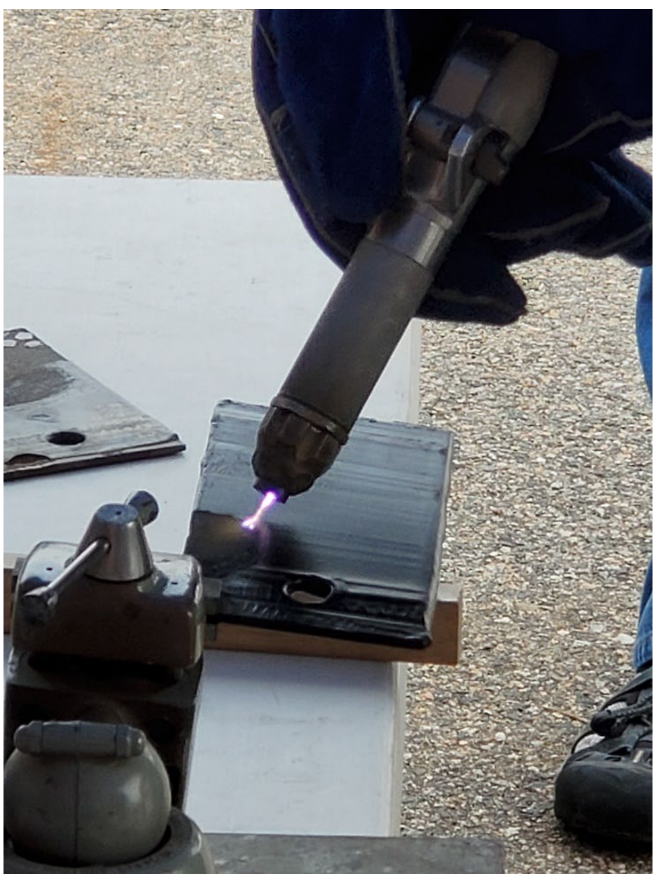
BUREAU OF RECLAMATION

Final Report No. ST-2023-21062-01
Technical Report No. 8540-2024-32

# Atmospheric Plasma Coating Removal

Science and Technology Program
Research and Development Office



U.S. Department of the Interior April 2024

| REPORT DOCUMENTATION PAGE | | | *Form Approved OMB No. 0704-0188* |
|---|---|---|---|
| The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.<br>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS. | | | |
| 1. REPORT DATE *(DD-MM-YYYY)*<br>30-04-2024 | 2. REPORT TYPE<br>Research | | 3. DATES COVERED *(From - To)*<br>October 2020 – September 2023 |
| 4. TITLE AND SUBTITLE<br>Atmospheric Plasma Coating Removal | | | 5a. CONTRACT NUMBER<br>XXXR4524KS-RR4888FARD2102801/F429A<br>5b. GRANT NUMBER<br>N/A<br>5c. PROGRAM ELEMENT NUMBER<br>1541 (S&T) |
| 6. AUTHOR(S)<br>Kevin L. Kelly, Ph.D., Research Chemist, kkelly@usbr.gov<br>David Tordonato, Ph.D., P.E., Materials Engineer<br>Stephanie Prochaska, P.E., Materials Engineer<br>Ryan Williams, Student Intern<br>Bo Raadam, Student Intern | | | 5d. PROJECT NUMBER<br>Final Report ST-2023-21062-01<br>5e. TASK NUMBER<br>N/A<br>5f. WORK UNIT NUMBER<br>86-68540 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Materials and Corrosion Laboratory<br>Technical Service Center<br>Bureau of Reclamation<br>U.S. Department of the Interior<br>PO Box 25077, Denver Federal Center<br>Denver CO 80225-0007 | | | 8. PERFORMING ORGANIZATION REPORT NUMBER<br>8540-2024-32 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>Science and Technology Program<br>Research and Development Office<br>Bureau of Reclamation<br>U.S. Department of the Interior<br>Denver Federal Center<br>PO Box 25007, Denver, CO 80225-0007 | | | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>R&D: Research and Development Office<br>Reclamation: Bureau of Reclamation<br>DOI: U.S. Department of the Interior<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S)<br>Final Report ST-2023-21062-01 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html | | | |
| 13. SUPPLEMENTARY NOTES<br>None | | | |
| 14. ABSTRACT<br>Two rounds of testing to evaluate and compare atmospheric plasma removal of coal tar enamel (CTE) to traditional abrasive blast processes were performed. Test samples were prepared as steel coupons measuring 3 inch x 6 inch x 1/8 inch with or without CTE coating on each, depending on the test parameter to be determined. Each round of testing was designed with separate test groups involving different surface preparation protocols, including one or a combination of atmospheric plasma, abrasive blasting, bristle blasting, and no removal (controls). Prepared test samples were tested for corrosion performance (rust creep) and adhesion properties (dry and wet) under different sets of conditions. Data from these results and the visual observations of CTE and smoke released into the environment during atmospheric plasma removal suggest that abrasive blasting and containment of hazardous waste streams generated during removal will still be required. In general, analyses of the results indicated that additional testing is needed to accurately determine whether any observed differences in performance are of statistical significance. | | | |
| 15. SUBJECT TERMS<br>Atmospheric Plasma, Coating, Coal Tar | | | |
| 16. SECURITY CLASSIFICATION OF:<br>a. REPORT: U \| b. ABSTRACT: U \| THIS PAGE: U | 17. LIMITATION OF ABSTRACT<br>U | 18. NUMBER OF PAGES<br>36 | 19a. NAME OF RESPONSIBLE PERSON<br>Kevin L. Kelly<br>19b. TELEPHONE NUMBER *(Include area code)*<br>720-663-7944 |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

# Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, Native Hawaiians, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.



**Acknowledgements** – The Science and Technology Program, Bureau of Reclamation, sponsored this research. Northwest Pipe provided courtesy coal tar enamel coating product and application for this project. Duromar provided epoxy product for testing.

**Cover Photo** – View of atmospheric plasma removing coal tar coating from a metal plate. (Bureau of Reclamation)

# Atmospheric Plasma Coating Removal

## Final Report No. ST-2023-21062-01
## Technical Report No. 8540-2024-32

Prepared by:

**Bureau of Reclamation**
**Technical Service Center**
**Materials and Corrosion Laboratory Group**
**Kevin L. Kelly, Research Chemist**
**David Tordonato, Materials Engineer**
**Stephanie Prochaska, Materials Engineer**
**Ryan Williams, Student Intern**
**Bo Raadam, Student Intern**

# Atmospheric Plasma Coating Removal

## Final Report No. ST-2023-21062-01
## Technical Report No. 8540-2024-32

KEVIN KELLY Digitally signed by KEVIN KELLY
Date: 2024.04.30 16:12:58 -06'00'

Prepared by: Kevin L. Kelly, Ph.D.
Research Chemist, Materials and Corrosion Laboratory, 86-68540

MEREDITH HEILIG Digitally signed by MEREDITH HEILIG
Date: 2024.05.02 09:56:51 -06'00'

Checked by: Meredith Heilig, Ph.D.
Materials Engineer, Materials and Corrosion Laboratory, 86-68540

ALLEN SKAJA Digitally signed by ALLEN SKAJA
Date: 2024.05.01 14:48:02 -06'00'

Technical Approval by: Allen Skaja, Ph.D.
Materials Engineer, Materials and Corrosion Laboratory, 86-68540

BOBBI JO MERTEN Digitally signed by BOBBI JO MERTEN
Date: 2024.05.01 14:01:00 -06'00'

Peer Review by: Bobbi Jo Merten, Ph.D.
Materials Engineer, Materials and Corrosion Laboratory, 86-68540

# Acronyms and Abbreviations

| | |
|---|---|
| AB | Dry Abrasive Blast |
| CTE | Coal Tar Enamel |
| DA | Dry Adhesion |
| DHS | Dilute Harrison's Solution |
| FOG | fog chamber |
| HAR | Immersion in dilute Harrison's Solution |
| PB | PlasmaBlast™ |
| RCRA | Resource Conservation and Recovery Act |
| Reclamation | Bureau of Reclamation |
| SSPC | Society for Protective Coatings |
| WAB | wet abrasive blasting |

## Symbols

| | |
|---|---|
| % | percent |
| °F | degree Fahrenheit |
| cm | centimeter |
| mm | millimeters |
| psi | pounds per square inch |
| μg/L | microgram per liter |

# Contents

Page



## Tables

## Figures

# Executive Summary

Protective coatings have been used for many years to protect Bureau of Reclamation (Reclamation) assets from corrosion. Legacy coatings such as coal tar enamel (CTE) were traditionally used in immersion and burial applications, particularly as a liner for pipes, penstocks, and outlet works and as a coating for buried pipe. These products are no longer specified but remain common on existing infrastructure. The waste generated during CTE removal may be considered a hazardous material and may need to be contained, tested, and disposed of properly. In general, the process for removing degraded linings has evolved incrementally throughout the years with advances in technology, health, and safety. However, removing and containing hazardous materials in coatings is still complicated, time consuming, costly, and can be hazardous to the environment and human health.

This project investigated the use of atmospheric plasma to remove CTE. In simple terms, plasma is ionized gas molecules. At ambient temperature and pressure, the plasma is often termed "cold plasma." In theory, when used to remove coatings, it reacts with and vaporizes the coating from a surface. Depending on relative ratio of organic and inorganic constituents in the coating. Atmospheric plasma removal of coating may be generating as much as 60 percent (%) of the coating into harmless gases, carbon dioxide, and water vapor, according to plasma equipment vendor. The remainder of the coating is reduced to dry dust that may be contained and disposed of as solid waste, which may or may not be hazardous waste. Key benefits of this technology are the reduction in the generation of hazardous waste streams during coating removal, increased safety and health benefits resulting from the reduction of vibration and noise, a more simplified process of containing waste streams and lower impact on the environment compared to traditional methods, and requires only electricity and air to create the plasma reactive enough to remove coatings.

Two rounds of testing to evaluate and compare atmospheric plasma removal of CTE to traditional blast processes were performed. Test samples were prepared as steel coupons measuring 3 x 6 inch x 1/8 inch with or without CTE coating on each, depending on the test parameter to be determined. Each round of testing was designed with separate test groups involving different surface preparation protocols, including one or a combination of atmospheric plasma, dry abrasive blasting, bristle blasting, and no removal (controls). Prepared test samples were tested for corrosion performance (rust creep) and adhesion properties (dry and wet) under different sets of conditions.

Data from these results and the visual observations of CTE and smoke released into the environment during atmospheric plasma removal suggest that abrasive blasting and containment of hazardous waste streams generated during removal will still be required. In general, analyses of the results indicated that additional testing is needed to accurately determine whether any observed differences in performance are of statistical significance.

# 1. Introduction

Protective coatings have been used for many years to protect Bureau of Reclamation (Reclamation) assets from corrosion. Legacy coatings such as coal tar enamel (CTE) were traditionally used in immersion and burial applications, particularly as a liner for pipes, penstocks, and outlet works and as a coating for buried pipe. These products are no longer specified but remain common on existing infrastructure. The waste generated during CTE removal may be considered a hazardous material and must be contained, tested, and disposed of properly. Removal of coal tar products requires dry abrasive blasting (DAB), wet abrasive blasting (WAB), and/or ultra-high pressure water jetting. The ease of removal varies depending on the age, condition, and thickness of the existing material. Thick enamels can pose significant challenges and require additional time to remove. Blasting methods create a large quantity of solid waste which must be handled and disposed of appropriately. While WAB can be used to mitigate dust, this approach carries the disadvantage of creating both liquid and solid waste. If water jetting is used, the solid waste stream is reduced, but the water still must be captured and treated before release. Surfaces undergoing spot repairs may be prepared using AB or handheld power tools, depending on the lining condition and the extent of preparation required. Either approach requires containment of any dust from removed material.

In general, the process for removing degraded linings has evolved incrementally throughout the years with advances in technology, health, and safety regulations. However, removing and containing hazardous materials in coatings is still complicated, time consuming, costly, and can be hazardous. Atmospheric plasma is a new method of coatings removal which has gained attention in recent years. Reclamation researchers investigated its use for CTE removal, and the results of the research are reported here.

## 1.1 Previous Work

The use of atmospheric plasma to remove coatings was not previously studied at Reclamation. Reclamation investigators on this project first relied on previous work performed by Atmospheric Plasma Solutions, Inc. in Cary, North Carolina. As a proof of concept, panels coated with coal tar epoxy and aged coal tar enamel previously prepared during another research project (ST-2017-1546-01) were sent to this vendor for demonstration of their PlasmaBlast® process. The vendor successfully performed spot coating removal and provided a video to the team in June 2021. The vendor also markets a small backpack unit called the PB 7000-M which is available for rental and employs a patented cold plasma technology (https://apsplasma.com/product/pb7000-m/). This provided the impetus to propose this work as a new Science and Technology project to carry out further investigations in the use of atmospheric plasma to remove CTE.

## 1.2 Literature Review

While the use of atmospheric plasma to remove common coatings is documented in the literature, very little information exists on the use of atmospheric plasma to remove materials containing coal tar commonly found in pipe linings in Reclamation facilities (Merati, 2017; Yancey, 2018; Astolfi, 2022; Ranieri, 2022; Yancey, 2020; Piascik, 2023). Coating specialists at Reclamation hypothesized coal tar coatings and linings are a greater challenge to remove by atmospheric plasma due to its thickness and organic composition consisting of over 10,000 chemical compounds, mostly polycyclic aromatic hydrocarbons. For this reason, the project described here was proposed and funded to investigate the feasibility of using atmospheric plasma as a method for CTE removal.

Atmospheric plasma is considered most practical for small spot repair jobs. This is currently performed by either by bristle blasting or by abrasive blasting. Bristle blasting is a handheld power tool cleaning method which uses a spinning wire wheel with angled tips and an accelerating bar to strike the surface creating an anchor profile. Abrasive blasting is a common method used for general surface preparation of varying scale. Both mechanical blast methods are capable of both coating removal and imparting a surface profile to the substrate. The experiments evaluated and compared atmospheric plasma with the two mechanical surface preparation methods and also investigated the potential use of atmospheric plasma supplemental surface preparation method to be used following mechanical removal for performance enhancement.

# 2. Methodology

To evaluate and compare CTE removal with PB to a traditional dry abrasive blasting, a PB 7000-M machine was rented from the vendor in two consecutive summers (2021 and 2022) and used to perform surface preparation on selected test panel sets. Following surface preparation activities, panels were coated with a 100% solids epoxy coating and then subjected to exposure and/or performance testing.

## 2.1 Surface Preparation

### 2.1.1 Round 1

In the summer of 2021, three groups of fifteen 3 x 6-inch x 1/8-inch bare steel test panels were abrasive blasted by Reclamation staff and sent to be coated with CTE. After receiving coated panels, a total of 20 DFT readings taken on 5 representative panels averaged 127 mils. The three groups of CTE-coated panels were then prepared with either PlasmaBlast (PB), AB to Society for Protective Coatings (SSPC)-SP5 white metal condition, or the former followed by the latter (ASTM, 2021). Two additional groups of panels consisted of bare metal with mill scale prepared with either PB or AB to SSPC-

SP5 white metal condition. Table 1 summarizes the sample preparation plan for the five test groups. Figure 1 shows PB preparation of one of the samples, note that the approach simulates a spot repair by leaving the outer edge of the panel with intact coating.

**Table 1.—Round 1 sample preparation plan consisting of varied combinations of PB and/or AB on CTE and bare steel panels**

| Group number | Group name | Surface preparation description | Surface profile target |
|---|---|---|---|
| 1 | CTE-PB | CTE removed using PB | Not applicable |
| 2 | CTE-AB | CTE removed using AB to SSPC-SP5[1] | 4 mils |
| 3 | CTE-PBAB | CTE removed using PB followed by AB to SSPC-SP5[1] | 4 mils |
| 4 | BM-AB | Bare metal with no mill scale prepared with AB to SSPC-SP5[1] | 4 mils |
| 5 | BM-PB | Bare metal with mill scale prepared with PB | Not applicable |

[1] SSPC-SP5 denotes abrasive blast cleaning to white metal condition (ASTM, 2021).


**Figure 1.—Sample preparation using the PlasmaBlastTM system.**

Figure 2 shows the Group 3 panels after PB preparation. The plasma melted the CTE and did not produce a good enough surface to perform spot repairs on many of the samples. Researchers attribute the difficulties in removing the CTE with both PB and dry abrasive blasting to the high coating thickness and lack of aging-induced brittleness. As a result of the difficulties with CTE removal, many of the sample panels were not used and the original testing plan was modified to exclude the use of test panels with exceptionally poor CTE removal results.

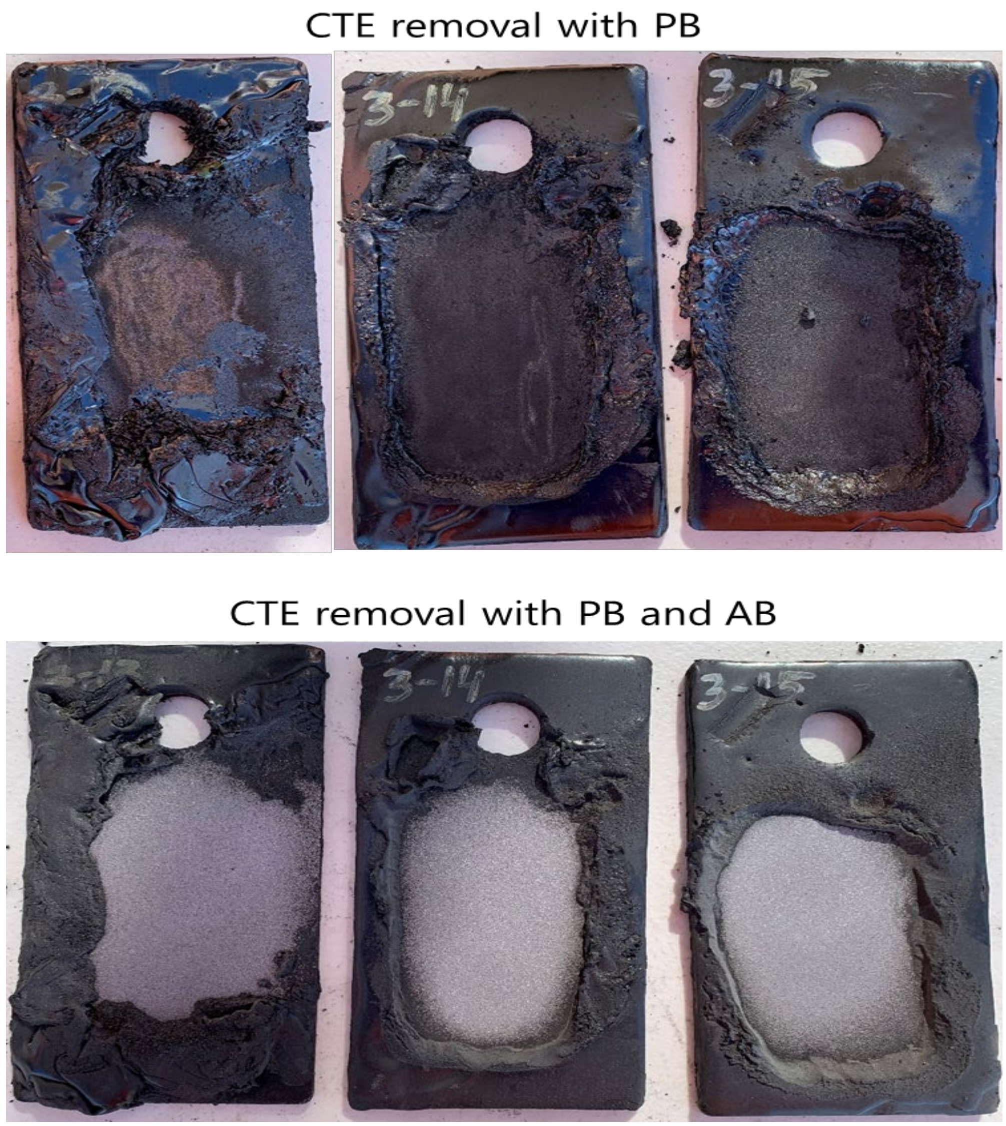



**Figure 2.—Group 3 test panels shown after CTE removal with PlasmaBlast™ (PB) in the top image and with PB followed with dry abrasive blasting (AB) in the bottom image. The melted CTE along the perimeter of the blast area is not acceptable for spot repairs.**

### 2.1.2 Round 2

A second round of testing was initiated during the summer of 2022 to further evaluate plasma as a surface modifying technique to promote adhesion and to evaluate removal of epoxy coatings using plasma and comparing to a traditional spot repair technique.

The sample preparation plan for Groups 6–10 is described in table 2. Only 12 epoxy-coated panels were available for Groups 8–10, so researchers performed dry adhesion and rust creep tests on opposite sides of the same panel. After surface preparation, each panel was coated with a two-part 100% solids epoxy.

**Table 2.—Round 2 sample preparation plan consisting of varied combinations of PB and/or (AB on bare steel, CTE, and 100% solids epoxy**

| Group number | Group name | Description |
|---|---|---|
| 6 | CTE-PB APS | CTE removal using PlasmaBlast™ performed by vendor |
| 7 | BM-ABPB | Bare metal prepared with AB to SSPC SP5[1] followed by PB |
| 8 | EP-BBPB | Epoxy removed with bristle blasting followed by PB |
| 9 | EP-BB | Epoxy removed with bristle blasting |
| 10 | EP-PB | Epoxy removed with PB |

[1] SSPC-SP5 denotes abrasive blast cleaning to white metal condition (ASTM, 1997).

## 2.2 Coating Application

After surface preparation, each set of panels was coated with a brush-applied two-part 100% solids epoxy.

### 2.2.1 Group 6

The CTE-coated panels in Group 6 for were sent to the vendor for plasma removal and subsequent coating with the same epoxy product. The coating was brush-applied to both faces of each panel in two coats with a total target dry film thickness of 30 mils. According to the vendor, the samples were surface activated (using the plasma tool) prior to the initial coating for both sides.

## 2.3 Exposure Conditions

Following surface preparation and coating application, the 3-inch x 6-inch x 1/8-inch steel test panels were placed in varying environmental exposure conditions. Harrison immersion exposure (HAR) was done at room temperature in a dilute Harrison's solution (DHS). Cyclic testing (HAR+FOG) was performed by rotating panels every seven days between exposure in DHS immersion and a fog chamber (FOG) circulating DHS. HAR and HAR+FOG tests ran for 30-week durations.

## 2.4 Coating Performance Evaluation

Four types of tests were used to evaluate coating performance: dry adhesion, wet adhesion, and rust creep testing. Dry adhesion tests were performed before environmental exposure in either HAR or HAR+FOG, wet adhesion was performed after approximately 5-7 weeks of exposure, and rust creep tests were performed after a 30-week exposure.

### 2.4.1 Rust Creep Testing

Rust creep was evaluated on panels which had been scribed prior to environmental exposure. After removing the sample from HAR or HAR+FOG, the evaluator chiseled all loose coating away from the scribe line, measuring the full width of the exposed rust area perpendicularly across the scribe mark at five random locations as well as the overall minimum and maximum. The rust creep value is the full width value minus the initial scribe width (0.075 inches), divided by two. The maximum rust creep measurement is reported for immersion samples. The average of the five rust creep measurements are reported for cyclic testing samples, along with the minimum and maximum values.

### 2.4.2 Adhesion Testing

Researchers performed dry and wet adhesion testing according to the ASTM D4541 standard in which the adhesion strength of each coating is evaluated using a pull-off strength test (ASTM, 2018). In the procedure, a 20-millimeter (mm) dolly, which serves as the loading fixture, is secured to the test panel's coated surface with a two-component adhesive. The evaluator pulls the dolly off with a fixed-alignment portable adhesion tester, which steadily increases pull-off pressure until failure occurs. The applied pressure at failure (pull-off strength) is recorded, and the corresponding dolly and pull-off locations are visually evaluated for area percentages exhibiting one of three failure modes: adhesion (between the coating metal substrate), cohesion (within the coating), and glue (within the adhesive).

For wet adhesions tests, the sample panel is removed from the exposure condition, rinsed, and allowed to dry before the dolly is glued down. Prior to testing, the glue is allowed to cure for one hour in ambient conditions and approximately 24 hours in 100% humidity.

Table 3 and table 4 provide summaries of the Round 1 and 2 testing.

**Table 3.—Round 1 test summary showing the exposure conditions and the number of replicates (panels) and tests (dollies) used for dry adhesion (dry), wet adhesion after Harrison's solution immersion (HAR) or cyclic testing (HAR+FOG), and rust creep testing**

| **Test type** | Adhesion | Adhesion | Adhesion | Rust Creep | Rust Creep |
|---|---|---|---|---|---|
| **Exposure [1,2,3]** | Dry | HAR | HAR+FOG | HAR | HAR+FOG |
| **Group 1 (CTE-PB)** | 2 (3 tests) | 1 (2 tests) | N/A | N/A | N/A |
| **Group 2 (CTE-AB)** | 4 (6 tests) | 2 (4 tests) | N/A | N/A | N/A |
| **Group 3 (CTE-PBAB)** | 2 (2 tests reported, 1 omitted) | 1 (2 tests) | N/A | N/A | N/A |
| **Group 4 (BM-AB)** | 3 (5 tests reported, 1 omitted) | 3 (9 tests) | 3 (9 tests) | 3 | 3 |
| **Group 5 (BM-PB)** | 3 (6 tests) | 3 (9 tests) | 3 (9 tests) | 3 | 3 |

[1] ASTM D870: Dilute Harrison's Solution (DHS) is 0.5 g/L NaCl, 3.5 g/L $(NH_4)_2SO_4$; testing performed at room temperature (ASTM, 1997).
[2] FOG exposure cycling per ASTM G85 Annex A5; 1-hour fog at ambient temperature and pressure using DHS solution alternating with 1-hour dry at 35°C (ASTM, 2002).
[3] HAR+FOG indicates 1-week alternating exposure of HAR and FOG.

**Table 4.—Round 2 test summary showing the exposure conditions and the number of replicates (panels) and tests (dollies) used for dry adhesion (dry), wet adhesion after HAR) or cyclic testing (HAR +FOG), and rust creep testing**

| **Test type** | Adhesion | Adhesion | Adhesion | Rust Creep | Rust Creep |
|---|---|---|---|---|---|
| **Exposure [1,2,3]** | Dry | HAR | HAR+FOG | HAR | HAR+FOG |
| **Group 6 (CTE-PB APS)** | 3 (3 tests) | 1 (1 test) | 1 (1 test) | 5 | 1 |
| **Group 7 (BM-ABPB)** | 3 (6 tests) | 3 (9 tests) | 3 (9 tests) | 3 | 3 |
| **Group 8 (EP-BBPB)** | 3 (9 tests) | 3 (9 tests) | 3 (9 tests) | 3 | 3 |
| **Group 9 (EP-BB)** | 3 (9 tests) | 3 (9 tests) | 3 (9 tests) | 3 | 3 |
| **Group 10 (EP-PB)** | 3 (9 tests) | 3 (9 tests) | 3 (9 tests) | 3 | 3 |

[1] ASTM D870: Dilute Harrison's Solution (DHS) is 0.5 g/L NaCl, 3.5 g/L $(NH_4)_2SO_4$; testing performed at room temperature (ASTM, 1997)]
[2] FOG exposure cycling per ASTM G85 Annex A5; 1-hour fog at ambient temperature and pressure using DHS solution alternating with 1-hour dry at 35 C (ASTM, 2002).
[3] HAR+FOG indicates 1-week alternating exposure of HAR and FOG.

# 3. Results

In general, the use of atmospheric plasma to remove and convert CTE to harmless carbon dioxide and water products was challenging, presumably due to the high coating thickness. When panels with CTE were subjected to PB, the CTE could be seen becoming more fluid and pushed aside to the edges around the area where the PB was applied. A large amount of visible smoke was also observed emanating from the PB application to the CTE. Occasionally, large chunks of the CTE was released during the process. From a hazardous material perspective, it would be necessary to utilize containment during removal to prevent the release of CTE into the surrounding environment and for the protection of coating removal workers.

## 3.1 Dry Adhesion Results

Figure 2 shows the Group 3 panels after PB preparation. The plasma melted the CTE and did not produce a good enough surface to perform spot repairs on many of the samples. Researchers attribute the difficulties in removing the CTE with both PB and dry abrasive blasting to the high coating thickness and lack of aging-induced brittleness. As a result of the difficulties with CTE removal, many of the sample panels were not used and the original testing plan was modified to exclude the use of test panels with exceptionally poor CTE removal results.

Results of dry adhesion testing are shown in figure 3 and summarized in table 5, with failure levels reported in pounds per square inch (psi). Note that Groups 1, 3, and 6 have three or fewer tests so additional testing could be useful to confirm any trends observed in this study. In addition, contributions from glue and cohesive failures are present in varying fractions in most test groups and will tend to result in underestimating the true adhesion values.

The highest strength was achieved when no coating was removed (BM-AB and BM-ABPB). In the case of BM-ABPB, the failure was primarily glue, so the actual strength is higher than reported. Comparing CTE-PB and CTE-PB APS where CTE was removed with plasma only, the vendor's panel achieved a greater adhesion which indicates that performance is sensitive to the process, operator, and technique used. In comparing the two control groups (BM-AB and BM-PB), the abrasive blast achieves greater adhesion than plasma alone, but abrasive blast followed by plasma (BM-ABPB) is likely higher than BM-AB if not for the glue failure. Note that the results shown are for just one epoxy product and may vary if additional products were tested. The results from the epoxy removal groups were somewhat unexpected; the highest adhesion was achieved by EP-PB whereas EP-BBPB produced the lowest adhesion. It is likely that EP-PB outperformed EP-BBPB and EP-BB because the original abrasive blasted surface profile remained intact. EP-BBPB and EP-BB are close and within the standard deviation, so plasma blasting doesn't alter dry adhesion significantly after bristle blasting. Note that one dolly placement inadvertently included a small portion of the original epoxy and failed at exactly at the group average of 1388 psi.

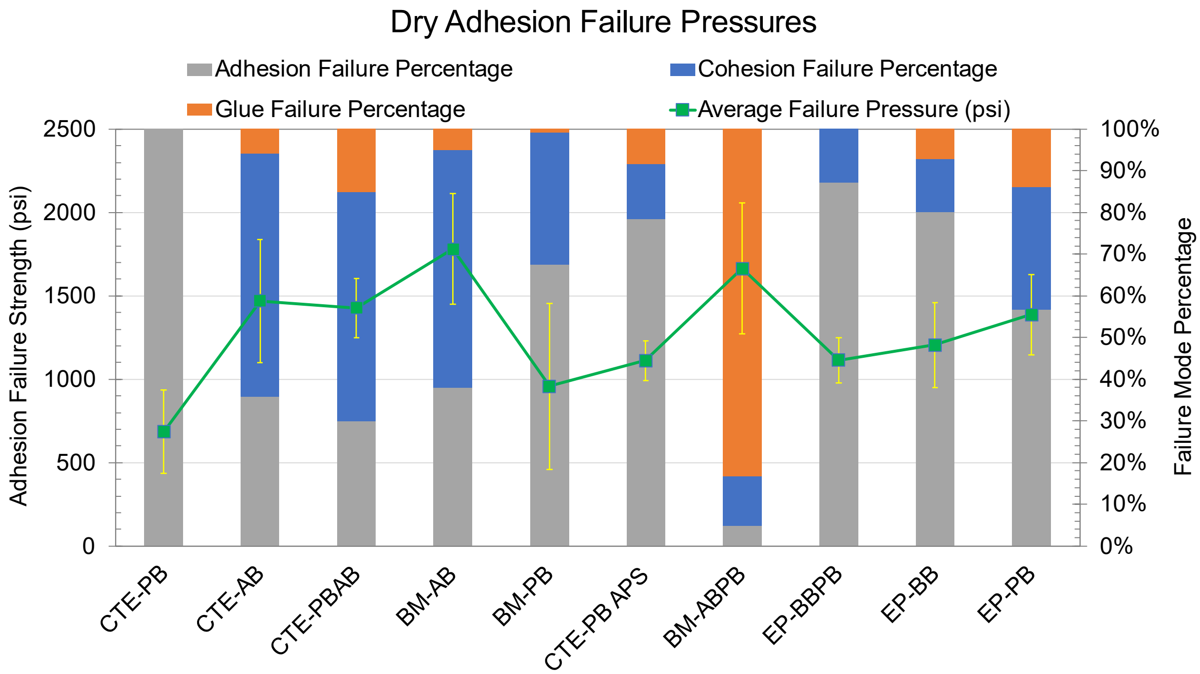



**Figure 3.—Results of dry adhesion testing are plotted with the failure mode percentages for each material group.**

**Table 5.—Dry adhesion results summarized. Samples are not excluded due to glue or cohesive failure**

| Group | | Average failure pressure (psi) | Average adhesion failure percentage | Average cohesion failure percentage | Average glue failure percentage |
|---|---|---|---|---|---|
| 1 | CTE-PB | 685 +/- D249 | 100.0 | 0.0 | 0.0 |
| 2 | CTE-AB | 1469 +/- 368 | 35.8 | 58.3 | 5.8 |
| 3 | CTE-PBAB | 1428 +/- 178 | 30.0 | 55.0 | 15.0 |
| 4 | BM-AB | 1782 +/- 331 | 38.0 | 57.0 | 5.0 |
| 5 | BM-PB | 957 +/- 498 | 67.5 | 31.7 | 0.8 |
| 6 | CTE-PB APS | 1112 +/- 119 | 78.3 | 13.3 | 8.3 |
| 7 | BM-ABPB | 1665 +/- 392 | 5.0 | 11.7 | 83.3 |
| 8 | EP-BBPB | 1115 +/- 136 | 87.2 | 12.8 | 0.0 |
| 9 | EP-BB | 1205 +/- 257 | 80.0 | 12.8 | 7.2 |
| 10 | EP-PB | 1388 +/- 242 | 56.7 | 29.4 | 13.9 |

## 3.2 Wet Adhesion Results

Wet adhesion test results are shown in figure 4 and table 6 and are compared with dry (initial) adhesion in figure 5.

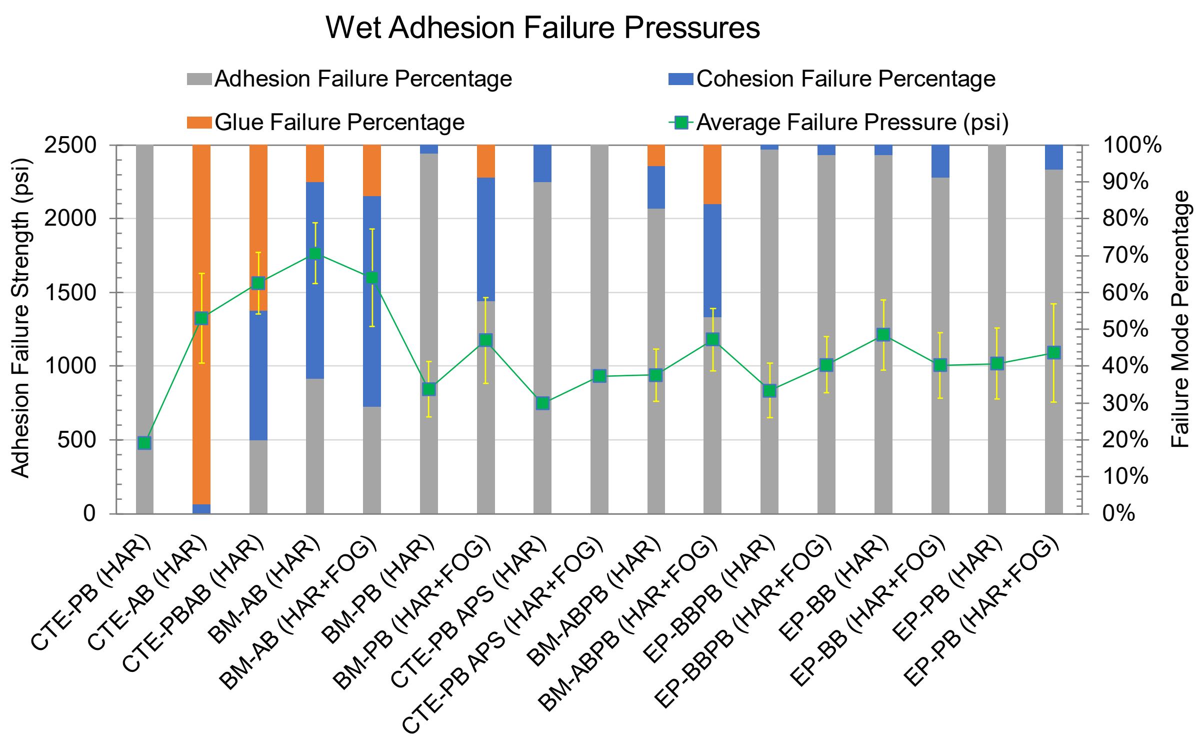



**Figure 4.—Results of wet adhesion testing are plotted with the failure mode percentages for each material group.**

**Table 6.—Wet adhesion test results**

| Group | | | Average Failure Pressure (psi) | Average Adhesion Failure (%) | Average Cohesion Failure (%) | Average Glue Failure (%) |
|---|---|---|---|---|---|---|
| 1 | CTE-PB | HAR | 479 +/- 18 | 100.0 | 0.0 | 0.0 |
| 2 | CTE-AB | HAR | 1325 +/- 302 | 0.0 | 2.5 | 97.5 |
| 3 | CTE-PBAB | HAR | 1564 +/- 209 | 20.0 | 35.0 | 45.0 |
| 4 | BM-AB | HAR | 1766 +/- 208 | 36.7 | 53.3 | 11.1 |
| | | HAR+FOG | 1600 +/- 331 | 28.9 | 57.2 | 13.9 |
| 5 | BM-PB | HAR | 841 +/- 188 | 97.8 | 2.2 | 0.0 |
| | | HAR+FOG | 1176 +/- 291 | 57.8 | 33.3 | 8.9 |
| 6 | CTE-PB APS | HAR | 746 +/- NA | 90.0 | 10.0 | 0.0 |
| | | HAR+FOG | 932 +/- NA | 100.0 | 0.0 | 0.0 |
| 7 | BM-ABPB | HAR | 939 +/- 176 | 82.8 | 11.7 | 5.6 |
| | | HAR+FOG | 1182 +/- 211 | 53.3 | 30.6 | 16.1 |
| 8 | EP-BBPB | HAR | 835 +/- 187 | 98.9 | 1.1 | 0.0 |
| | | HAR+FOG | 1010 +/- 190 | 97.2 | 2.8 | 0.0 |
| 9 | EP-BB | HAR | 1212 +/- 237 | 97.2 | 2.8 | 0.0 |
| | | HAR+FOG | 1006 +/- 222 | 91.1 | 8.9 | 0.0 |
| 10 | EP-PB | HAR | 1017 +/- 240 | 100.0 | 0.0 | 0.0 |
| | | HAR+FOG | 1090 +/- 333 | 93.3 | 6.7 | 0.0 |

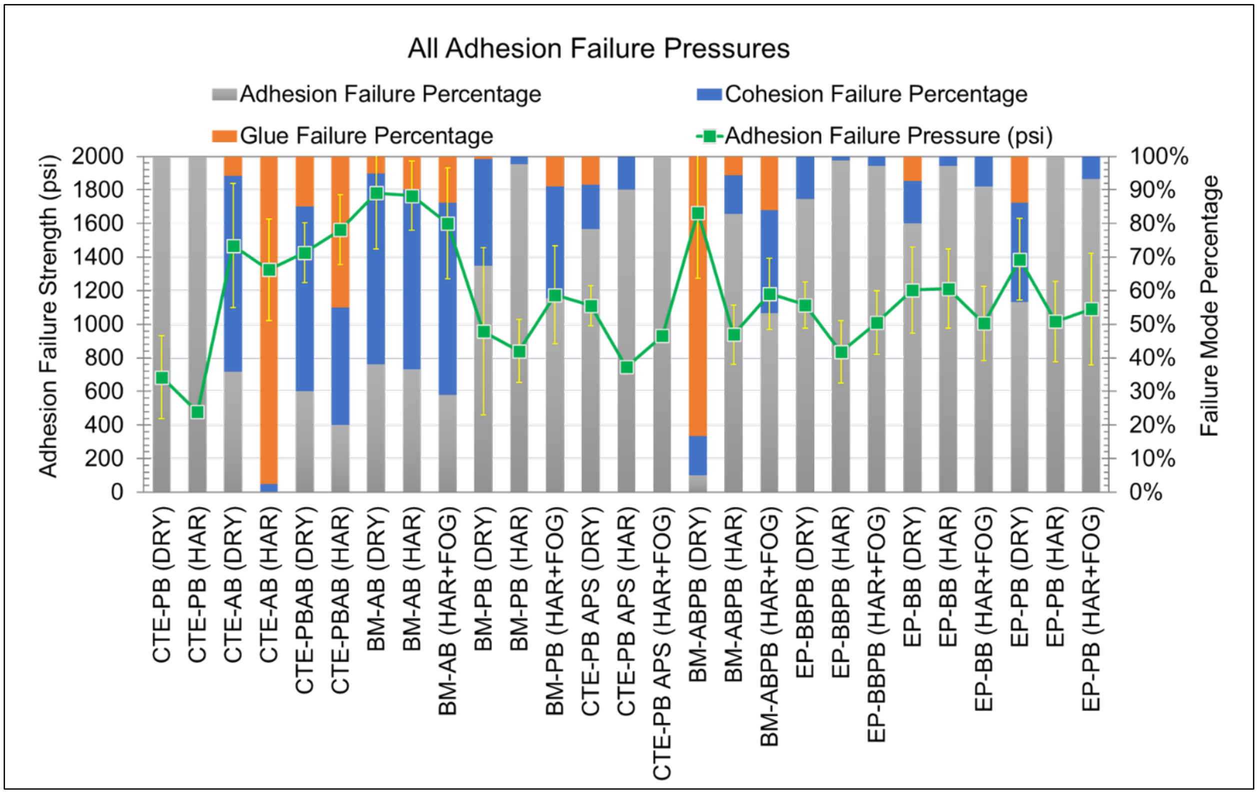



**Figure 5.—Results of dry and wet adhesion testing are plotted with the failure mode percentages for each material group. Error bars represent plus or minus one standard deviation for values from a set of three or more test panels.**

The highest wet adhesion values (1766 psi) were achieved in the BM-AB group. Interestingly, BM-ABPB had lower values than BM-AB (939 psi for HAR immersion and 1182 psi for HAR+FOG). This suggests there was no increase in wet adhesion performance resulting from the plasma surface treatment. Adding the FOG cycle to the exposure had no obvious effect on adhesion. Dry adhesion values were higher on average than HAR samples by 208 psi. For samples prepared with plasma as the final step, this difference was 344 psi. For samples prepared with abrasive blast as the final step, there was no significant difference (4 psi).

On average the panels treated with plasma for the final step (CTE-PB, BM-PB, CTE-PB APS, BM-ABPB, EP-BBPB, EP-PB) averaged 95% adhesion as the failure mode after HAR immersion. For panels where abrasive blast was performed as the final step (CTE-AB, CTE-PBAB, BM-AB), percent adhesion failure was 19% after HAR immersion, indicating better adhesion than plasma prepared samples.

## 3.3 Rust Creep Results

Rust creep data was collected for Groups 4–10 after 30 weeks of alternating exposure between immersion and fog testing. The results are shown in figure 10.

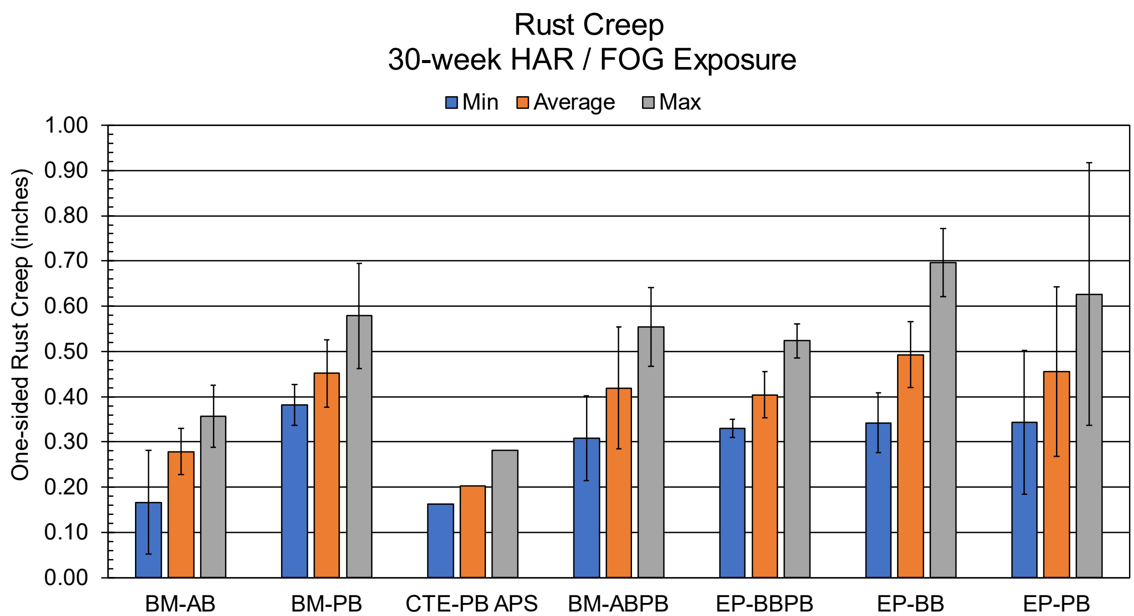



**Figure 6.—Rust creep after 30 weeks of alternating exposure between HAR and FOG. Error bars represent plus or minus one standard deviation for values from a set of three or more test panels. Only one panel was evaluated for CTE-PB APS.**

The best performing group was CTE-PB APS at 0.2 inches of single sided rust creep on average. However, only one panel was prepared for this set due to an error so there is low confidence in this measurement due to the limited area available for analysis. The next best group was BM-AB whereas EP-BB had the highest maximum rust creep at 0.70 inches. Excluding CTE-PB APS, BM-AB is the best performer in this test. BM-AB outperformed BM-ABPB with an average rust creep measurement of 0.28 inches versus 0.42 inches. Figure 7 shows the photographs of the panels after testing.


**Figure 7.—Photos showing rust creep after 30 weeks of alternating exposure (HAR+FOG).**

Rust creep values were much lower for the HAR exposure test with all groups performing satisfactorily; see figure 8. Max values ranged from 0.03 inches to 0.14 inches and in this test, the group with the lowest maximum rust creep was BM-AB and BM-ABPB. Figure 9 shows the photos of each set of rust creep panels after coating removal.

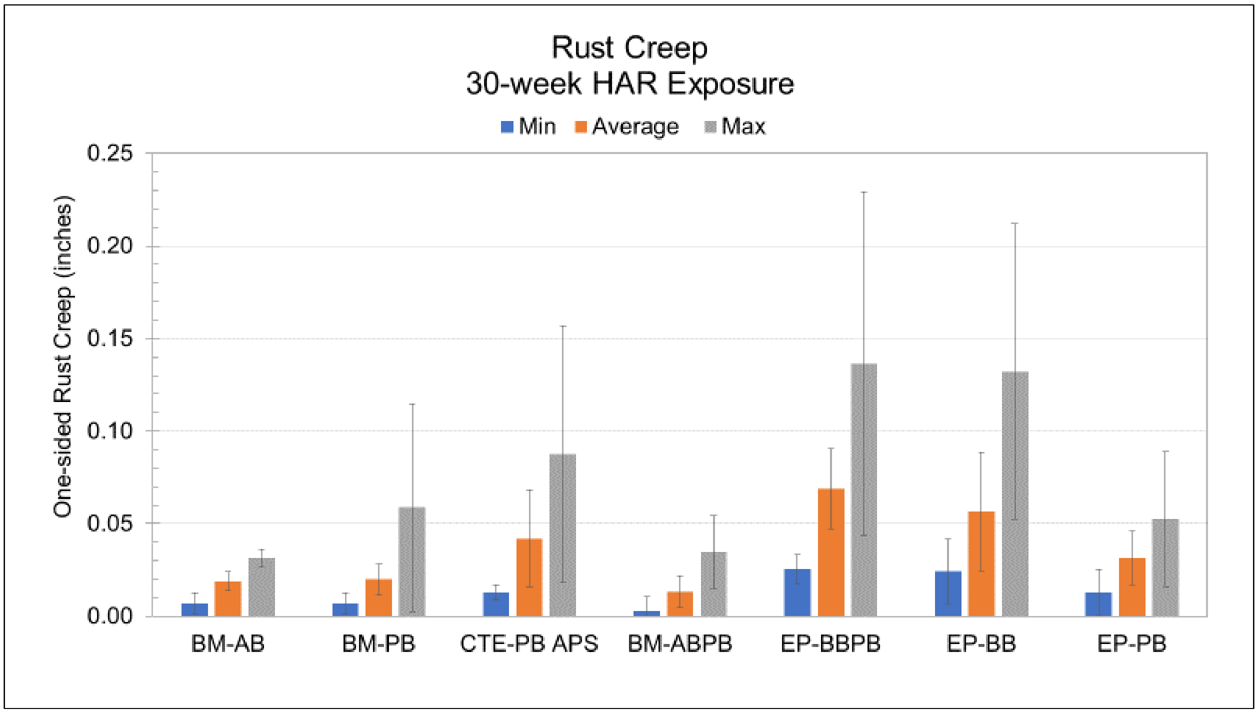



**Figure 7.—Rust creep after 30 weeks of HAR exposure.**


**Figure 8.—Photos showing rust creep after 30 weeks of immersion exposure (HAR).**

# 4. Discussion

The primary objective of this study was to evaluate the feasibility and effectiveness of using plasma blasting as a means of surface preparation. If proven successful, it is envisioned that the process could be most readily adopted for use in performing spot repairs. The goal was to evaluate the process in terms of coating performance and to determine whether plasma blasting can enhance coating adhesion on a conventionally prepared surface. Pull-off adhesion testing and rust creep performance were evaluated in this study for different combinations of surface preparation protocols including dry abrasive blasting, plasma blasting, and bristle blasting. Test groups included bare steel panels and panels with an existing coating of either coal tar enamel or a polyamide epoxy. After the prescribed surface preparation, all panels received the same final coating of 100% solids epoxy.

The highest dry pull-off adhesion values were achieved when no coating was removed (BM-AB and BM-ABPB). The BM-ABPB had a large percentage of glue failure so it's possible that plasma produced a beneficial effect on initial coating adhesion, but the results are inconclusive. Adhesion results were lowest on the no coating scenario when plasma alone was used over mill scale. This suggests a surface profile is still required to achieve optimum performance for the 100% solids epoxy tested.

For a spot repair scenario with an existing profile, removing epoxy with plasma provided similar adhesion to using a handheld bristle blast tool. In the case of CTE removal, the results were improved when an experienced operator i.e., the external vendor, performed the removal. While plasma blasting successfully removed the CTE, abrasive blasting was needed to achieve the highest initial adhesion.

Wet adhesion is a useful test because coatings can lose some adhesion strength after prolonged immersion. Wet adhesion results were similar to dry adhesion in that the highest pull-off adhesion values were realized when abrasive blasting was used on the uncoated samples. Overall, dry adhesion values were 208 psi higher on average than wet adhesion after HAR immersion. This difference between dry and wet adhesion was 344 psi for panels prepared with plasma blasting as the final step and no significant difference (4 psi) for panels prepared with abrasive blasting as the final step. Additional testing is needed to determine if this result is statistically significant and for adhesion performance to be directly compared.

Comparing the bristle blasting coating removal to plasma removal where there is an existing surface profile could be more appropriate if the process is envisioned for spot repairs. The effect on initial(dry) adhesion was mixed with EP-BBPB coming in at 90 psi lower than EP-BB, and EP-PB 183 psi higher than EP-BB but any differences were within one standard deviation. The EP-PB samples were also slightly higher than the EP-BB by 85 psi (8%) after HAR+FOG exposure. However, the HAR samples prepared with bristle blasting (EP-BB) outperformed EP-PB by 121 psi (16%) and EP-BBPB by 377 psi (31%). Again, any differences were within one standard deviation. Hence there is no clear trend favoring plasma or bristle blasting for wet adhesion performance.

HAR+FOG proved to be the more aggressive exposure condition in terms of overall rust creep. The CTE-PB APS, although only represented by a single replicate, had the lowest rust creep observed in this test and was therefore the best performing group. Similar to adhesion, the plasma provided no clear benefit in reducing rust creep versus abrasive blasting when the same operator performed the removal. However, there may be a small improvement in rust creep performance using plasma vs bristle blasting but any differences were within one standard deviation.

A secondary objective was to determine if the use of atmospheric plasma to remove CTE would eliminate the waste streams that are typically generated during traditional removal methods. The waste generated during traditional CTE removal methods is considered a hazardous material and must be contained, tested, and disposed of properly. Environmental regulations such as the Resource Conservation and Recovery Act (RCRA) control hazardous wastes, from generation to final disposal (RCRA, 1976). However, during CTE removal using atmospheric plasma during this project, pieces of CTE in the forms of chips and flakes could be seen flying off the coated steel coupons. A large amount of smoke was also visible. Based on these anecdotal observations, it is likely containment will still be required when using atmospheric plasma to remove CTE and the contained waste stream contained will still be required to be tested and disposed properly in accordance with environmental regulations. The visible smoke emanating from the steel coupons during CTE removal using atmospheric plasma adds an additional concern for environmental contamination. If used on construction projects to remove CTE, it is unlikely that atmospheric plasma will provide a more simplified process of containing waste streams with a lower impact on the environment compared with traditional removal methods.

# 5. Conclusion

This project investigated the use of atmospheric plasma to remove CTE. Test groups of steel coupons were prepared with or without CTE coating on each, depending on the test parameter to be determined. Different test groups were subjected to different surface preparation protocols, including one or a combination of atmospheric plasma, dry abrasive blasting, bristle blasting, and no removal (controls). Testing included corrosion performance (rust creep) and adhesion properties under different sets of conditions.

Data from these results and the visual observations of CTE and smoke released into the environment during atmospheric plasma removal suggest that abrasive blasting and containment of hazardous waste streams generated during removal will still be required. In general, analyses of the results indicated that additional testing is needed to accurately determine whether any observed differences in performance are of statistical significance.

# 6. References

American Society for Testing and Materials (ASTM). 2021. D4541-22 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. https://compass.astm.org/. Date accessed 5/15/2021.

American Society for Testing and Materials (ASTM). 2018. D6677-18 Standard Test Method for Evaluating Adhesion by Knife. https://compass.astm.org/. Date accessed 5/15/2021.

American Society for Testing and Materials (ASTM). 1997. D 870-97 Standard Practice for Testing Water Resistance of Coatings Using Water Immersion. https://compass.astm.org/.

American Society for Testing and Materials (ASTM). 2002. G 85-02 Standard Practice for Modified Salt Spray (Fog) Testing. https://compass.astm.org/.

Astolfi, G., Yancey, P., Wood, A., Snowden, L., Piascik, J., and Ross, R. 2022. Atmospheric Plasma Coating Removal for Navel Engineering and Maintenance Applications. https://www.astm.org/. Date accessed 4/6/2024.

Atmospheric Plasma Solutions. https://apsplasma.com/. Date accessed 11/12/2023.

Merati, A., Yanishevsky, M., Despinic, T., Lo, P., and Pankov, V. 2017. Alternate Environmentally Friendly De-Painting Process for Aircraft Structures – Atmospheric Plasma. https://www.scirp.org/journal/paperinformation?paperid=77478. Date accessed 04/04/2024.

Merten, B. 2017. Corrosion Protection of Steel Structures by Coal Tar Enamel: 80 Years of Performance. https://www.usbr.gov/research/projects/researcher.cfm?id=2334. Date accessed 05/04/2021.

Piascik, J., Yancey, P., Astolfi, G. Snowden, L., and Stimson, J. 2023. Using Atmospheric Plasma for Enhance Coating Adhesion to Limit the Onset of Corrosion. https://www.astm.org/. Date accessed 4/6/2024.

Ranieri, P., Stimson, J., Snowden, L., and Yancey, P. 2022. Atmospheric Plasma: One-Step Precision Process to Remove Coating and Promote Chemical Adhesion. https://www.astm.org/. Date accessed 4/6/2024.

Resource Conservation and Recovery Act. 42 USC §6901 et seq. (1976). https://www.epa.gov/laws-regulations/summary-resource-conservation-and-recovery-act. Date accessed 5/26/2023.

Yancey, P., Astolfi, G., Nixon, R., Hauser, G.D., Brown, C., and Pope, G. 2018. Atmospheric Plasma Coating Removal: The Future Without Spent Abrasive. https://www.astm.org/. Date accessed 4/6/2024.

Yancey, P., Hubner, R., and Chute, D. 2020. Plasma Coating Removal: a Safety and Industrial Hygiene Analysis. https://www.astm.org/. Date accessed 4/6/2024.