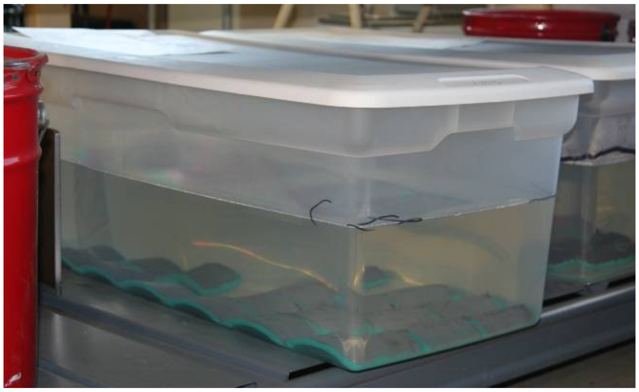
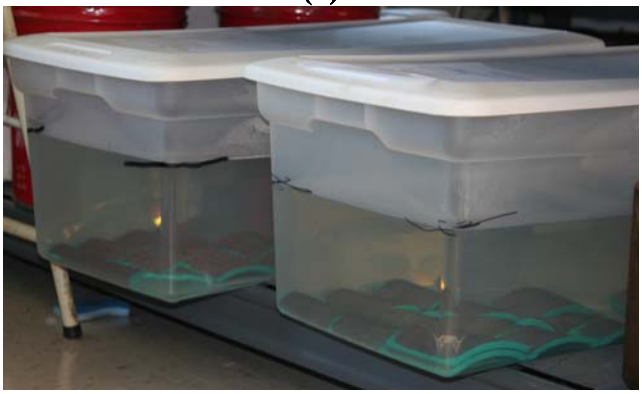


Figure 5: Schematic of the coating droplet contact angle against water on steel surface.



(a)



(b)

Figure 6: The long term water soak test setup

Figure 7: Cathodic disbondment (CD)in progress

Figure 8: The cell for EIS testing

Figure 9: An illustration of the layout of the installed pipes along a pipeline in Virginia.

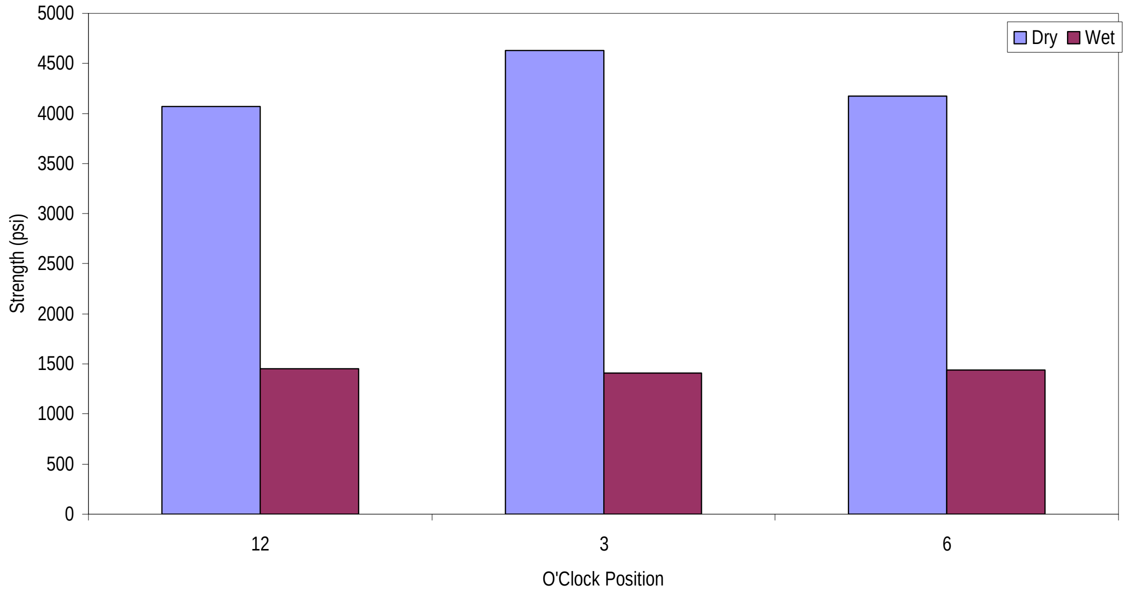


Figure 10: A comparison of adhesion for SPC SP4888 coating on both dry and wet surfaces. The adhesion tests were performed 24 hours after the coating was applied.

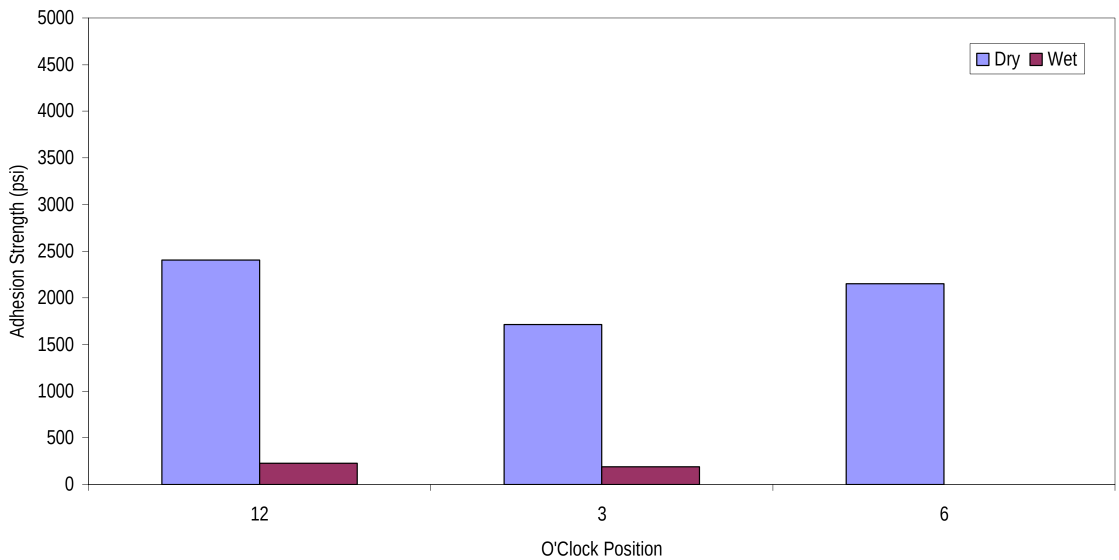


Figure 11: A comparison of adhesion for Tapecoat 7100 Wetbond coating on both dry and wet surfaces. The adhesion tests were performed 24 hours after the coating was applied. No adhesion test was performed at 6 o'clock on the coating applied to wet surface.

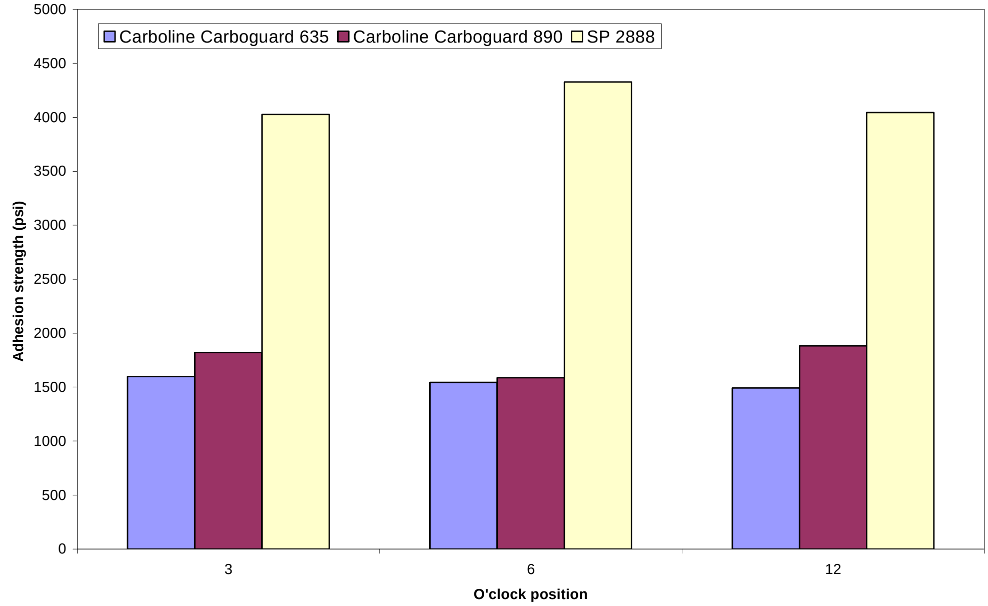


Figure 12: Adhesion strength vs. o'clock position on dry surfaces for Carboline Carboguard 635, Carboline Carboguard 890 and SP 2888.

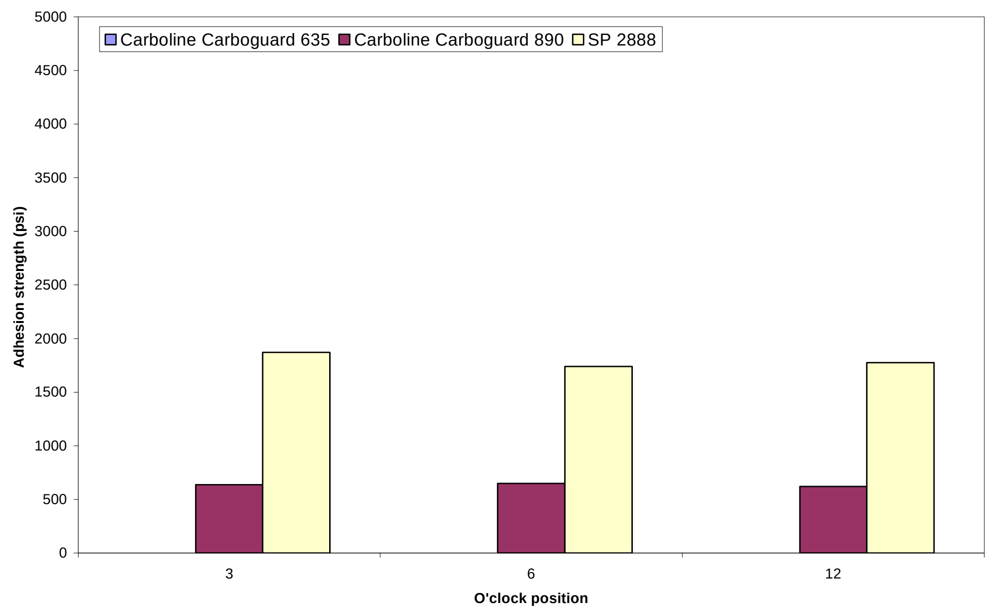


Figure 13: Adhesion strength vs. o'clock position on wet surfaces for Carboline Carboguard 635, Carboline Carboguard 890 and SP 2888.

Figure 14: Cured coating on a pipe surface that was wetted by misting. The front dark portion is the 12 o'clock on the pipe.

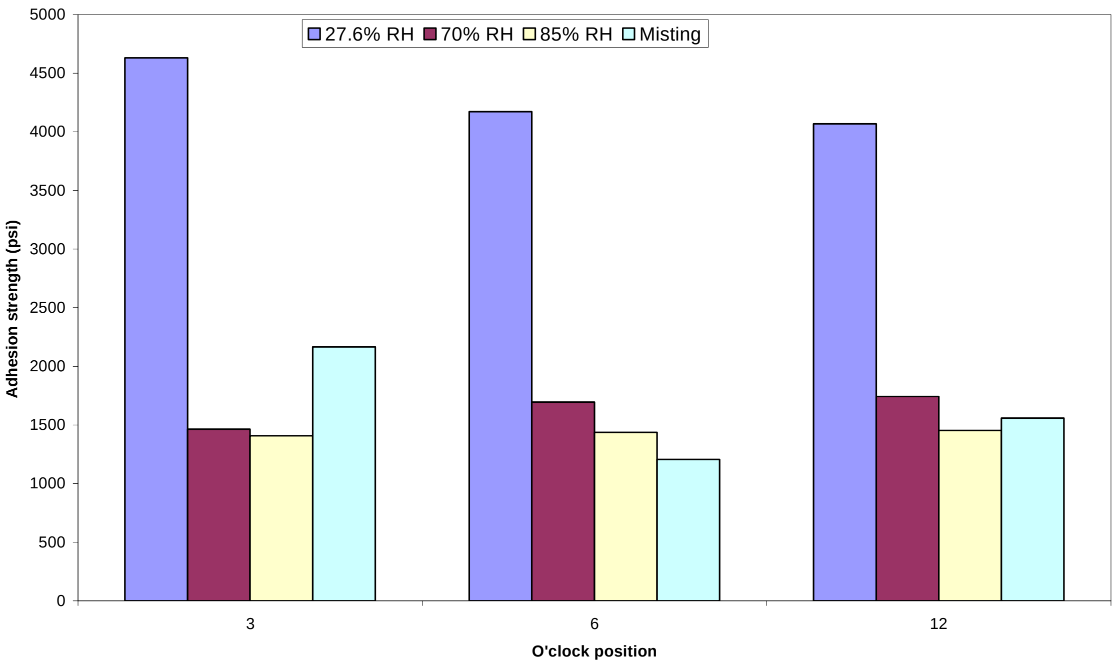


Figure 15: The adhesion strength at different o'clock positions vs. relative humidity for SP 4888 coated samples.

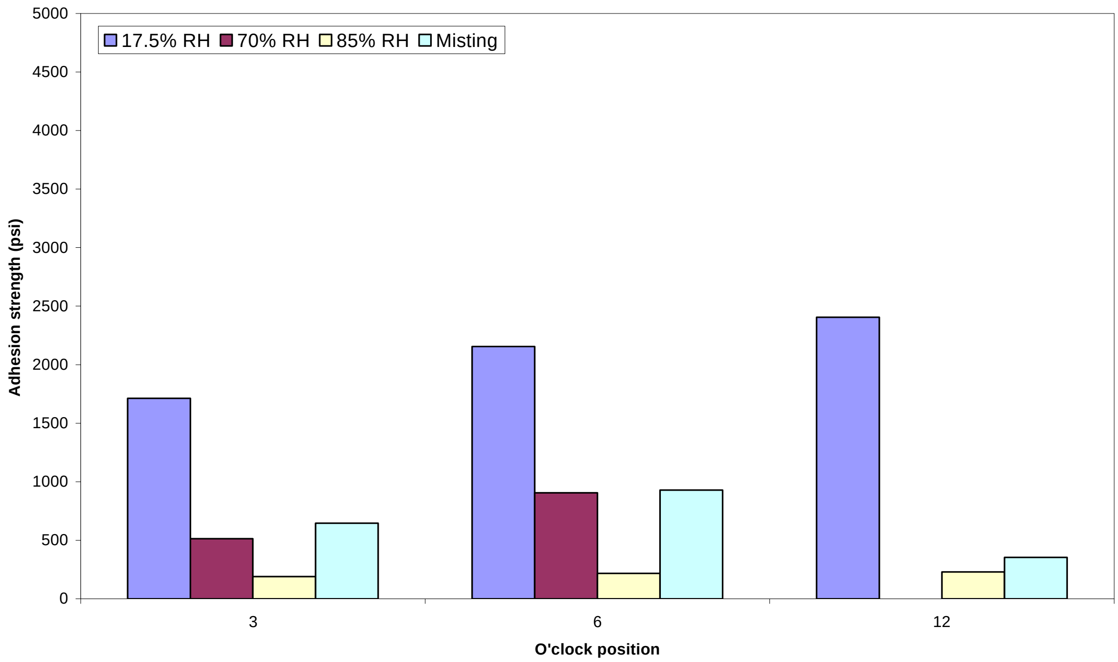


Figure 16: The adhesion strength at different o'clock positions vs. relative humidity for Tapecoat 7100 Wetbond coated samples.

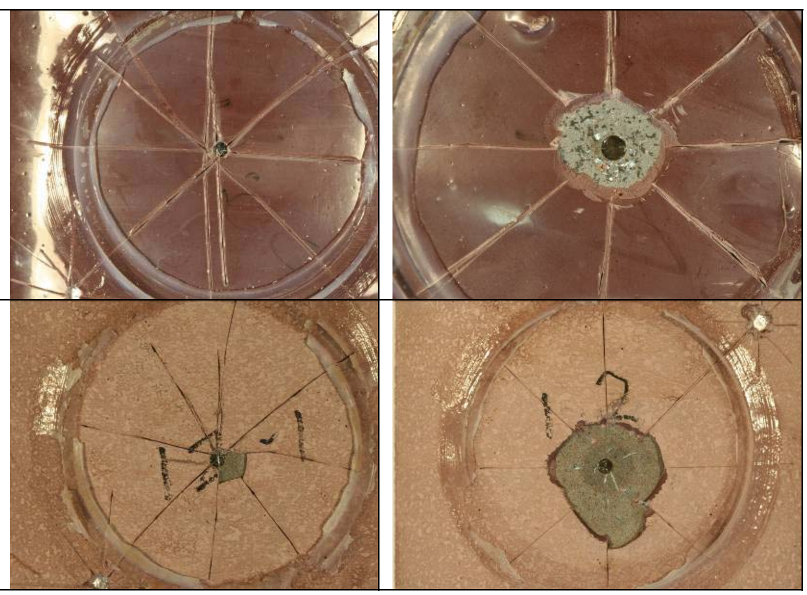
SP4888	Dry	
	Wet	

Figure 17: A comparison of disbonded areas for dry and wet conditions for SP4888 after 30 and 90 days exposure.

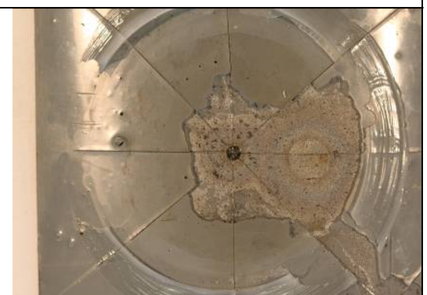
Coating	Application condition	30 days exposure	90 days exposure
Tapecoat 7100	Dry		
	Wet		

Figure 18: A comparison of disbonded areas for dry and wet conditions for Tapecoat 7100 after 30 and 90 days exposure.

Coating	Application condition	70 days
Carboguard 635	Dry	
	Wet	

Figure 19: A comparison of disbonded areas in dry and wet conditions for Coating Carboguard 635.

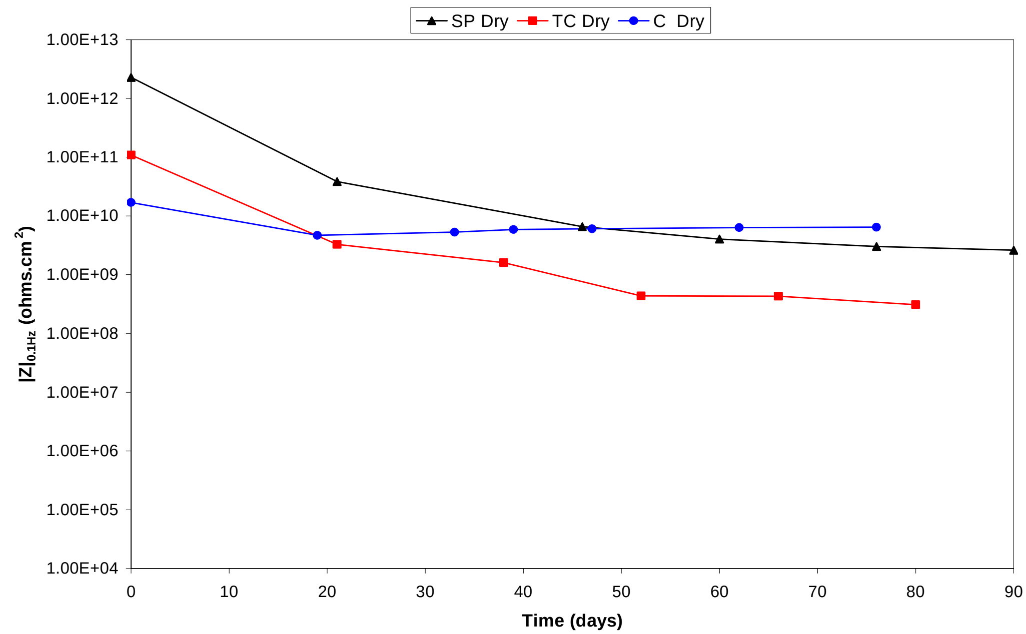


Figure 20: The change of impedance at 0.1 Hz over time for the coating products applied under dry condition (SP: SP4888; TC: Tapecoat 7100; C: Carboguard 635).

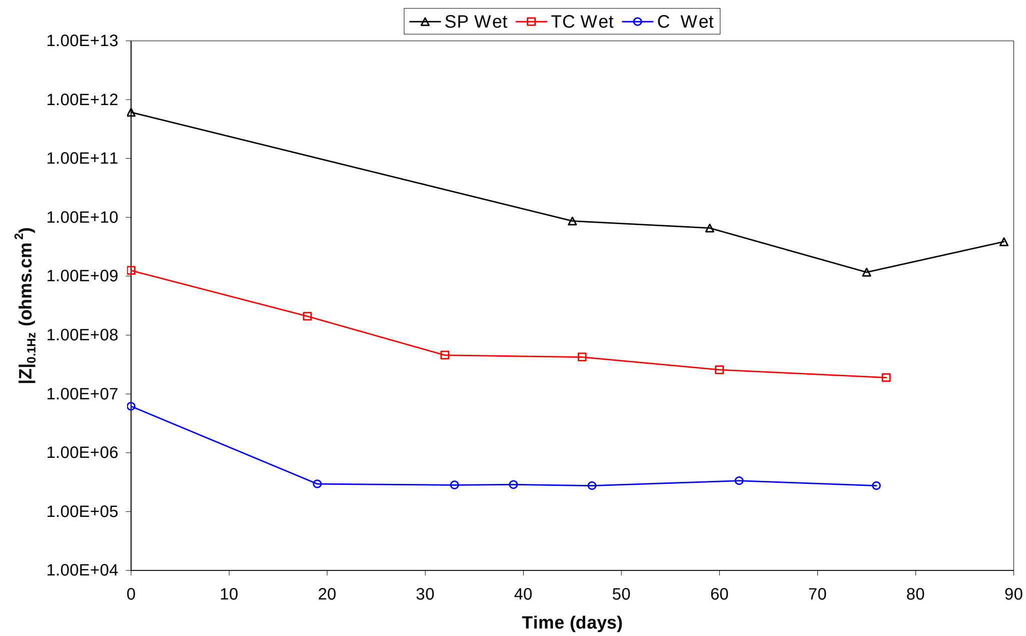


Figure 21: The change of impedance at 0.1 Hz over time for the coating products applied under wet condition (SP: SP4888; TC: Tapecoat 7100; C: Carboguard 635).

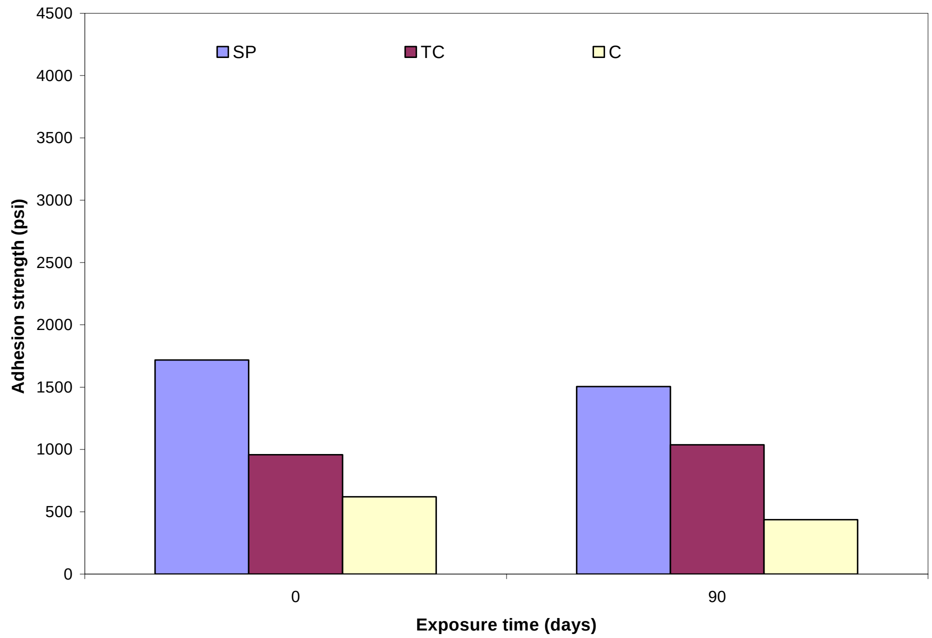


Figure 22: A comparison of adhesion strength before and after immersion in DI water for coating products applied under dry condition. Note that zero day of exposure represents the adhesion on a set of samples without being immersed in water (SP: SP4888; TC: Tapecoat 7100; C: Carboguard 635).

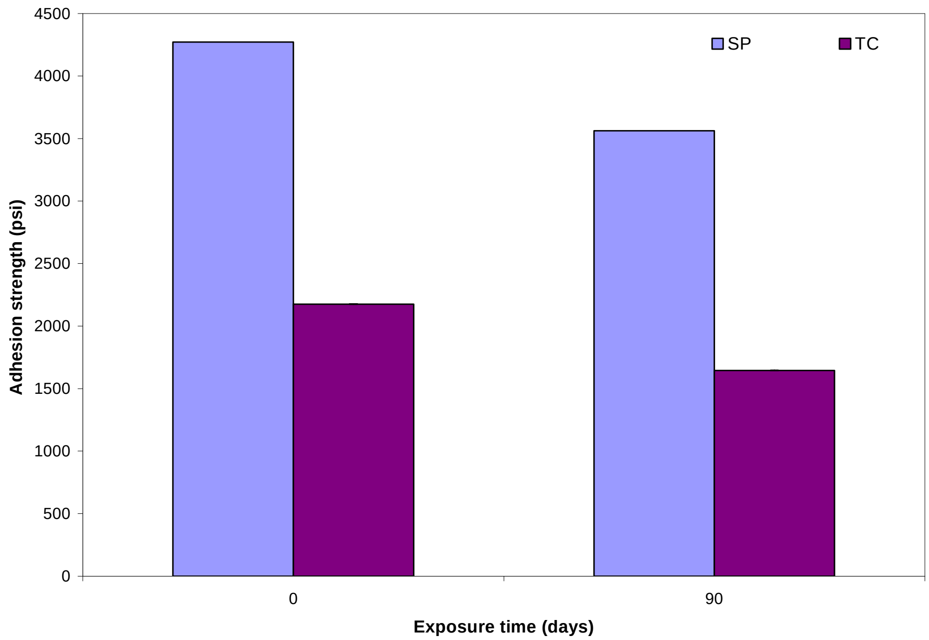


Figure 23: A comparison of adhesion strength before and after immersion in DI water for coating products applied under wet condition. Note that zero day of exposure represents the adhesion on a set of samples without being immersed in water (SP: SP4888; TC: Tapecoat 7100).

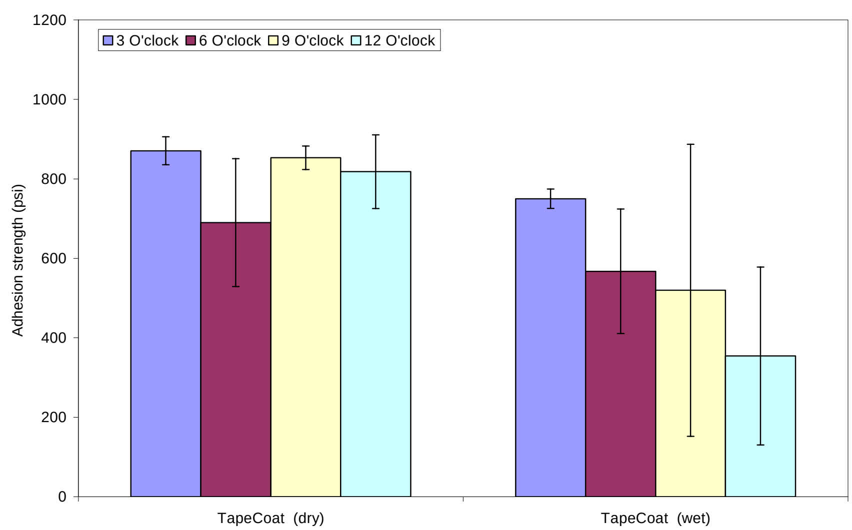


Figure 24: A comparison of the pull strength adhesion of the Tapecoat 7100 coating at different o'clock positions on the pipe exposed for one year in the field.

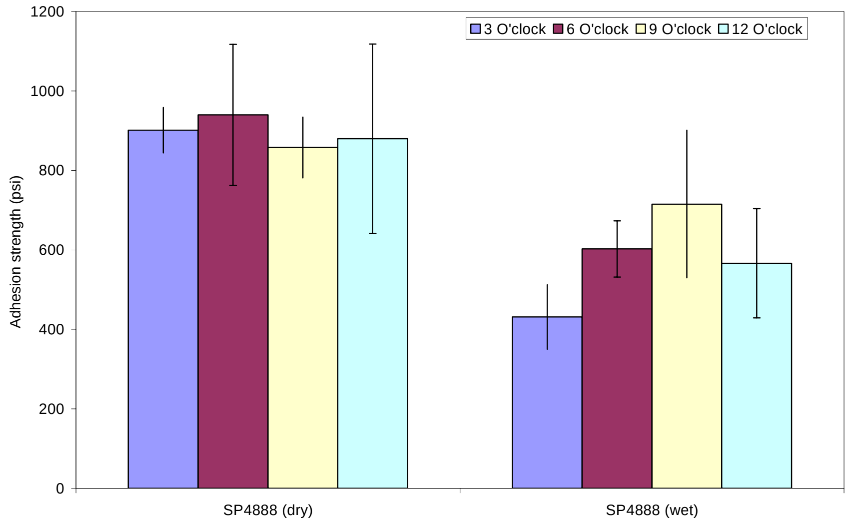
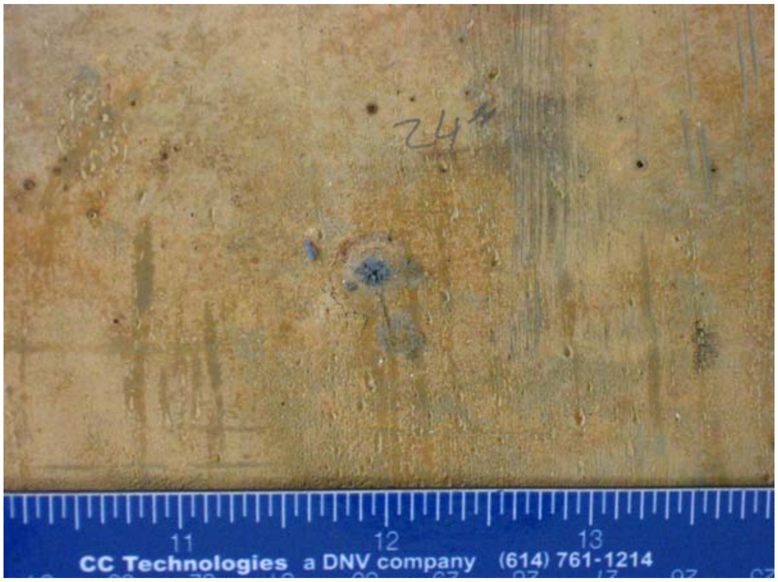
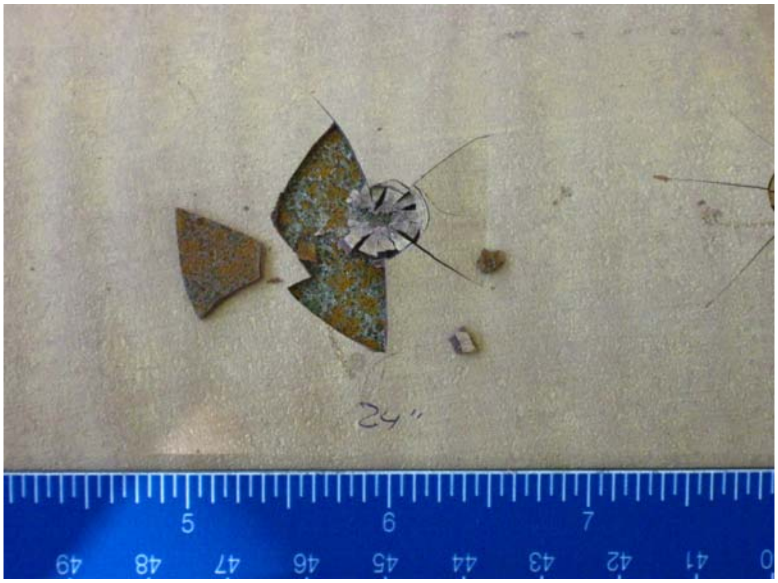


Figure 25: A comparison of the pull strength adhesion of the SP4888 coating at different o'clock positions on the pipe exposed for one year in the field.



(a)



(b)

Figure 26: A comparison of the sample appearance after impact testing using the same weight and at the same height (24"). These are the samples tested in the field for one year. (a) Tapecoat 7100; (b) SP4888.

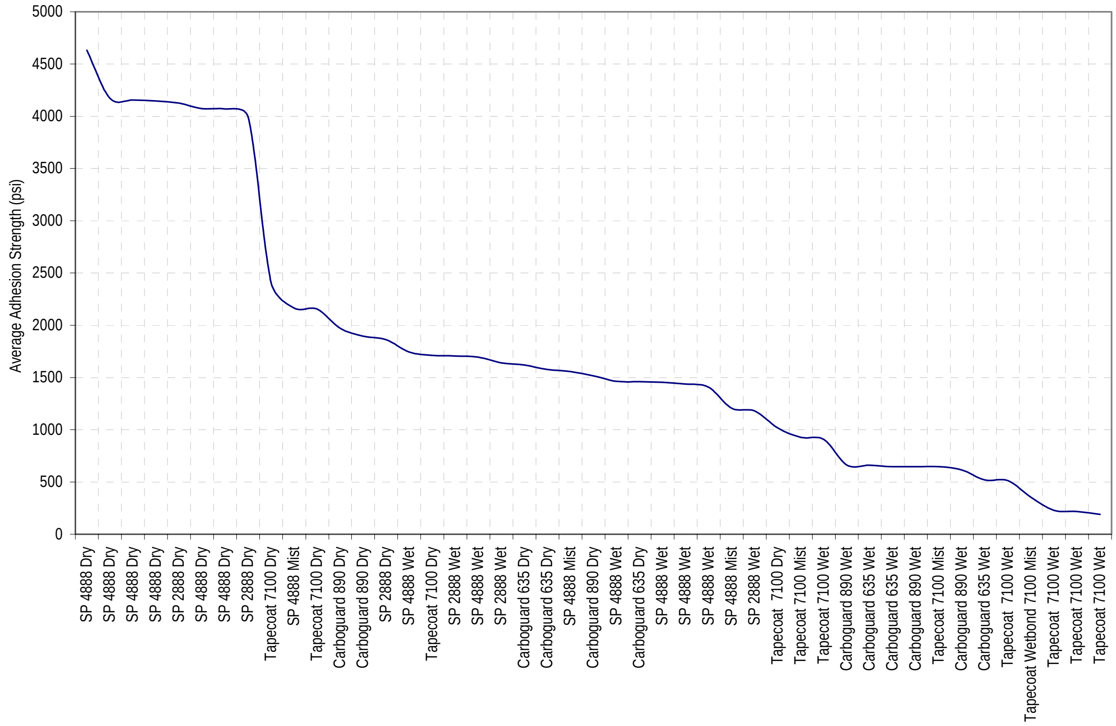


Figure 27: The coating adhesion strength for all coating products applied to both dry and wet surfaces

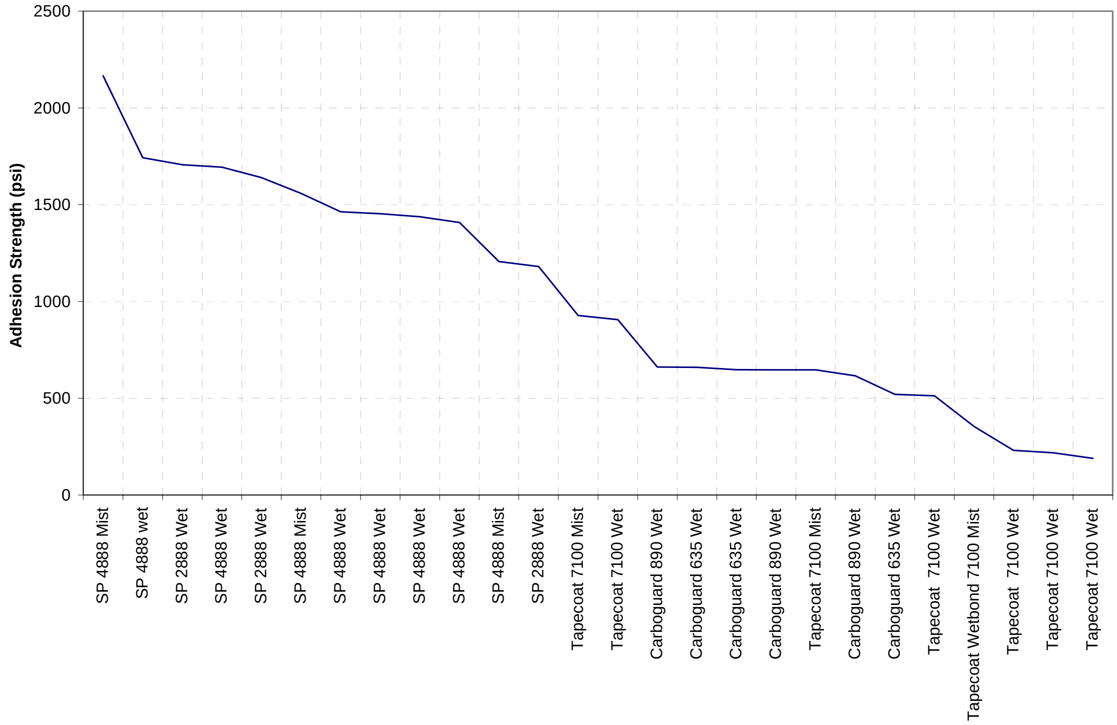


Figure 28: The coating strength for all coating products applied to wet surfaces

Figure 29: The appearance of a cured coating product applied to wet surface.

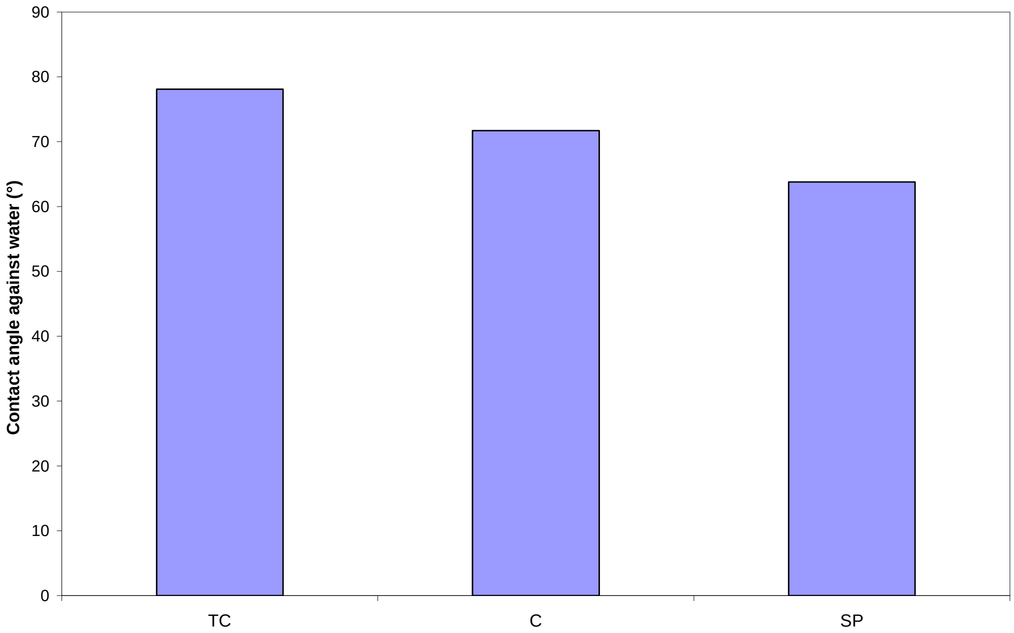


Figure 30: The contact angle of the wet surface tolerant coating products against water (SP: SP4888; TC: Tapecoat 7100; C: Carboguard 635).

DNV Energy

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DNV Energy Regional Offices:

Asia and Middle East
Det Norske Veritas Sdn Bhd
24th Floor, Menara Weld
Jalan Raja Chulan
50200 Kuala Lumpur
Phone: +603 2050 2888

North America
Det Norske Veritas (USA), Inc.
16340 Park Ten Place, Suite 100
Houston, TX 77084
United States of America
Phone: +281-721-6600

Europe and North Africa
Det Norske Veritas Ltd
Palace House
3 Cathedral Street
London SE1 9DE
United Kingdom
Phone: +44 20 7357 6080

Offshore Class and Inspection
Det Norske Veritas AS
Veritasveien 1
N-1322 Hovik
Norway
Phone: +47 67 57 99 00

Cleaner Energy & Utilities
Det Norske Veritas AS
Veritasveien 1
N-1322 Hovik
Norway
Phone: +47 67 57 99 00

South America and West Africa
Det Norske Veritas Ltda
Rua Sete de Setembro
111/12 Floor
20050006 Rio de Janeiro Brazil
Phone: +55 21 2517 7232

Nordic and Eurasia
Det Norske Veritas AS
Veritasveien 1
N-1322 Hovik
Norway
Phone: +47 67 57 99 00

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