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The Behavior of Environmentally Friendly Corrosion Preventative Compounds in an Aggressive Coastal Marine Environment

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ABSTRACT

The shift to use environmentally friendly technologies throughout future space-related launch programs prompted a study aimed at replacing current petroleum and solvent-based corrosion preventive compounds (CPCs) with environmentally friendly alternatives. The work in this paper focused on the identification and evaluation of environmentally friendly CPCs for use in protecting flight hardware and ground support equipment from atmospheric corrosion. The CPCs, while a temporary protective coating, must survive in the aggressive coastal marine environment that exists throughout the Kennedy Space Center, Florida. The different protection behaviors of fifteen different soft film CPCs, both common petroleum-based and newer environmentally friendly types, were evaluated on various steel and aluminum substrates. The CPC and substrate systems were subjected to atmospheric testing at the beachside atmospheric corrosion test site located in Kennedy Space Center, Florida, as well as cyclic accelerated corrosion testing. Each CPC also underwent physical characterization and launch-related compatibility testing. The initial results for the fifteen CPC systems are reported.

Key words: corrosion preventive compound, CPC, spaceport, environmentally friendly, atmospheric exposure, marine, carbon steel, aluminum alloy, galvanic corrosion, wire on bolt, CLIMAT.

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INTRODUCTION

The objective of the work presented in this paper is to determine if environmentally-friendly corrosion preventive compounds (CPCs) will provide adequate temporary corrosion protection for spaceport structures and related hardware used at NASA's Kennedy Space Center^[1]. Typically when a bare metal surface could or should not be coated with a permanent coating (paint or sacrificial coating), a temporary CPC coating is used to protect the exposed surface from corrosion. CPCs commonly contain corrosion inhibitors suspended in a mixture of solvents and a base oil or grease. The base oil acts as a carrier fluid for the inhibitors and also a protective barrier to environmental elements. The solvent acts as a base oil and inhibitor dispersant and is intended to evaporate after application. CPCs can be soft or hard films, and can be primarily composed of a petroleum, hydrocarbon, or fluoropolymer material depending on their end user requirements. Although CPCs provide corrosion protection, there are a number of environmental and safety issues:

- Base oils are not environmentally benign
- Solvents can be high in volatile organic compounds (VOCs) and toxic
- Corrosion inhibitors can be toxic
- Worker safety issues

Current petroleum-based CPCs are becoming increasingly impractical for use at this location due to environmental concerns and cumbersome containment procedures required during application and removal. These difficulties are encountered in the field, where nearly all CPCs are applied at KSC, and thereby CPC use at KSC has not been fully realized. KSC is known to be one of the most corrosive places in North America,¹ and CPCs offer a much needed option for corrosion protection to metallic materials that cannot be painted or will only be exposed to the corrosive atmosphere for a temporary time period. KSC is located within the Merritt Island National Wildlife Refuge^[2]; therefore, environmentally-friendly alternatives are highly sought after. Identifying successful environmentally-friendly CPC alternatives will relieve environmental and worker safety concerns, and also open new avenues for CPC use across KSC that were previously avoided. This paper focuses on the use of soft film CPCs, including common petroleum-based types and environmentally-friendly alternatives. Corrosion evaluations were performed at KSC's beachside atmospheric corrosion test site.

BACKGROUND

CPC Applications of Interest

CPCs for Spaceport Ground Support Equipment

The Corrosion Control and Treatment Manual, TM-584C⁵, highlights multiple applications where CPCs are to be used to control corrosion of materials in facilities, systems, and equipment at KSC. The manual cites for CPC use in the protection of exposed bearing surfaces, tubular structural steel, electrical connectors, steel cabling, piano-type hinges, adjustable parts, and bare metal piston surfaces using corrosion inhibiting lubricants in the form of oil and greases. The manual cites several military specifications to refer to many of the spaceport-approved CPC types. The specifications are listed as: MIL-PRF-16173E⁶, grades, 2, 3, and 4, MIL-DTL-23549D⁷, MIL-PRF-81322G⁸, MIL-PRF-46000D⁹, MIL-PRF-46010D¹⁰, and MIL-PRF-46002D.¹¹

CPCs are used for temporary corrosion protection on both bare metal and coated, often damaged, surfaces on ground support equipment, including but not limited to the mobile launcher platform (MLP), the fixed service structures at the launch pads, the crawler-transporters. One major use is on the thrust vector control (TVC) frames that structurally support components of the TVC system that is located in

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the aft skirt of the solid rocket booster (SRB).³ TVC frames are exposed to the coastal environment after refurbishment, and seawater immersion after splashdown and during tow-back to refurbishment facilities. During refurbishment operations it was found that numerous TVC frames were experiencing internal corrosion and coating failures, both from salt air and seawater intrusions. Inspectors using borescopes would visually examine the internal cavities of the complicated aluminum alloy welded tubular structure. It was very difficult for inspectors to examine cavity corners and tubing intersections and particularly, to determine the extent of the corrosion and coating anomalies. Physical access to TVC frame internal cavities for corrosion removal and coating repair was virtually impossible, and an improved method using a CPC for preventing initiation of new corrosion, and mitigating and/or stopping existing corrosion growth has been used ever since.³

CPCs are used on the international space station (ISS) for the international low docking system (iLIDS), which is a government furnished connector design made for anyone to manufacture and dock to the ISS. The iLIDS components consist of mixed metals, such as aluminum alloys (UNS A92219, UNS A92024, and UNS A97075), Stainless steels, titanium (for hook assembly), and UNS S44004 and UNS G52986 high alloy steel (for bushing and bearing materials), and Aluminum-bronze (for bushings and pins). There are issues with faying surfaces and galvanic couples that are corrected using CPCs.¹² One problem noted was that, although the more corrosion resistant alloy UNS S44004 is specified, the less corrosion resistant alloy UNS G52986 is often used due to alloy availability issues. Should this problem continue, extra corrosion precautions will have to be taken that will require an increased use of temporary CPC coatings.¹³

In the past, CPCs were used on the space shuttle orbiters to cover paint nicks between repairs.¹⁴ Because the CPCs must survive the launch environment, low earth orbit, and other flight cycle environments, thickened grease materials were used. The greases are often fluorinated vacuum greases with corrosion inhibitor additives.^{13,15} When the space shuttles were flying, the frequency of corrosion issues on the orbiters regularly exceeded 400 cases annually.¹⁶ Typically locations where CPC are used on the orbiters were the rudder speed brake, vertical tail, elevons, wing leading edge, ET door cavity, and the body flap.¹² The longest time a CPC protected the substrate was for four mission cycles.¹³

One problem that has been identified as a possible future use for CPCs at spaceports is to temporarily cover space flight hardware that consists of bare metal components prior to launch. Current material specifications require that all manufacturers' coatings (usually CPCs) be removed prior to use. When space flight hardware is exposed to coastal environmental conditions while awaiting launch, atmospheric corrosion occurs on the surface. A temporary CPC coating that could be removed prior to launch would be considered an ideal solution to this problem.¹⁷

CPC Applications throughout DoD^[1] and Aerospace Industry

CPC are used heavily throughout the military in aircraft, ship, transport vehicle, and armored vehicle applications, as well as on many types of ground support structures and munitions. From a materials perspective, metal substrates are clearly used in the majority of vehicles and structures, therefore the opportunities for corrosion problems abound. It is estimated that the cost of corrosion to the military is estimated between \$10 billion and \$20 billion annually.¹⁸ Because military locations exist worldwide, there are many different environments with which the corrosion control personnel must contend. The harshest are those that are close to or in seawater environments because sea salts accelerate the corrosion process.

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Aircraft Applications.

Aircraft face some of the most common corrosion problems throughout the military and in the general aerospace industry. The constant cycling of wetting and drying due to condensation that occurs during take-off and landing is a root cause of much of the corrosion problems. Because of the shape of aircraft, there are many crevices and occluded areas built into the design that become traps for moisture. Aircraft have many components that are bare metal, as the substrates are almost always aluminum-based alloys. The lack of a protective layer, other than the natural oxide film, makes it more likely for corrosion to form on the substrate. Military services all face the same types of problems with their aircraft regardless of type. The most common areas of corrosion where CPCs are used include beams, joints, fastener areas, electrical wiring components,¹⁹ inner and outer mold lines, cargo floor end fittings, fuselage belly skins, wheel well aft bulkheads, mainframes, stringers,²⁰ landing gear, flapwells,²¹ lap joints, beneath the floorboards in the bilge areas,²² the lavatory and galley, wing interior sections, doors and hatches, and skin panel faying surface.²³ The F-18 has had some of the most severe corrosion problems thus far because dissimilar metal corrosion and moisture build-up due to absent drain holes were corrosion problems inadvertently included in the aircraft design. CPCs have been used to control this type of this corrosion, ever since the problems first surfaced.²⁰

Marine Applications.

Many of the vehicles used in marine applications, especially those deployed at sea, use paints and cathodic protection to manage corrosion because they need more permanent solutions to block the direct metal contact with the seawater. One common vehicle that routinely uses CPCs for corrosion control is the expeditionary fighting vehicle (EFV). The EFV is an amphibian type that sees both seawater, freshwater, and many cycles of drying. The seal frame, armor panel frame, threaded inserts, fasteners, and the environmental seal areas are the most common places that CPCs are used.²⁴

Ground Operations Applications.

Ground operations face multiple corrosion problems with fixed structures, transport vehicles, and armored vehicles. The Army^[1] and Marines^[2] have the common problems with corrosion on the ground. CPCs are heavily used for electrical hardware, fuel cell rooms,²⁵ occluded sites (hinges, fasteners, under lap seams),²⁶ and hydraulic lifts.²⁷ Both transport and armored vehicle types heavily use CPCs as a last layer of corrosion defense over their vehicle paint.²²

Launch Applications.

Non-governmental launch vehicles and structures also face critical corrosion issues. In 2008, Space Exploration Technologies^[3] faced a failure of their Falcon 1 launch due to a corroded aluminum bolt.²⁸ Depending on their location to seawater, launch structures will face differing degrees of corrosion; however, corrosion will most commonly exist on the fixed structures (fasteners, exposed metal, and all areas similar to those identified in the NASA Corrosion Control and Treatment Manual), the rocket interior and exterior, the fuel cell areas, and the mixer assembly areas.²⁹

CPC Technologies

Current CPC Technologies.

Since the beginning of their use, CPCs have primarily been comprised of petroleum-based carrier oils, corrosion inhibitors, surfactants, and solvents.³⁰⁻³² The use of petroleum gives CPCs an unlimited shelf life, because the oils slowly oxidize over time. In general, these petroleum-based products require personal protection equipment during use and are harmful to the natural environment if spilled.³³ Some CPCs are made using a lanolin-based carrier oil³⁴ or a high grade machine oil.³⁵ The CPC manufacturers have begun to lower the solvent content in their CPCs so that they have low volatile

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organic components (VOCs).³⁶ This effort is primarily due to public and subsequent regulatory demand to make the CPCs less harmful to the environment.

Environmentally Friendly CPCs: State of the Art.

New CPC products are being made with canola, soy, and other vegetable-based carrier oils.^{37, 38} These products are also made so that they are solvent free, thus they contain no VOCs. The advantage to these products is that they are easy to dispose of and non-toxic. They are made without carcinogenic compounds or hazardous materials. There are questions as to the durability of these new plant-based CPCs, as the carrier oils are more likely to degrade at a faster rate than their petroleum-based counterparts. Because CPCs are meant, in most cases, to be used as a temporary line of defense from corrosion, many CPC manufacturers claim that their products perform the same as or better than petroleum-based products as a temporary protection in the normal use time.

Corrosion Challenges at Kennedy Space Center, Florida

The beachside atmospheric corrosion test site at the Kennedy Space Center, Florida has been documented as the most corrosive place known in the United States.¹ Figure 1 displays the location of the beachside test site along Florida's Atlantic coast. The environmental challenges at this location are both natural and man-made. The already higher-than-typical aggressive marine conditions are intermittently enhanced by the emission of 70 tons of hydrochloric acid into the atmosphere during launches that use rockets with solid fuel. Despite the corrosive environment, launch structures are largely made using structural steel, namely AISI⁽¹⁾ 1010 (UNS G10100). Different coatings, such as sacrificial coatings and paints, are used to slow corrosion in many areas; however, in areas where metals cannot be painted the corrosiveness of the environment is blatantly recognized over time. CPCs are and may be used in the future in areas across KSC where spaceport-specific environments, such as liquid oxygen or hypergolic fluids, may also be used. Special consideration was made to account for compatibility issues with future launch environments.

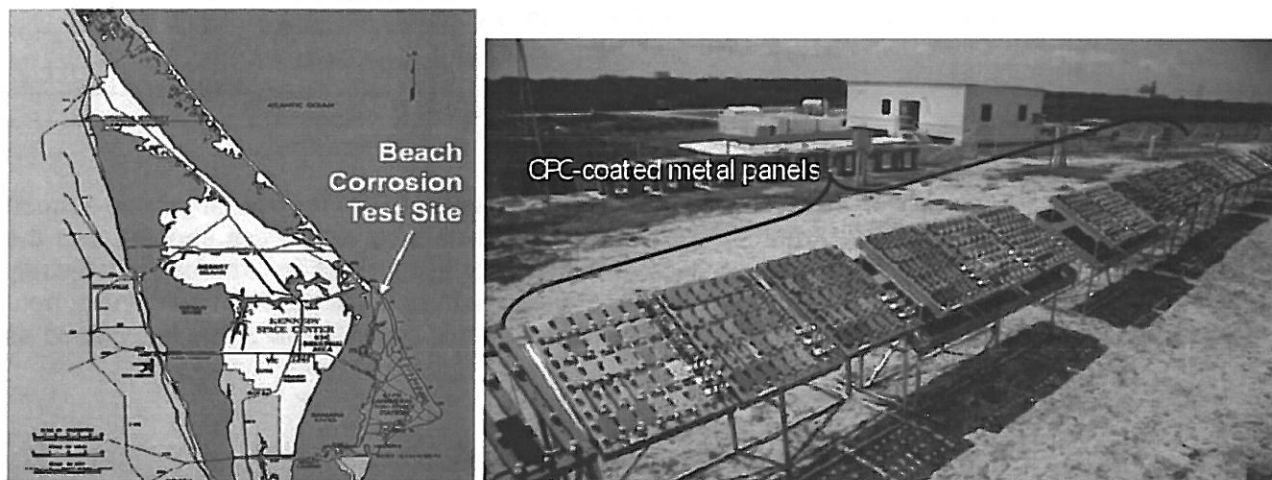


Figure 1: Location of the beachside corrosion test site at Kennedy Space Center, Florida along the Atlantic Ocean (left) and panels after initial CPC application and exposed to the marine atmosphere at the test site (right).

EXPERIMENTAL PROCEDURES

Test Plan Summary

Topics addressed in this study of environmentally-friendly CPC alternatives at KSC include:

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- 1) Determining the physical properties of each CPC type in relation to their end use at KSC.
- 2) Determining the degree of corrosion protection that each CPC provides on various substrates.
- 3) Determining the compatibility of each CPC with NASA spaceport-specific environments.

This paper is based on ongoing work. The test plan, including alloys and CPC types, was chosen based on considerations for current and future possible end use of CPCs at spaceport-related entities. Table 1 displays the techniques and alloy types that are being used in the current test plan. Experimental results reported in this paper include: application characteristics, removability, long-term beachside atmospheric exposure, crevice corrosion, galvanic corrosion via fasteners, wire on bolt atmospheric galvanic corrosion, stress corrosion cracking, and hypergol fluid compatibility.

Table 1
Experimental Test Plan Summary

Topic	Alloy Tested	Test Criteria
Physical Characteristics	UNS 10100	Application characteristics
	MIL-DTL-22759/87, MIL-DTL-22759/16	Wire compatibility
	UNS A92024	Removability
	UNS A93003	Wettability of CPC via contact angle
	UNS A93003	Hydrophobicity on substrate via contact angle
	UNS A97075	Functional penetration
	n/a	Viscosity
Corrosion	UNS 10100, UNS A97075, UNS A92219, UNS A92024	Cyclic salt fog
	UNS 10100, UNS S30403, UNS A97075, UNS A92219, UNS A92024	Long-term beachside atmospheric exposure
	UNS S30403, UNS S31603, UNS A97075, UNS A92219, UNS A92024	Galvanic/Crevice Corrosion via Fasteners
	UNS 10100, UNS C11000, UNS A01100	Wire on bolt atmospheric galvanic corrosion
	UNS A97075, UNS A92219, UNS A92024	Stress corrosion cracking (SCC)
	UNS S30403, UNS A97075, UNS A92219, UNS A92024	Sandwich corrosion test
Spaceport Compatibility	n/a	Hypergolic fluid compatibility
	UNS A96051	Upward flame propagation

A literature and vendor survey was conducted to down-select possible CPCs for use on ground support equipment. Although multiple CPC products are currently used, two controls were chosen, and the remaining CPC types were included for comparison purposes. For this project, environmentally friendly refers to CPCs that have low VOCs (less than 100g/L), are non-hazardous air pollutant containing, non-toxic, and noncarcinogenic. The new CPC candidates chosen for this study, Table 2, are designated as such.

Table 2
Corrosion Preventative Compounds Reviewed in this Study

	CPC Type	Number Designation	Product Classification	Primary Composition
Soft Film: Oily	Oily film	1	Control	Petroleum distillates
	Oily film	2	Comparison	Petroleum distillates
	Oily film	4	Comparison	Petroleum distillates
	Oily film	5	Comparison	High grade machine oil
	Oily film	6	Candidate	Canola oil

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CORTEC	Oily film	7	Candidate	Soy/Canola oil	Ecoline 3220
	Oily film	8	Candidate	Soy and canola oil	
	Oily film	9	Candidate	Lanolin	
	Oily film	15	Candidate	High grade oil, biodegradable	
CORTEC Soft Film: Wax or Grease	Wax	10	Control	Petroleum distillates	VpCI- 368
	Wax	11	Comparison	Petroleum distillates	
	Wax	12	Comparison	Petroleum distillates	
	Wax	13	Candidate	Soy and canola oil based	
	Grease	14	Candidate	Soybean oil and clay thickener	

Physical Testing

Functional Penetration.

This test was completed to provide visual evidence of a CPC's ability to penetrate a crevice or faying surface. Sandwich panels were assembled in such a way that created a crevice. The panels were elevated on one end creating a 10 degree slope. One mL of CPC was poured on the surface and allowed to seep in the crevice over 24 hours. An example of the test assembly with the initial application of several CPCs is shown in Figure 2. The sandwich panels were separated and the area of penetration was calculated using a grid system. The grid was created from a transparency, where measurements were made in 6mm x 6mm sections across the crevice area. The number of squares covered by the CPC was divided by the total number of squares to get a percent penetration value.

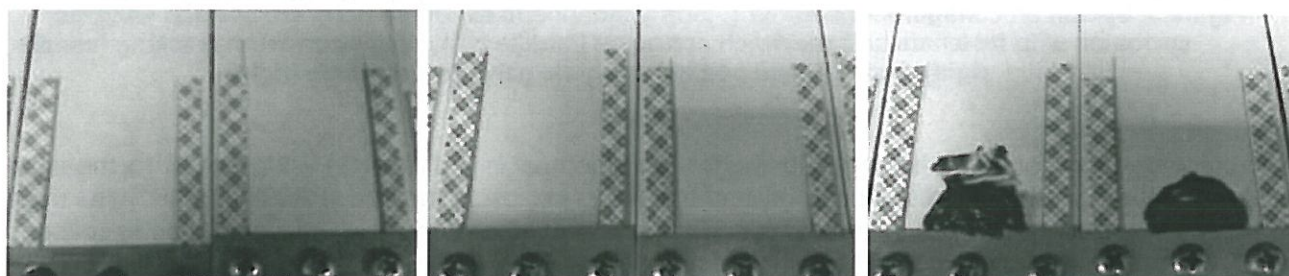


Figure 2: Functional penetration assembly with examples of a soft film (7), wax (13), and grease (14).

Removability.

The CPCs were evaluated for removability using mineral spirits. A mineral spirit-soaked lint-free cloth was wiped across each CPC-coated panel surface for four continuous passes. The excess mineral spirits were wiped off of the panel using clean lint-free cloths. Once dry, the panels were inspected for excess film residue.

Atmospheric Corrosion Testing

Specimens were prepared for evaluation of long-term corrosion, crevice corrosion, stress-corrosion cracking, galvanic corrosion using fasteners, and galvanic corrosion using wires on bolt in atmospheric corrosion conditions. For atmospheric exposure testing, the specimens were placed at 30-degree angles towards the Atlantic Ocean at the beachside atmospheric corrosion test site. The test racks are located 150 feet from the high tide line (Figure 1). Each exposure rack consisted of specimens representing all of the different atmospheric corrosion tests. Each rack was treated with its corresponding CPC type, where the CPCs were sprayed onto the specimens when possible or otherwise brushed on. The specimens were exposed for six months, from April through September 2012.

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Panel Configurations.

The specimens for crevice corrosion, sandwich corrosion, and galvanic corrosion using fasteners were combined into a single configuration. Each panel consisted of two panels of the same alloy that were separated by CPC-soaked filter paper. The panels were attached using 316 stainless steel (UNS S31603) washers. The washers were used to induce crevice corrosion and also for galvanic corrosion in combination with the aluminum alloys. The specimens for SCC were made using configuration a) in ASTM^[1] G30³⁹. Specimens for long-term corrosion consisted of flat panels. The specimens for the wire on bolt galvanic corrosion were made according to ASTM^[1] G116⁴⁰. Photographs of the panel configurations are shown in Figure 3 and a photograph of the exposure racks after the initial atmospheric exposure is shown in Figure 1.

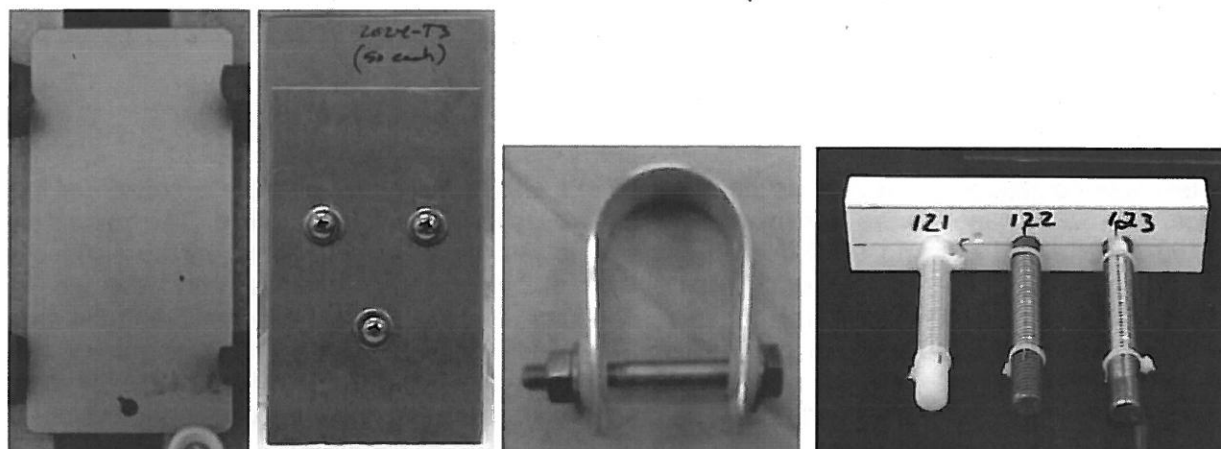


Figure 3: Specimen configurations for long-term atmospheric exposure (left), crevice and galvanic corrosion with fasteners and sandwich corrosion (middle left), stress corrosion cracking (middle right), and wire and bolt atmospheric galvanic corrosion (right).

Corrosion Evaluation.

For the long-term corrosion testing, the weight loss method in ASTM^[1] G1⁴¹ was used to measure corrosion rates for the carbon steel panels, and the pitting corrosion method in ASTM^[1] G46⁴² was used to measure corrosion of the aluminum alloys. The SCC and wire on bolt galvanic corrosion specimens were evaluated according to the ASTM^[1] specifications, G30³⁹ and G116⁴⁰ respectively. The crevice and galvanic corrosion using fasteners was evaluated by creating a grid of 1mm x 1mm squares in the same footprint as the washer. The number of squares relating to the galvanic corrosion were calculated and recorded as a percent of the total surface area. The crevice corrosion was calculated from the percent of the total circumferential area of the fastener where a crevice formed.

Spaceport Environment Compatibility

Casual Contact with Oxidizers.

Casual contact with oxidizers was used to evaluate the effects on coatings from casual exposure to hypergolic fluids (nitrogen tetroxide (N₂O₄), hydrazine (N₂H₄), and monomethylhydrazine (MMH)). This procedure provides the method to determine if a fluid could react exothermically or spontaneously ignite on contact with a material. This test was necessary per spaceport launch requirements. The CPCs were applied to aluminum foil weigh boats and evaluated in triplicate.

RESULTS AND DISCUSSION

Physical Testing

¹ ASTM International, Conshohocken, PA, USA

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Functional Penetration.

Table 3 shows the percent penetration of each CPC into the crevice after a 24-hour period. Interestingly, even the seemingly thicker and more static CPCs did penetrate into the crevice. For example, the thickest CPC, 14, eventually penetrated enough to result in 30 percent penetration across the crevice area. CPC type 10, a wax-like CPC, penetrated at 28 percent. The remaining CPCs penetrated at or near 100 percent.

Removability.

All of the CPC types were easily removed; meaning that the film were removed with little effort and no time for film dissolution using the mineral spirits; however, CPC types 10, 12, and 14 required twice as much effort, but were still considered easily removed. For all but three CPC types, a thin film residue remained on the surface after removal. CPC 12 had a slightly tacky film residue that remained after the initial film removal. Table 3 shows the CPC removability results.

Spaceport Environment Compatibility

The oxidizer compatibility testing for the CPCs showed that two of the CPCs, 6 and 7, are incompatible with casual exposure to the oxidizer, as some smoking and color change occurred. Varying degrees of color change was noted for six different CPCs (1, 2, 4, 8, 12, and 13). This color change was not considered to be detrimental. The remaining six CPCs had no reaction to HNO_3 , MMH, or N_2H_4 . The temperature change was recorded to determine if the contact with the hypergolic fluids induced a significant exothermic or endothermic reaction, which would indicate incompatibility. No significant temperature changes were noted. The cumulative results are shown in Table 3.

Table 3
Functional Penetration, Removability, and Oxidizer, HNO_3 , Casual Exposure Capability Results

	CPC Type	Penetration	Removability	NASA Environmental Compatibility	
		Percent	Remaining CPC	Temperature Change	Observations
Soft Film: Oily	1	100	All removed	2.0	Color change
	2	100	Thin film	2.2	Slight color change
	4	100	Thin film	2.0	Color change
	5	100	All removed	1.5	None
	6	100	Very thin film	3.1	Smoking, bubbling, Color change
	7	100	Very thin film	2.7	Minimal smoking. Color change.
	8	100	Very thin film	3.6	Color change.
	9	100	All removed	2.6	None
	15	100	Thin film	2.6	None
Soft Film: Grease or Wax	10	28	Thin film	3.3	None
	11	100	Thin, tacky film	3.0	Slight color change.
	12	79	Very thin film	2.9	Slight color change.
	13	96	Thin film	4.1	None
	14	30	Thin film	1.8	None

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Atmospheric Corrosion Testing

Long-term Atmospheric Exposure.

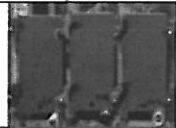
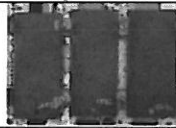
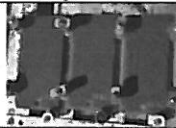
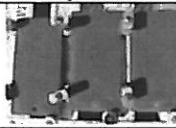
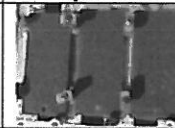
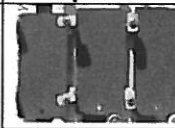


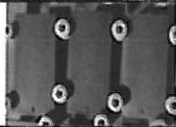
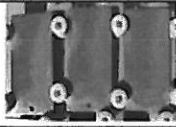
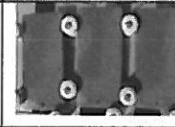
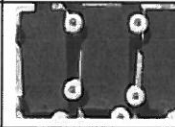
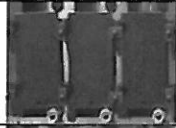
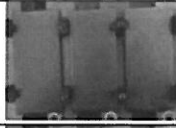
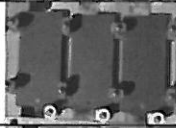
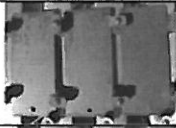
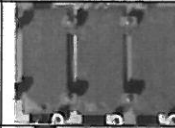
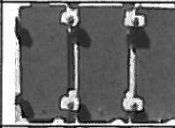





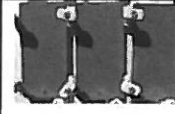
The atmospheric exposure results were most apparent for the CPCs on carbon steel, and Table 4 shows the progression of protection and corrosion after the six months of exposure. By day 22, CPC types 9, 19, 11, 12, and 13 performed the best, but only CPC types 10 and 12 exhibited no corrosion products. All of the CPCs performed better than the control. After the twenty-two day period, CPC types 1, 2, 4, 5, and 15 CPC types seemed to have been severely degraded by the UV, moisture, and high temperature conditions at the exposure site. The mass loss results for the 6-month exposure period show that all of the CPC types performed better than or nearly the same as the control CPC, 1, and all performed better than the uncoated carbon steel specimens (Figure 4).

The aluminum and stainless steel alloys were rated for pitting corrosion and staining (stainless steel only), which was present for all of the specimens, except those treated with CPC 10. Examples of typical pitting corrosion results are shown in Figure 5, where the untreated 7075 alloy (UNS A97075) is shown along with CPC types 4 and 10. The pitting ratings were performed according to ASTM¹ G46⁴², where only the pit density (a) and pit size (b) were examined at this point. Methods are currently being considered to consistently measure the pit depth (c). Figure 7 shows the pit density and size for all of the alloys.

Crevice and Galvanic Corrosion.

The crevice and galvanic corrosion analysis were performed on the sandwich panels in the area where the stainless steel washer and the substrate were in direct contact. The crevice and galvanic analysis were recorded as a percent of the total area affected by corrosion. Figure 6 shows examples of both stainless steel and one of the aluminum alloys where crevice corrosion was evident. Both the uncoated stainless steel and CPC-treated specimens had crevice corrosion, while the aluminum alloy exhibited both extensive galvanic and crevice corrosion from the dissimilar metal contact even in the presence of the CPC film (Figure 6). It is important to note that the washers were fastened prior to the CPC treatment.

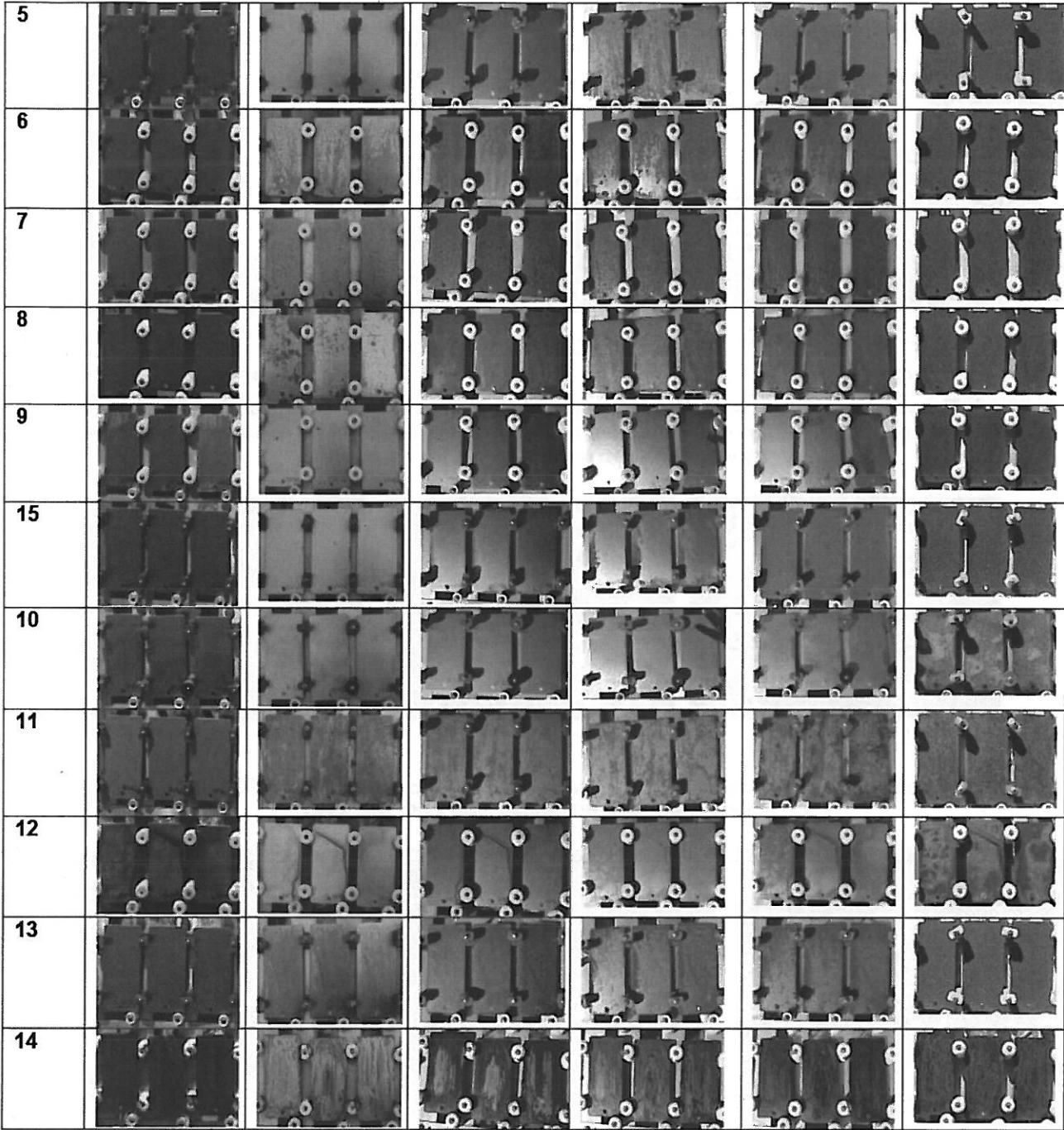
Table 4
CPC-coated Carbon Steel Panel from Initial Exposure through 6 Months.

CPC Type	0 days exposure	3 days exposure	6 days exposure	13 days exposure	22 days exposure	6 months exposure
Blank						
1						
2						
4						

¹ Trade name

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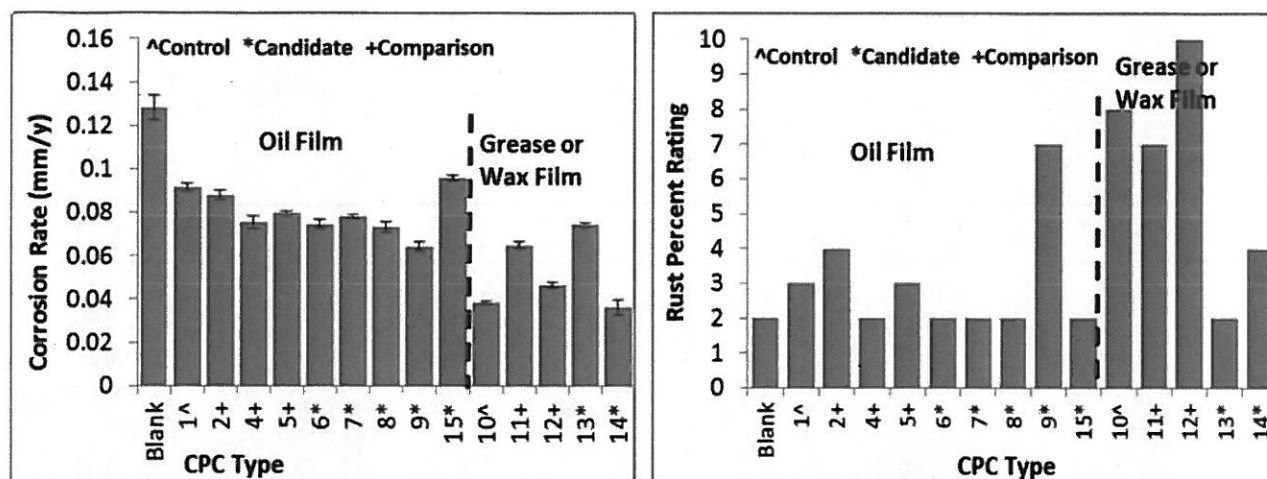


Figure 4: Mass loss results for long-term atmospheric exposure of CPC-coated carbon steel, UNS 10100, (left), and corrosion ratings of CPC-coated stainless steel panels (right) exposed to a beachside atmospheric corrosion test site for six months.

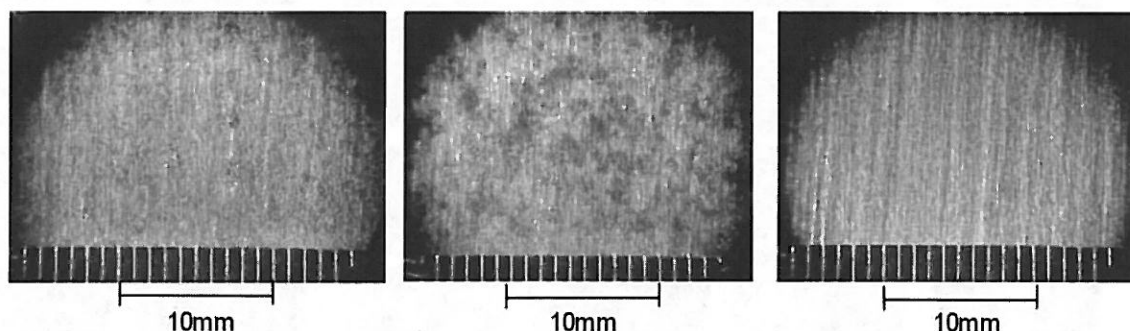


Figure 5: Examples of pitting results for long-term atmospheric exposure of CPC-coated UNS A92219: blank (left), CPC 4 (center), and CPC 10 (right).

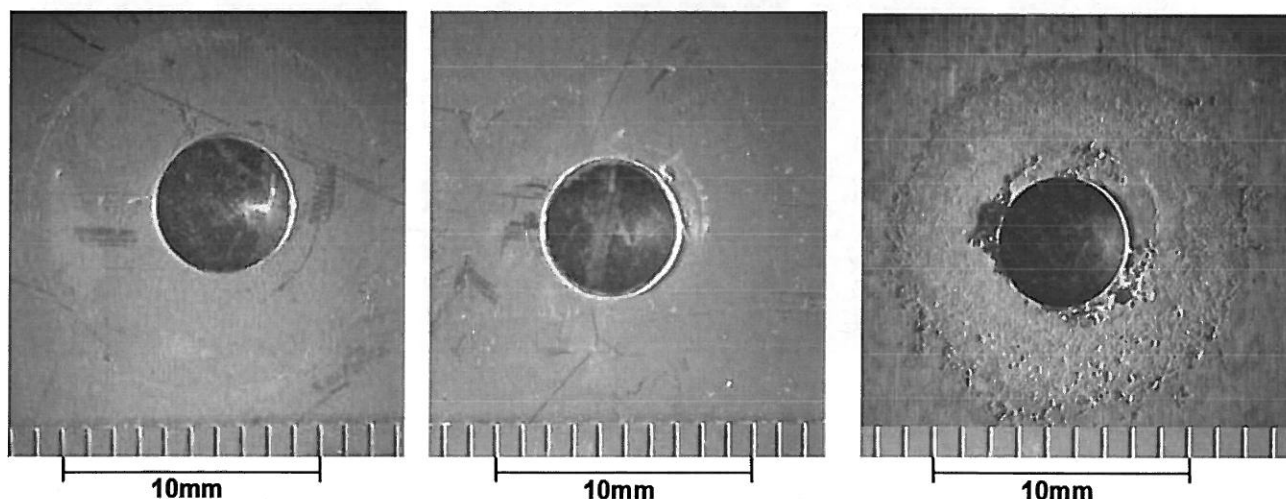


Figure 7: Examples of crevice corrosion for atmospheric exposure of CPC-coated stainless steel (left - blank and center- CPC 6), and crevice and galvanic corrosion of UNS A97075 (right -CPC 7).

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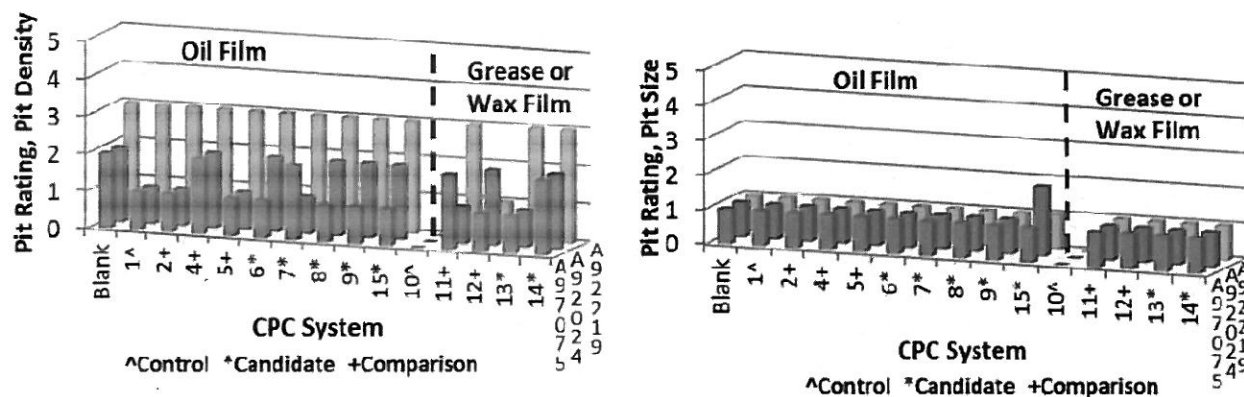


Figure 6: Pit density (left) and size (right) results for CPC-coated aluminum alloy panels exposed to a beachside atmospheric corrosion test site for six months.

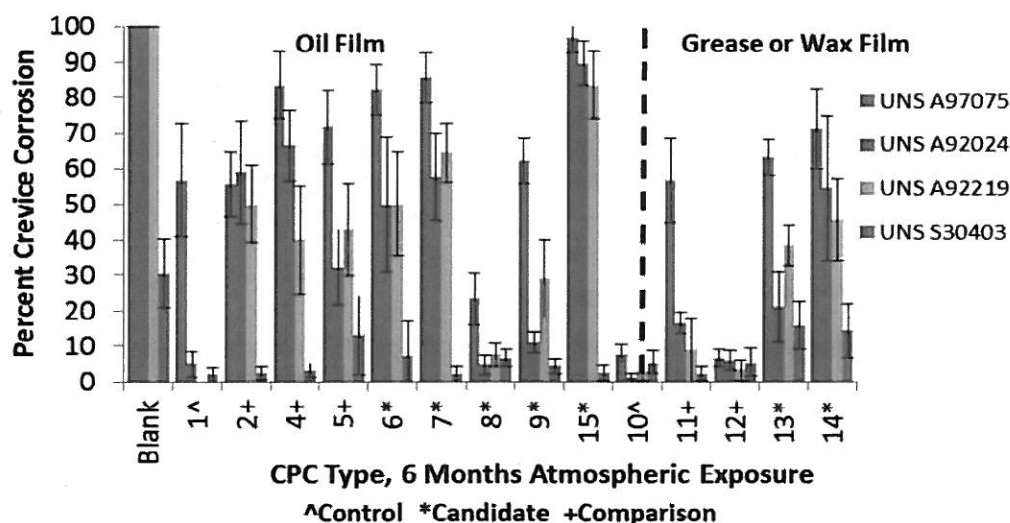


Figure 8: Percent crevice corrosion via fasteners results for CPC-coated aluminum and stainless steel panels exposed to a beachside atmospheric corrosion test site for six months.

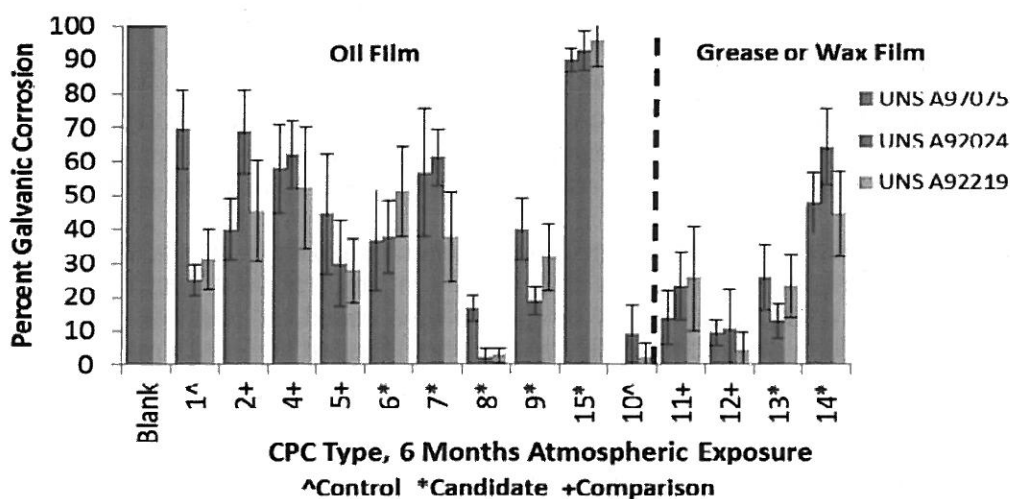


Figure 9: Percent galvanic corrosion via fasteners results for CPC-coated aluminum alloy panels exposed to a beachside atmospheric corrosion test site for six months.

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Stress Corrosion Cracking.

None of the stress corrosion cracking specimens, including the control, exhibited any degree of cracking after the 6 month exposure period.

Wire on Bolt Atmospheric Galvanic Corrosion.

Analysis of the data in Figure 10 clearly shows that CPC types 1, 8, 9, and 13 provided the most effective protection against corrosion for both the aluminum-iron and aluminum-copper galvanic couples. Although other CPC types were successful against the iron-based galvanic corrosion, a CPC will be considered successful if the more aggressive copper galvanic corrosion is also protected. None of the CPCs accelerated corrosion since they all exhibited mass losses lower than the control, designated as blank.

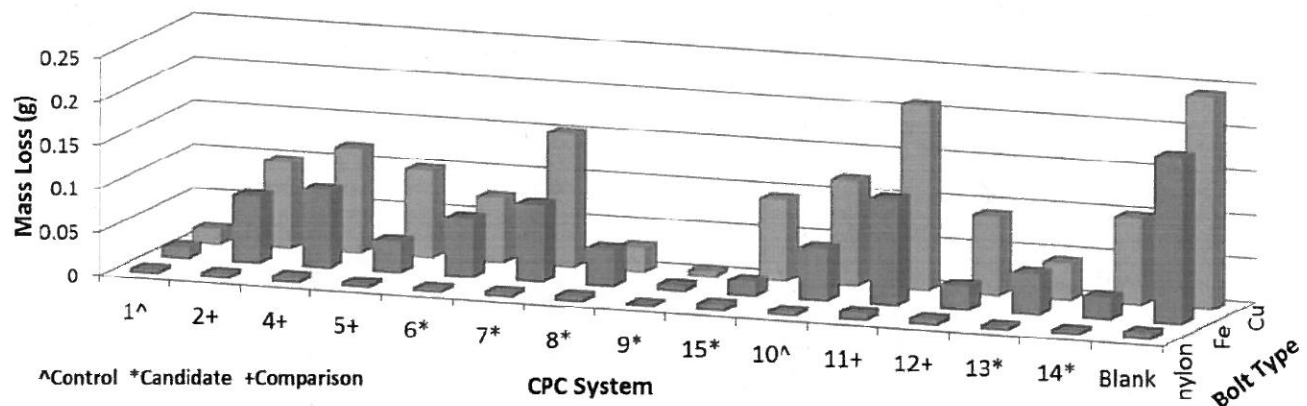


Figure 10: Mass loss results for wire on bolt galvanic corrosion. Test specimens were exposed to a beachside atmospheric test site for six months.

SUMMARY

Although this work is in progress, a summary of current results and analysis can be made.

- All of the CPCs, whether environmentally-friendly candidate or petroleum-based for comparison, performed better than the untreated specimens and better than or similar to the control CPC.
- All of the CPCs exhibited some crevice and galvanic corrosion in the galvanic corrosion with fasteners evaluations. CPCs 8, 10, and 12 exhibited the least amount of both crevice and galvanic corrosion, seeming to have penetrated successfully under the fastener and provide relatively good protection considering the long atmospheric exposure time period.
- CPC 10 was the only CPC type to resist corrosion for all of the aluminum alloys, but it did not fare well in the wire on bolt galvanic corrosion testing. CPC 10 is not an environmentally-friendly CPC type.
- The remaining corrosion, physical, and spaceport compatibility testing is ongoing, and a second phase of the best-performing CPCs will continue in the next year. The CPC types cannot be ranked yet, and different CPCs will be categorized based on possible end-use applications, application frequency, and compatibility with other spaceport non-metal materials.

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