



Durable Hydrophobic Surface Treatment for Enhanced Corrosion Protection Small Business Innovation Research (SBIR) Grants for branches of US Military

Galvanic corrosion (also called “dissimilar metal corrosion”) occurs when two or more dissimilar materials are brought into contact under water. When this happens, one of the metals becomes the anode and corrodes faster than it would all by itself, while the other becomes the cathode and corrodes slower than it would alone. This happens even if both metals would not corrode by themselves.

This phenomenon was first discovered and put into practical application by Alessandro Volta who built, in 1800, the first electrical cell, or battery: a series of metal disks of two kinds, separated by cardboard disks soaked with acid or salt solutions. This principle is the basis of all modern wet-cell batteries.

The sacrificial corrosion of one metal such as zinc, magnesium or aluminum is a widespread method of cathodically protecting metallic structures. Galvanic corrosion can be one of the most common forms of corrosion as well as one of the most destructive.

To counteract the effects of corrosion (galvanic or otherwise), UltraTech has commercialized a sol-gel technology called Gentoo, which revolutionizes corrosion control and protection. Gentoo is a durable, clear, hydrophobic coating that acts as a thin repellent and barrier coating, providing corrosion protection by both its dense barrier properties and its ability to shed water from the surface of the coating. Gentoo is also extremely thin (4-6 microns on average) and flexible. The following is a summary of testing performed during its development under multiple Small Business Innovation Research (SBIR) programs under different branches of the United States Military.

Introduction

Landing gear are flight and safety critical items. The metals used to produce landing gear are prone to corrosion when the surface is marred or damaged. Like other aircraft components, corrosion and damage on landing gear has the potential for catastrophic failure and must be minimized or eliminated. Currently, mitigation of corrosion on United States Air Force (USAF) landing gear is accomplished using various types of coatings, including sacrificial plating (cadmium, low hydrogen embrittlement zinc-nickel [LHE Zn-Ni]), barrier plating (chromium, HVOF, nickel, anodization, etc.) and chromated primer/paint combinations. Under operational conditions, landing gear are subject to numerous damage modes including abrasion/impact damage due to foreign object debris (FOD), rain, sand and dust erosion, runway debris, mechanical abrasion, etc. which remove the corrosion protective coatings, exposing the underlying bare metal. In addition, water pooling on plating/painted surfaces and threaded parts can promote corrosion. Ultimately, repairing or replacing landing gear parts due to corrosion is a significant maintenance cost, particularly with obsolete replacement parts in aging aircraft. There is a critical need for advanced coating technologies that are easily applied, cost effective, mechanically durable and more corrosion



resistant than those currently available. Such coating technologies will shed water and corrosion initiators, be durable and abrasion/impact resistant and, as a result, provide longer term corrosion protection of the steel and aluminum that comprise landing gear. These properties will enable reuse of parts instead of replacement, extend part lifetimes, reduce depot maintenance expense and reduce or eliminate hazardous waste (Cr, Cd) disposal costs and increase reliability and readiness of USAF assets.

Gentoo is a durable hydrophobic surface treatment system, to meet this need. Gentoo has shown exceptional durability and ability to shed water and other fluids (jet fuel, transmission fluid, deicing fluid) and has led to a significant improvement in both the delay and lower rate of corrosion over that of current United States Military qualified (MIL) paint and plating. This reduction in corrosion will directly translate to cost savings through decreased maintenance of landing gear components, and reduced rejection of corroded parts.

The hydrophobic surface treatment is comprised of a transparent, hybrid organic-inorganic matrix based on silane-modified polymer chemistry. The surface treatment combines the flexibility, impact resistance, durability, abrasion resistance, corrosion protection and UV resistance of commercially available organic polymer coatings combined with a low surface energy for enhanced watershed performance. The ultra-thin (<5 μm), rapid-cure, single coat system has been applied to previously-painted, bare metallic and polymeric surfaces using common application techniques such as flow coat, brush or spray. The high optical transparency of the hydrophobic treatment does not alter the appearance of target substrates, but enhances water shed capability, improves corrosion resistance, resists mechanical abrasion and impact damage, reduces salt accumulation, and resists weathering degradation of the object.

Coating Preparation and Data

Gentoo is a simple, transparent, one coat system that self-assembles to orient fluoro groups on the surface. The fluoro-functionalities are covalently bonded into the coating, imparting long-term hydrophobicity and watershed properties. Due to the low concentration of fluoro groups necessary to impart hydrophobicity, they do not interfere with adhesion to the substrate. The silane-functionalities of this hybrid coating provide a mechanism for covalent bond formation between Gentoo and the metal substrate, resulting in superior adhesion to metallic, plated and painted surfaces. The organic portion of Gentoo imparts flexibility and durability to the coating system. These features combine to produce a highly durable coating with excellent watershedding capability and abrasion resistance. Key attributes of the hydrophobic polymer/inorganic hybrid surface treatment are shown in Table 1.

Table 1
Key Attributes of Gentoo

Hydrophobicity and Watershed	Exhibits > 110° contact angle and <5° watershed angle.
Corrosion protection	Excellent water shedding attributes reduces corrosion and extends the service lifetime of metal components.
Flexibility, abrasion resistance	Exhibits excellent flexibility via a tough crosslinked polymer matrix and abrasion/wear resistance.
Thickness and Weight	The surface treatment is extremely thin (1-5 µm) and lightweight
Adhesion	Robust adhesion to metallic (aluminum, steel, etc.) substrates, glass, polymer (acrylic, polycarbonate), and paint (polyurethane, latex, acrylic).
Environmental Durability	Excellent resistance to degradation resulting from salt spray and UV exposure.
Ease of application	Applied in a single coat using spray, flow or brush methods with minimal surface preparation.

Material Property	Test Method	Desired Response	Outcome
Gentoo Characteristics			
Pot life	ASTM D1200	4 h minimum	PASS; 6 h at 75°F
Storage Stability	MIL-PRF-32239, 85285;	6-12 months, 35-115°F; 100, 77, 40°F @ 3mo. ea.	PASS; 12 months
Physical Characteristics of Gentoo			
Hydrophobicity	Measurement	Contact Angle 105 + 3°; Watershed 10 + 2°	PASS
Flexibility	ASTM	No cracking	PASS ¼" mandrel; cracking on 1/8" with paint but no cracking on Gentoo only
Heat Resistance	ASTM D2244, D522, MIL- PRF-32239	ΔE<1.0, no cracking after 1h at 121.2°C	PASS; No change CA/WS, gloss or DE
Strippability	MIL-PRF-32239 with CeeBee A-235	Removal	PASS with Cee Bee A-235 stripper
Durability of Gentoo			
Abrasion	ASTM D1044, D2486	ΔTransparency <5% ΔHaze <3% (per 150 cycles)	PASS
Adhesion	ASTM D 3359	5B on 6 h cured or mechanically abraded, full cured paint	PASS

Wet Tape Paint Adhesion	HSS Joint Test Protocol, ASTM D 3359	5B at RT, 49°C at 96h, and 65°C at 168h	PASS
FOD or Chip Resistance	ASTM D3170, corrosion evaluation TBD	Identical or better than control	PASS
Weather Resistance	ASTM G154 cycle 2 QUV-B, D4329	1000 h with Dgloss <20, DE < 1.0	PASS - better than control
Fluid Resistance of Gentoo			
Water Resistance	MIL-PRF-23377K	No effect	PASS
Chemical Resistance	MIL-PRF-32239, fuel JP-8	No/minimal effect & better than control	PASS - skydrol, degreaser, deicing, JP-8

For the purposes of this report, Gentoo has been applied by flow, spray, or dip coating onto selected substrates - glass, polycarbonate, acrylic, silicone, Nitronic 50 stainless steel (UNS S20910), 2024-T3 (UNS A92024) and 7075-T6 (UNS A97075) aluminum alloys, anodized 7075-T6 aluminum, Alodine and other non-chromate surface modification treatments and 316 stainless steel (UNS S31600) screws and washers. Treated substrates were air cured at ambient temperature or cured at 90°C for 15-60 minutes, depending on the application requirements. Coating thickness was measured at 4-6 μm depending on substrate and application method. Three specimens were used for each test and the data was averaged. Testing procedures are discussed below in the results section.

Hydrophobicity and Transparency

The hydrophobicity and light transmission properties of Gentoo when applied to glass substrates are shown in Table 2. The treatment exhibits contact angles of >110° and an average watershed angle of ~3-11°, depending on water drop size. Gentoo does not affect the transparency of the substrate, exhibiting negligible haze and retention of 100% clarity.

Table 2 Hydrophobicity and light transparency of coatings		
Test Method	Glass Substrate	Glass Substrate with Gentoo
Contact Angle	50	112
Watershedding Angle (50 μL droplet)	40	6
Watershedding Angle (120 μL droplet)	30	3
Transparency (%)	93.9	94.1

Chemical Resistance

Gentoo was also assessed for fluid resistance when applied over MIL-PRF-23377 epoxy primer with MIL-PRF-85285D grey urethane topcoat painted, LHE Zn-Ni plated 4130 steel panels according to MIL-PRF-85285D fluid immersion testing and the High-strength Steel Joint Test Protocol. For MIL-PRF-85285D fluid immersion testing, coated panels are cured, stored in a desiccator for at least 16 h, and weighed prior to immersion in the following solvents for 7 days at 37.8°C: Aircraft Deicing/Anti-icing fluid (SAE AMS 1424), Cleaning Compound (Degreaser), Aerospace Equipment (MIL-PRF-87937) and Paint Remover, PR-3500 epoxy paint remover.

Table 3
MIL-PRF-85285D Fluid Immersion Test Fluids and Conditions

Immersion Fluid	Fluid temperature	Time of immersion
Lubricating oil (conforming to MIL-L-23699)	121 ±3 °C (250 ±5 °F)	24 hours
Hydraulic fluid (conforming to MIL-PRF-83282)	66 ±3 °C (150 ±5 °F)	24 hours
JP-8 fuel (conforming to MIL-DTL-5624)	Room temperature	7 days

Gentoo demonstrated no blistering or coating defects and maintained hydrophobic performance following immersion in aircraft deicing fluid, cleaning compound (degreaser), lubricating oil, hydraulic fluid and JP-8 fuel. The Gentoo was removed using the PR-3500 epoxy paint remover, as expected. Commercially available superhydrophobic (SHP) paint was also assessed, and that coating lost all superhydrophobic and hydrophobic performance after immersion in all fluids, and was completely removed when immersed in most fluids, except deicing fluids. Figure 1 exhibits some representative images.

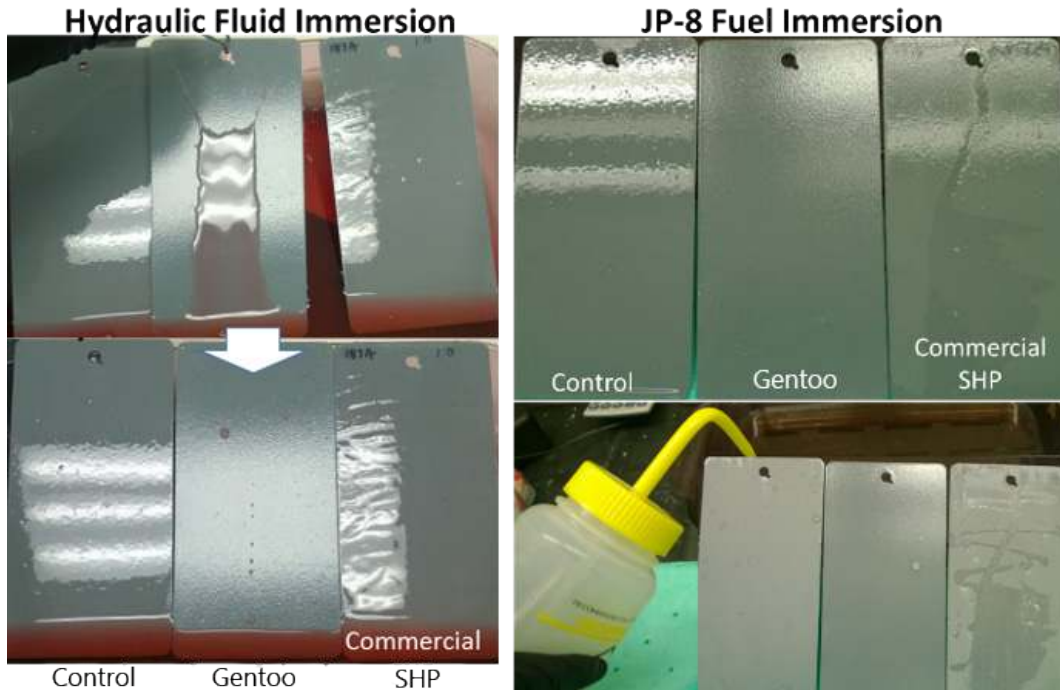


Figure 1

Fluid Immersion assessment of MIL-PRF-23377 Primer with MIL-PRF-85285D Topcoat painted aluminum panels untreated (control), Gentoo-treated, and commercial SHP treated in Hydraulic fluid at 66°C for 24 hours (Left) and JP-8 at room temperature for 7 days followed by an isopropanol rinse (Right)

Flexibility

Initial flexibility assessment is performed using a mandrel bend test where coated metal coupons are bent around mandrels ranging in diameter from 1/8 to 1 inch and assessed for cracking or delamination from the substrate according to ASTM D522. Bend Adhesion testing as specified in MIL-PRF-85285 to evaluate cold temperature flexibility of the Gentoo at -51°C is also performed.

Gentoo exhibits excellent flexibility at room and low temperatures (Figure 2). Gentoo at -51°C bent over a 3/4 inch mandrel cracked during low temperature flexibility assessment, but failure of the primer - aluminum panel interface resulted in complete coating failure. The Gentoo was not the source of the failure and the ragged edges are indicative of the Gentoo attempting to keep the coating system together despite the delamination event. An aluminum panel coated only with Gentoo was reevaluated at -51°C and passed 1/2 inch mandrel bend. Hydrophobic performance of the Gentoo retained as evident by the water drop on the tested surface.

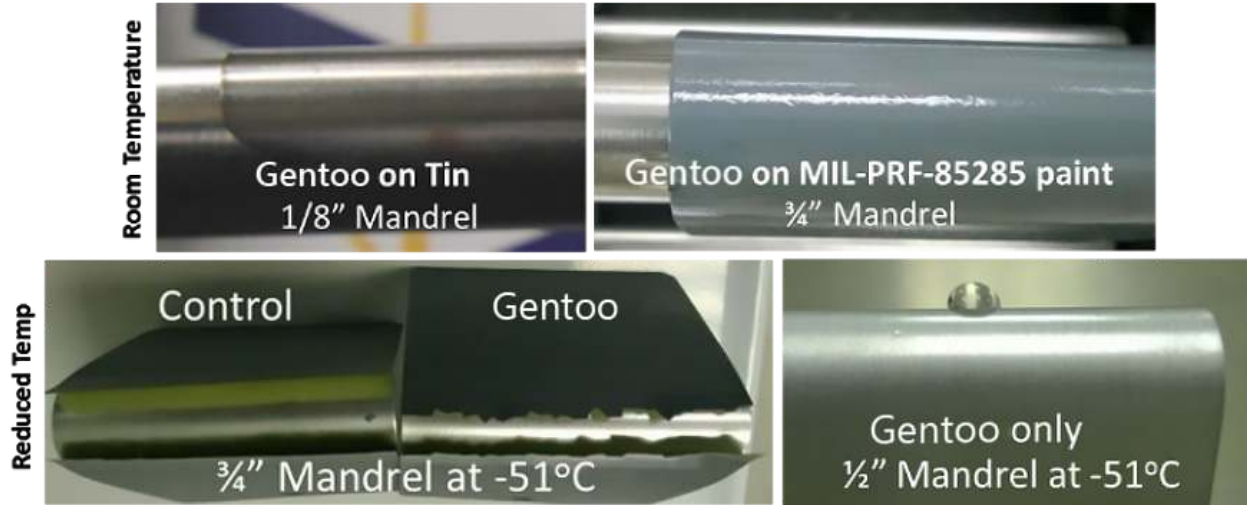


Figure 2

Mandrel Bend Flexibility of Gentoo Treatment at Room Temperature direct to metal and on MIL-PRF-85285 grey urethane topcoat (Top Row) and -51°C on MIL-PRF-85285 grey urethane topcoat (Bottom Row)

Gentoo is stable up to 200°C according to Figure 3 TGA decomposition curve. Thus, the coating has a wide range of operating temperatures from -51 to 200°C.; however, for continuous use (as opposed to temperature spikes) we recommend a maximum operating temperature of 160°C

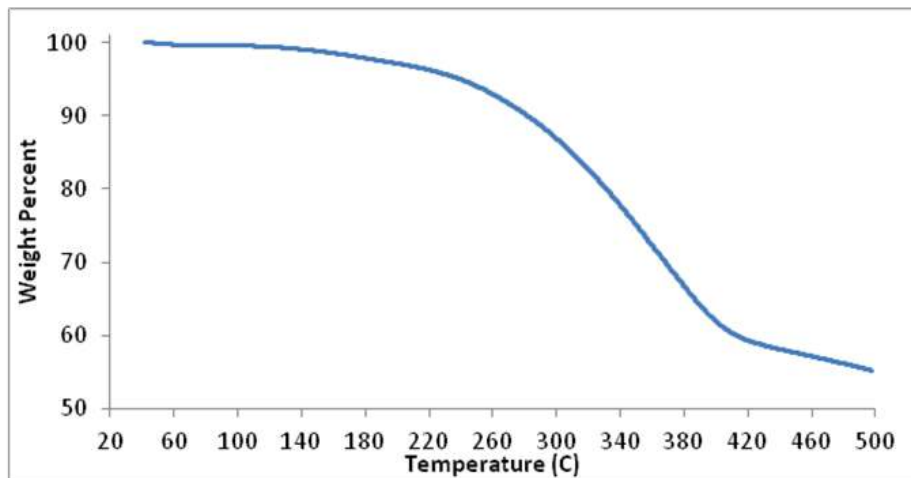


Figure 3

Decomposition TGA of cured, Gentoo formulation (ramp rate of 3°C/minutes)

UV Resistance

The UV resistance of the Gentoo treatment was determined in accordance with ASTM D4329. During the testing, a UVB-313 lamp with 0.63W/m² irradiance was used. The QUV test cycle was comprised of a 7 hour period of UV exposure at 50°C followed by a 5 hour period at 50°C with a 100% relative humidity condensation cycle. The QUV test cycle was repeated for 4 weeks. Table 4 shows the results of the QUV testing. Visually, it is evident that QUV exposure did not have a significant effect on the properties of the Gentoo, as no evidence of degradation, delamination, discoloration, etc. was observed. In general, the contact angle of the coating decreased by 7% after 4 weeks QUV exposure. The transparency and clarity of the control and Gentoo treatment remained relatively constant throughout the test. Haze increased for all the coatings throughout the test, though the haze remained under 1.65%, which is well under the visual limit in which coatings no longer appear transparent.

Table 4 Effect of 4 weeks of QUV exposure on hydrophobicity and light transmission properties of Gentoo		
Test Method	0 Weeks	4 Weeks
Contact Angle (°)	112	104
Transparency (%)	92.5	91.7
Haze (%)	0.78	1.64
Clarity (%)	99.8	99.7

UV resistance of the Gentoo on a MIL-PRF-85285E Type I Class H white gloss urethane topcoat was evaluated using ASTM G-154 Cycle 2, in which a UVB-313 lamp with 0.71W/m² irradiance was used. The QUV test cycle was comprised of a 4 hour period of UV exposure at 60°C followed by a 4 hour period at 50°C with a 100% relative humidity condensation cycle. Following 500 hours of exposure, no significant change in CIE color properties were observed with the addition of Gentoo. The Gentoo exhibited less color change and significantly less gloss change than the MIL-PRF-85285E Type I Class H white gloss urethane topcoat coating over the performance period.

Table 5
Effect of 500 hours of QUV exposure color properties of the MIL-PRF-85285E Coating with Gentoo

Test Method	Control	Gentoo
QUV Exposure Time (hours)	500	500
ΔL^*	-0.6	-0.8
Δa^*	0.2	0.1
Δb^*	-1	-0.5
ΔE	1.2	0.9
Initial Gloss	91.6	88.7
Δ Gloss	-8.9	-1.1

Barrier Properties and Galvanic Corrosion Resistance

Electrochemical Impedance Spectroscopy (EIS) was used to evaluate the barrier properties of the Gentoo coating. Aluminum alloy UNSA92024 coupons were coated with MIL-PRF-85285D grey polyurethane (1.0 mil thick) and tested with and without the addition of Gentoo. Initial testing (i.e. "dry") of the samples showed similar impedance across the full frequency range (Figure 4). After exposure to ASTM B117 salt fog conditions for 336 hours, the samples were retested. The polyurethane only sample showed a significantly larger reduction in impedance (~two decades) compared to the Gentoo, indicating significantly better barrier properties for the coupon.

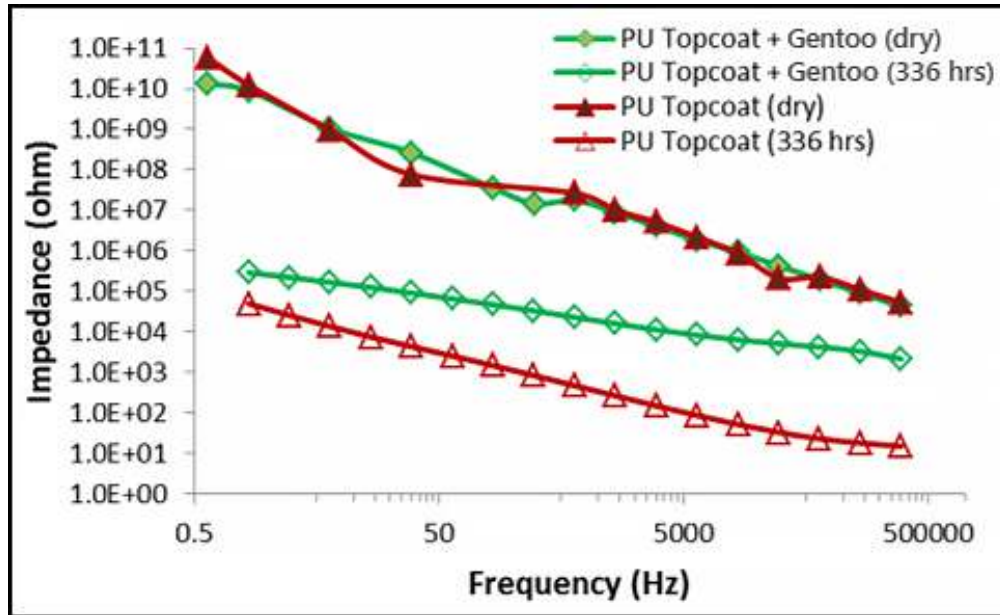


Figure 4

Electrochemical Impedance Spectroscopy (EIS) testing: MIL-PRF-85285D Polyurethane coated UNSA92024 aluminum alloy.

Galvanic corrosion around cathodic fasteners mated to anodic aluminum alloy structures is a common problem in the aircraft community. It is known that galvanic corrosion of aluminum is controlled by the available cathodic current, and that a reduction in available current should result in less corrosion damage. As an assessment of the possible galvanic protection attributes of Gentoo, polarization testing was conducted on a bare 316 stainless steel flat coupon and compared to a similar coupon with Gentoo applied. Results from the tests are observed in Figure 5. The addition of Gentoo resulted in an approximate two-order of magnitude reduction in cathodic current density compared to the bare 316 stainless steel coupon.

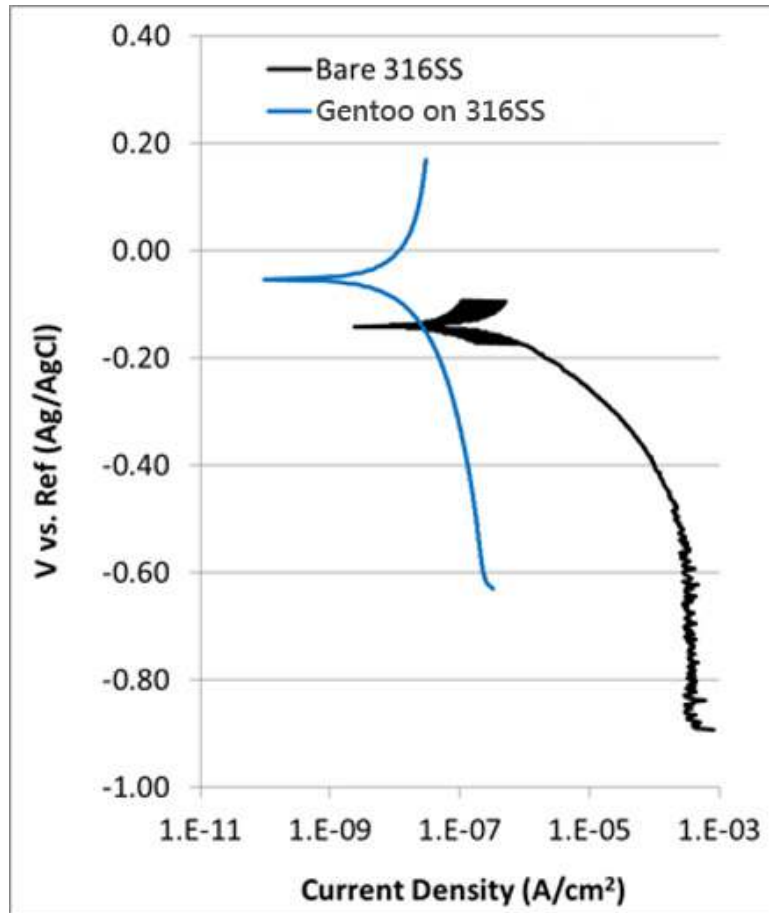


Figure 5

Polarization test results for a bare 316 stainless steel substrate compared to a similar substrate with Gentoo.

Fastener Assembly Galvanic Corrosion Testing

As a further assessment, several 316 stainless steel screws and washer assemblies were prepared bare, and separately coated with Gentoo. The fasteners were attached to primed and topcoated aluminum alloy 7075-T6 (UNS A97075) coupons and exposed to accelerated corrosion conditions for galvanic corrosion assessment. Specifically, the fastener assemblies consisted of ¼-20 x 1 inch full-thread screws and corresponding mated flat washers (Figure 6), with and without Gentoo. Select screws and washers were also cadmium plated per ASTM F1941 FE/CD 5A. The 7075-T6 aluminum coupons were approximately 1 x 1.375 x 0.032 inch and a ¼-20 drill and tapped hole was created in the middle region of each one for mated fastener attachment. All aluminum panels were initially deoxidized with Alumiprep 33 and treated with PreKoke, a non-chromate adhesion promoter for paints. Following

the pretreatment, a MIL-PRF-23377 epoxy primer and MIL-PRF-85285D grey polyurethane topcoat from PRC Desoto were applied to the surface. The coated coupons were hand-scribed to expose fresh, bare metal prior to fastener attachment. During galvanic assembly, nylon spacers and 18-8 stainless steel nuts were used on the backside of the aluminum coupons and torqued to 25 in-lbs. Each distinct assembly type was tested in triplicate via placement in ASTM B117 cyclic salt fog conditions.

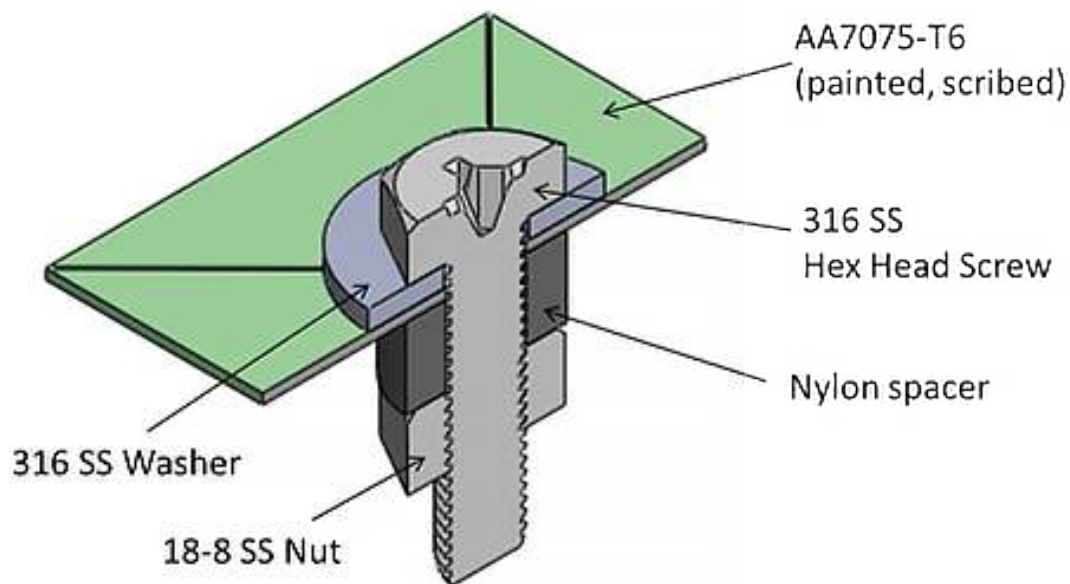


Figure 6

Schematic overview of the galvanic fastener assembly components used for corrosion assessment of Gentoo as applied to 316 stainless steel fasteners.

Bare B7 steel fastener and cadmium (Cd) plated B7 steel fastener assemblies were used for galvanic coupling with the scribed, painted aluminum panels. Control and Gentoo coated fastener assemblies were used. After 648 hours of B117 exposure, significant amounts of corrosion product was evident with the bare B7 steel fastener assemblies, while significantly less corrosion was evident after 1340 hours of salt spray with the cadmium plated B7 steel fasteners. The test assemblies were removed from B117, solvent stripped and cleaned using ASTM G1 guidelines and evaluated for weight loss and pit depth measurements due to corrosion. The parts were solvent stripped by first using a Rust-Oleum Aircraft Paint Remover soak at 49°C, followed by immersion in a 60-70% nitric acid stripping solution and rinsed with ethanol to remove any residue. Improved corrosion resistance from Gentoo treatment of

fasteners and painted panels were demonstrated visually, by corrosion based weight loss and pit depth measurements of the stripped aluminum panels on both the bare B7 and cadmium plated B7 fastener assemblies. The barrier effect of the Gentoo appears to be potentiated when combined with electrochemically deposited layers, such as Cd plating. Results are displayed in Figure 7.

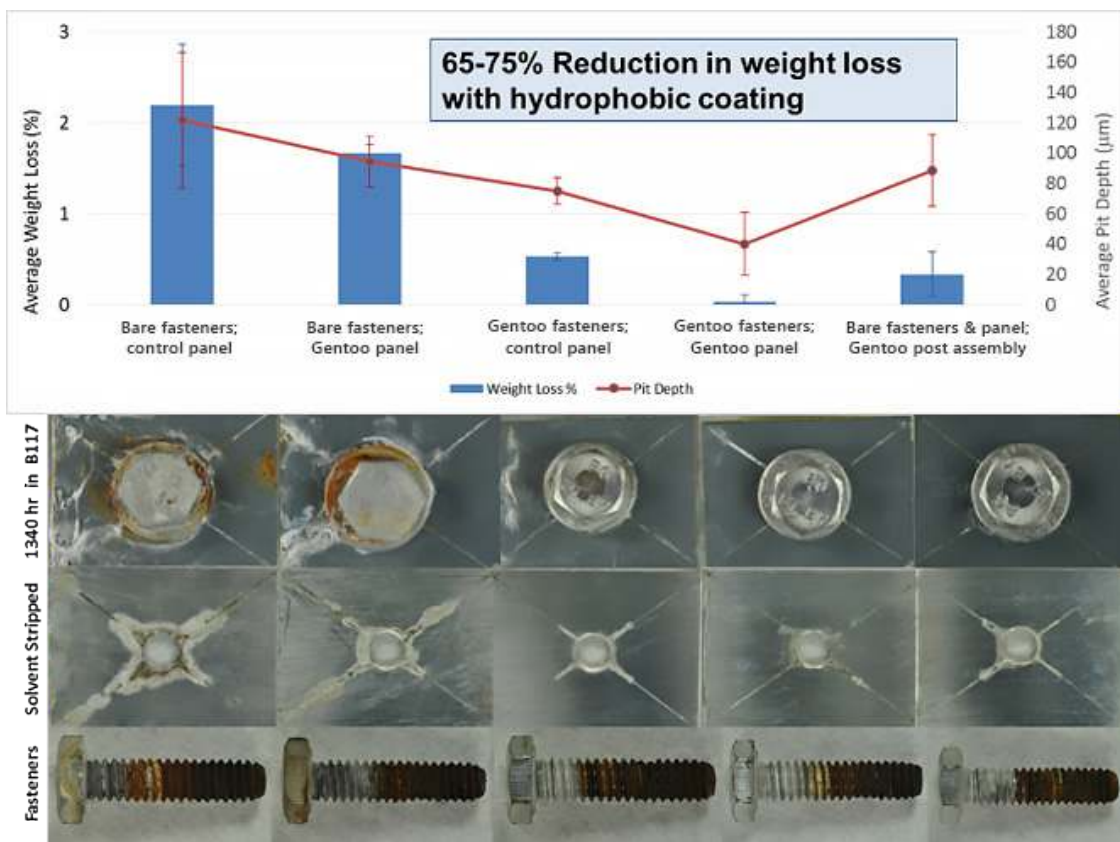


Figure 7

Galvanic Fastener Assembly Test Images of Cadmium plated B7 HSS bolts after 1340 hours of Salt Spray (top row images) and solvent stripped using ASTM G1, coated 7076-T6 aluminum panels (middle row) measured for weight loss and pit depth (accompanied graphs), and side images of representative fasteners (bottom row)

In the following sections, continuous salt fog corrosion resistance, chipping resistance combined with salt fog corrosion resistance, and galvanic and HSS accelerated corrosion resistance and environmental exposure at Kennedy Space Center in Florida results are reported in detail. Performance evaluations focused on LHE ZnNi plated 300M (UNS K44220) or 4130 (UNS G41300) high strength steel parts. All HSS threaded parts were 300M, while all HSS flat panels were 4130 alloy. All testing was performed in triplicate. Specific testing procedures are discussed in the results section.

Corrosion Resistance

Accelerated ASTM B117 corrosion testing was performed on LHE Zn-Ni plated 4130 HSS painted panels. The flat panels were primed with a MIL-PRF-85582 Class N chrome-free epoxy primer and topcoated with a CA8201/F17925 MIL-PRF-85285 Type I Class H white glossy urethane paint, or a CA8211/F3673 MIL-PRF-85285E Type I grey semi-gloss paint. Control panels included the primer and topcoats only. Gentoo was applied to selected control panels. All panels were "X" scribed according to MIL-PRF-32239 and placed in ASTM B117 salt fog with images taken every 500 h. Figure 8 displays the salt fog exposed panel images for the white and grey topcoat controls and Gentoo treated panels. Significant amounts of red rust are present on all the panels with the onset of rust by 500 h of exposure. The scribe corrosion is rated according to ASTM D1654 for each of the panels and is graphically displayed in Figure 9. For both the white and grey topcoats, the Gentoo treatment significantly reduces the scribe creep.

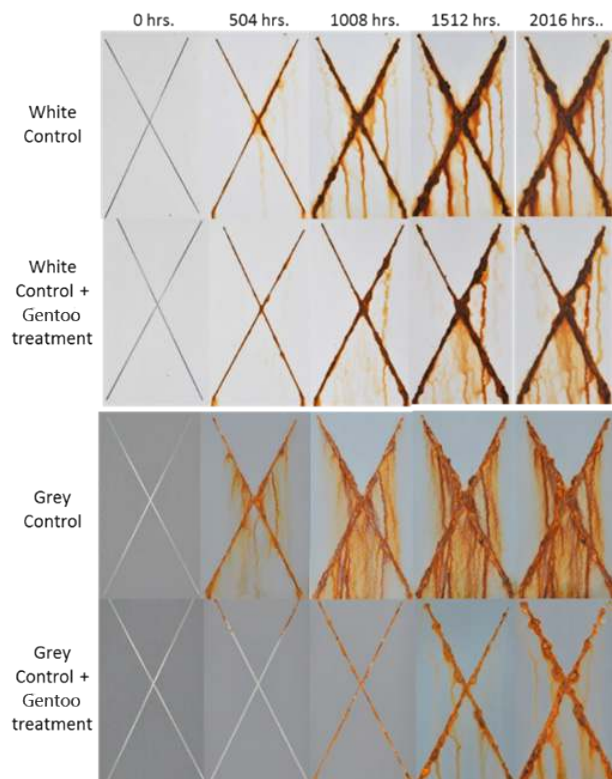


Figure 8

Images of MIL-PRF-32239 scribed LHE Zn-Ni 4130 HSS painted panels with either the MIL-PRF-85285 white glossy topcoat or the MIL-PRF-85285 grey semi-gloss topcoat with and without Gentoo following ASTM B117 Salt Fog Exposure

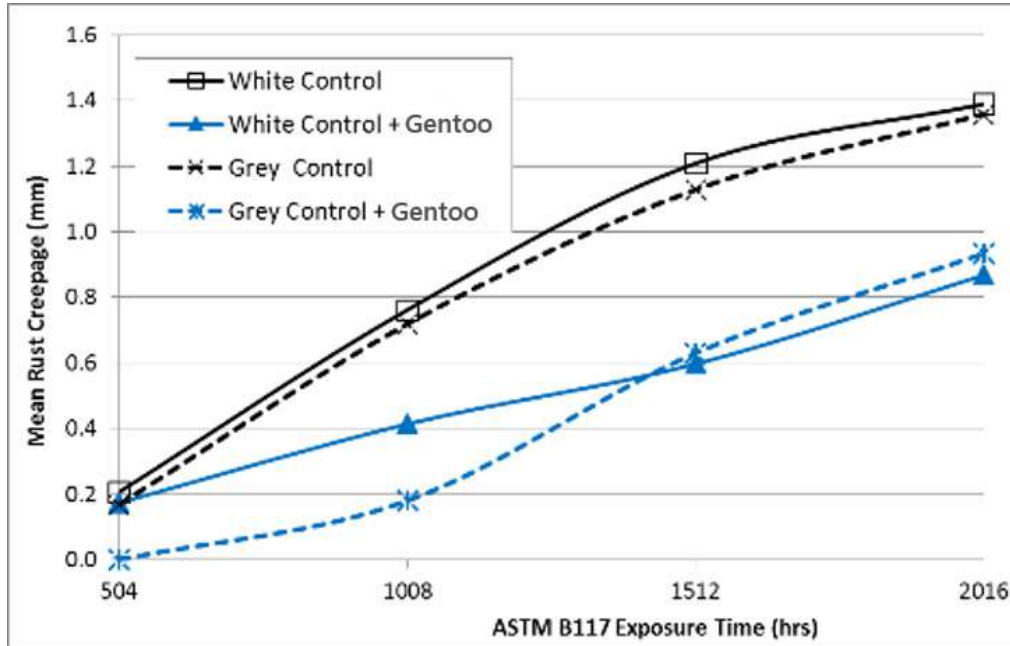


Figure 9

ASTM D1654 Scribe Corrosion Ratings of Scribed, ASTM B117 Salt Fog Exposed painted, LHE Zn-Ni 4130 HSS panels with and without Gentoo

Chipping Resistance Testing

University of Dayton Research Institute (UDRI) employs their CLG-LP-044 laboratory procedure for performing foreign object debris (FOD) testing on 4x6 inch coated panels according to ASTM D 3170 Standard Test Method for Chipping Resistance of Coatings. Cured, coated panels are tested in triplicate by mounting in the target chamber of the Gravelometer and firing one pint of 3/8 - 5/8-inch water eroded alluvial stones at the test panel with an air gun operating at 70 psi. Loose gravel is removed from the panel with an 898 filament tape, and the panel is rated by a visual comparison to transparent standard chips.

UDRI performed chipping resistance testing on Gentoo treated and untreated LHE Zn-Ni 4130 steel panels, as well as on Gentoo treated and control MIL-PRF-23377 epoxy primer with MIL-PRF-85285D grey urethane topcoat painted LHE Zn-Ni 4130 steel panels. No reportable differences were observed in coating chip protection between the Gentoo treated and untreated bare steel panels. After chipping resistance testing, the damaged panels were placed into an ASTM B117 salt fog chamber. After 2136 hours of exposure, the Gentoo treated steel and Gentoo treated primed/topcoated, steel panels demonstrate significant corrosion improvement over the bare steel and painted steel control panels. This Gentoo treatment is providing added exposure protection as a function of impact over the control panels.

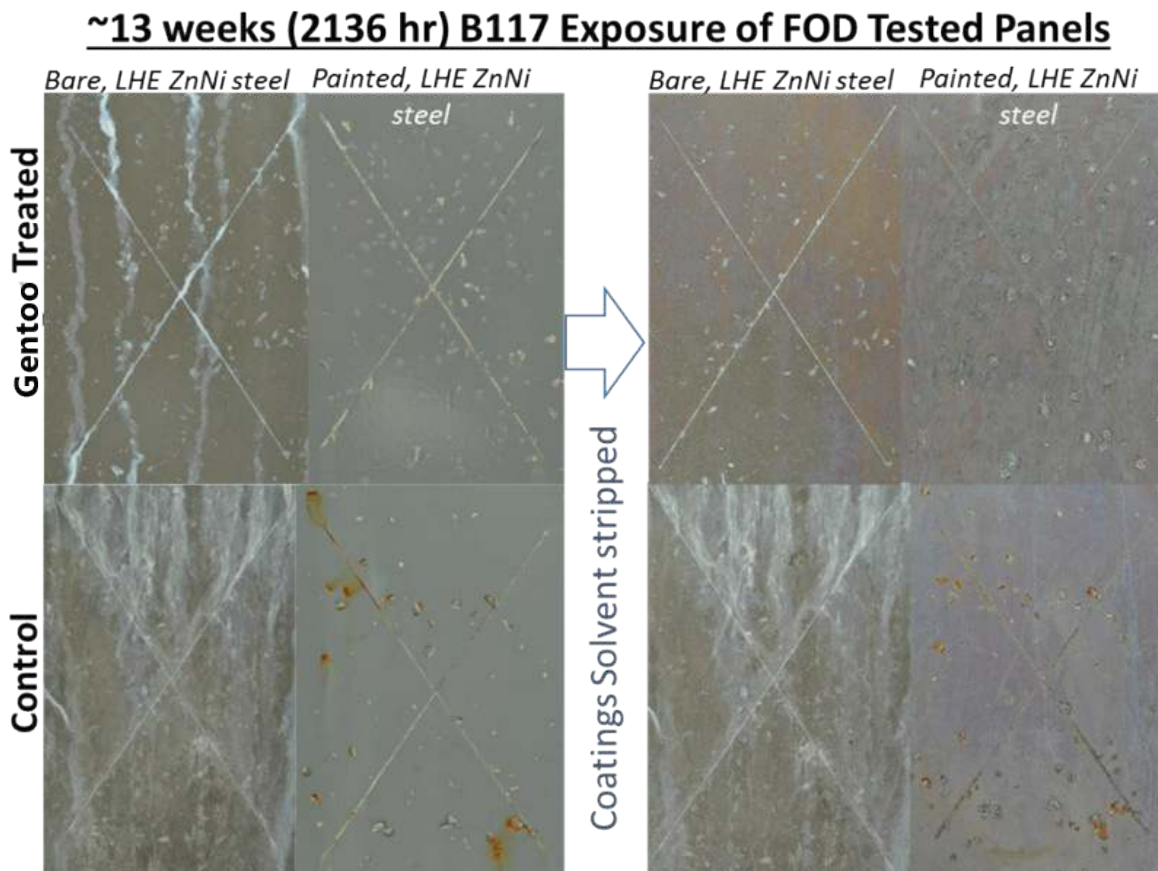


Figure 10

2136 hours of B117 Salt Fog Exposure of FOD Tested Bare and MIL-PRF-23377 primer with MIL-PRF-85285D topcoat painted LHE Zn-Ni plated HSS panels with and without Gentoo

Chipping resistance testing was repeated with LHE ZnNi plated 4130 HSS panels with a MIL-PRF-23377J Type I Class N chrome-free epoxy primer and topcoated with CA8201/F17925 MIL-PRF-85285 Type I Class H white glossy urethane paint with and without Gentoo. Bare LHE ZnNi 4130 with and without Gentoo surface treatment was also included. No significant differences resulted in the chip protection ratings between the surface treated and untreated panels. Panels were placed into ASTM B117 salt fog for 2000 h of exposure. Red rust spots are visible on the painted control panel, while the Gentoo panels remain unchanged (Figure 11).

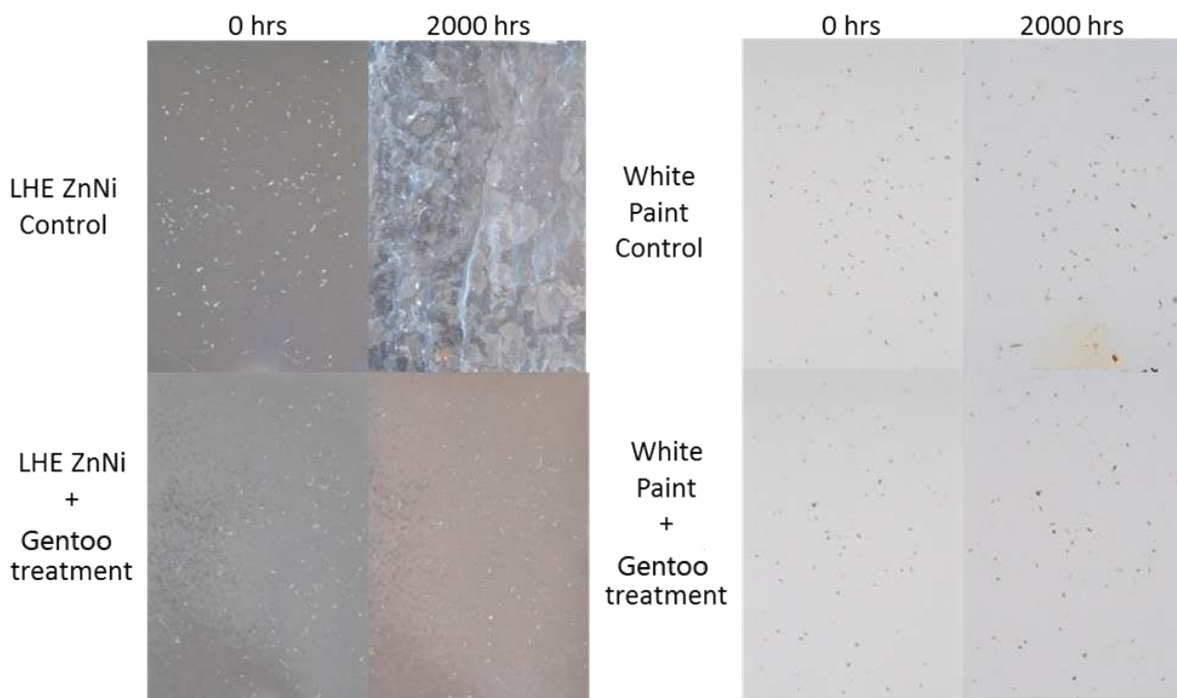


Figure 11

ASTM B117 Exposed, Chipping Resistance Tested LHE ZnNi plated 4130 HSS bare and painted panels with and without Gentoo

Threaded Part Evaluation

Threaded parts designed to represent a landing gear gland nut assembly were machined 300M steel in an open-end component that is intended to focus corrosion along the male/female threaded interface, as well as the flat interface where the two coupon halves meet. An additional combination using 7075-T6 aluminum female parts mated to a 300M male parts are included in the evaluation, creating a galvanic interface similar to mated surfaces on landing gear wheel assemblies and higher corrosion potential than straight 300M interfaces.

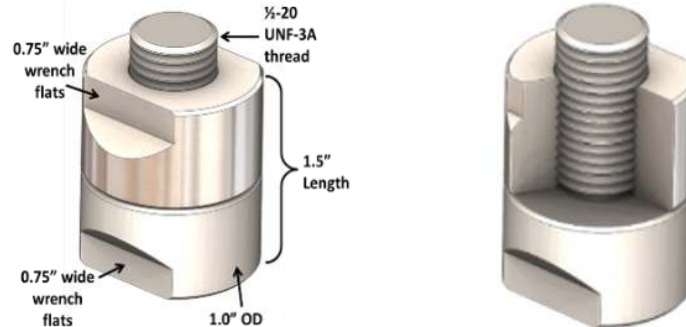


Figure 12

Example open-end threaded coupon for accelerated corrosion testing. Material of construction is 300M steel, as well as 7075-T6 aluminum female nuts with 300M male bolts for galvanic assemblies. The flat areas on each end will enable proper torque application. The design intent is to enable moisture ingress through the mated interface perimeter and along the thread interface, which characterize landing gear component configurations

LHE Zn-Ni is applied to all disassembled 300M coupon surfaces, with appropriate clearance in the threads for Gentoo application. MIL-PRF-85582 Class N epoxy primer and MIL-PRF-85285E Type I Class H polyurethane white topcoat is sprayed on all exterior surfaces. No primer/topcoat is applied to the male or female threads. This configuration leaves the threaded and flat mated coupon half interfaces LHE Zn-Ni plated only. Gentoo is then applied 1) along all outer faces over top of the polyurethane topcoat and 2) along the male/female threaded surfaces. This configuration enables comparison of how coupons with and without Gentoo applied behave under accelerated cyclic corrosion conditions, such as those specified in Table 6. In addition to accelerated corrosion testing, threaded parts were subjected to Florida environmental exposure at the Kennedy Space Center corrosion beach site. Thus, direct comparisons to accelerated and environmental performance exist.

Table 6 Accelerated Environmental Exposure Test Comparison		
	B117	GMW14872
Salt Solution	5% NaCl	0.9% NaCl, 0.1% CaCl ₂ , and 0.075% NaHCO ₃
Temperature	35°C	Varies; 23°C during salt
pH	6.5 - 7.2	Measured (6-9)
Conditions	Constant fog	8 h Ambient Stage w/ four 15 s salt sprays; 8 h Humid Stage 100%RH at 49°C; 8 h Dry Stage <30%RH at 60°C
Cycle Length	No cycle	1 cycle = 1 day (24 h)
Typical Test Length	8 - 3000 h	80-120 cycles



300M and galvanic (300M bolt with 7075-T6 aluminum nut) assemblies were painted in unassembled parts, half of which were Gentoo treated. The Gentoo was spray applied to the painted sides and flow coated over the threads. All systems were cured at room temperature. A corrosion inhibiting static joint compound, Corban-27L, was used on half of the assemblies. All control and Gentoo treated bolts and nuts were assembled to a torque of 50 in-lb and tested in triplicate. Upon test completion, a 40/60 urea plastic media was used to grit blast the threaded parts to remove paint and corrosion product for final comparisons.

300M assemblies are the most relevant to United States Air Force (USAF) landing gear. Thus, the 300M configuration results are described in detail, while the galvanic results are summarized in a table at the end of the section.

Figure 13 through Figure 15 highlight the differences observed between control and Gentoo treated 300M parts following 5040 h of ASTM B117 salt fog exposure. The parts were removed from testing due to the quantity of red rusting on the exposed threads of the control sample. Upon disassembly, significant amount of corrosion and salt product (white build-up) was found on the unexposed threads of the bolt and nut of the control. The Gentoo treated sample unexposed threads are pristine and shiny on the nut and large sections of the bolt. Following media blasting, the Gentoo treated bolt and nut threads remained a light grey - indicating the undisturbed presence of LHE Zn-Ni (Figure 14). The control bolt's threads are dark and show areas of red rust following media blasting. Similar features are present on the threads of the control nuts (Figure 15). The darkening around the threads indicates that the LHE Zn-Ni plating was completely consumed during testing for both the control bolt and nut threads. The Gentoo provided significantly more protection to the 300M parts in ASTM B117. The USAF specified epoxy primer and urethane topcoat paint system based on their usage. Small blisters erupted on all of the LHE ZnNi 300M threaded parts following a few weeks of accelerated corrosion exposure in both ASTM B117 and GMW 14872. Further investigation revealed an incompatibility between the recommended primer and topcoat systems on LHE ZnNi HSS parts, resulting in blistering. The effects of the blistering are visible as dark spots on the stripped parts (i.e. Figure 15). The blisters were not observed during atmospheric exposure, nor do they appear to affect the corrosion results on the threads of the parts.

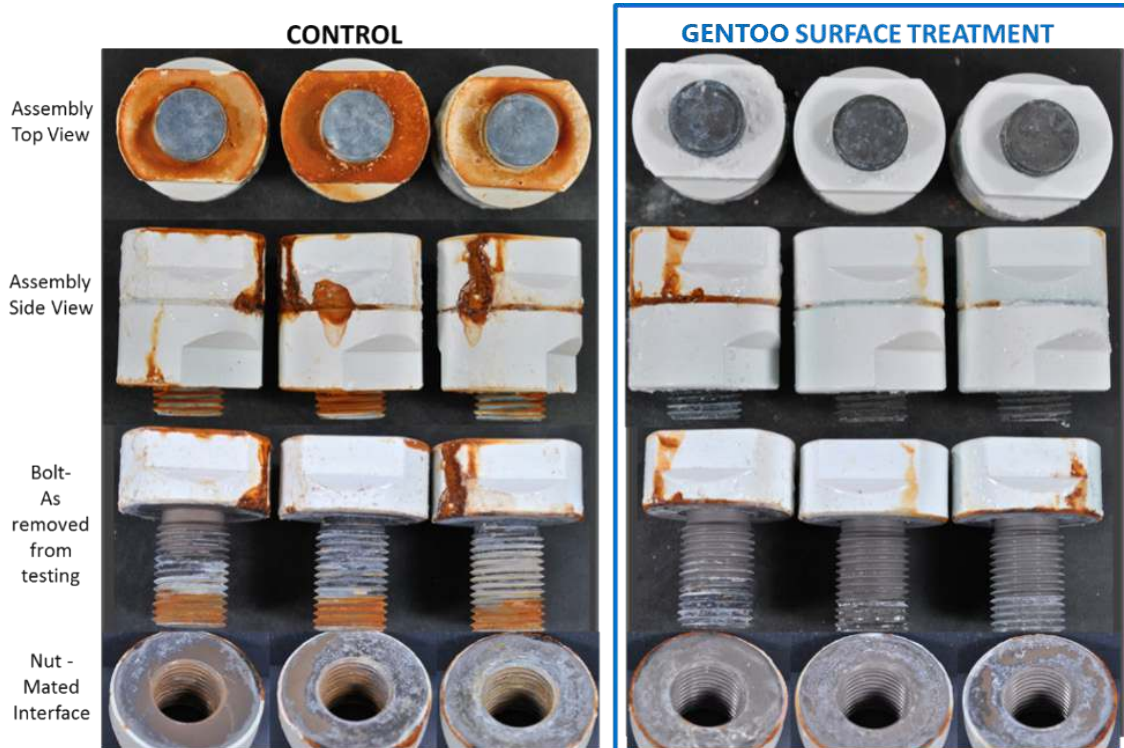


Figure 13

5040 h ASTM B117 Exposure of control and Gentoo treated (blue box) LHE Zn-Ni 300M threaded components, as removed from testing

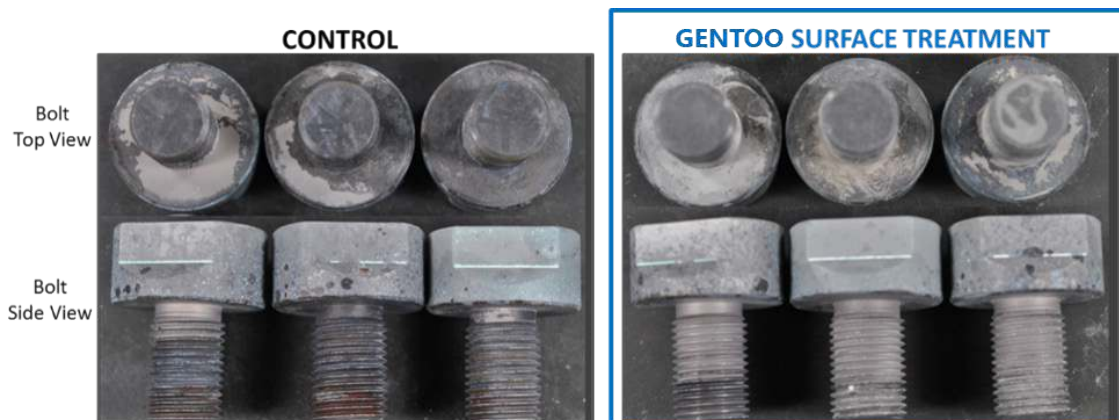


Figure 14

Plastic media stripped control and Gentoo treated (blue box) LHE Zn-Ni 300M bolts from 300M assemblies after 5040 h of ASTM B117 exposure

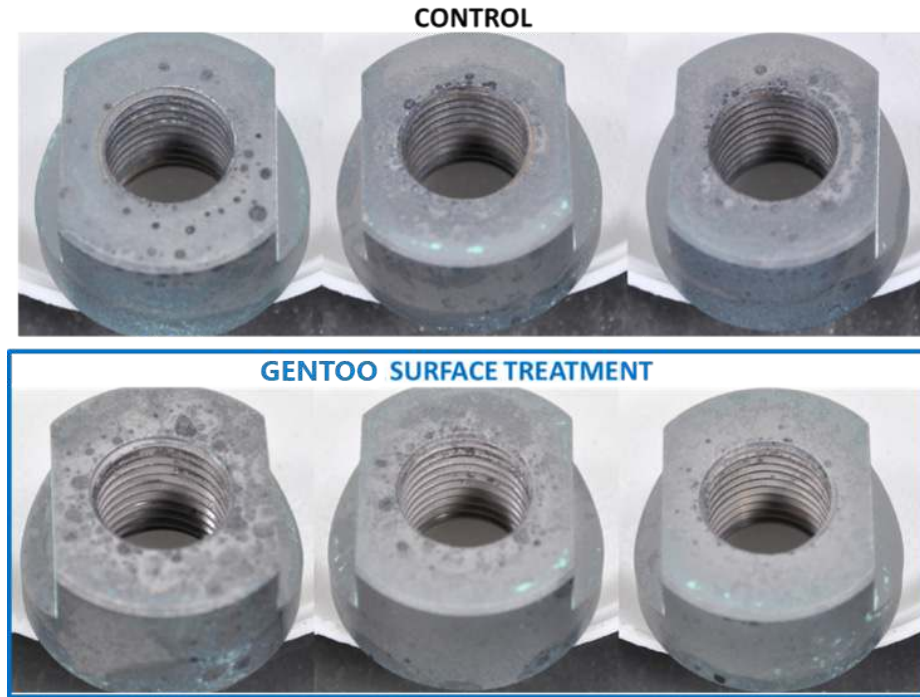


Figure 15

Plastic media stripped Control and Gentoo treated (blue box) LHE Zn-Ni 300M nuts from 300M assemblies after 5040 h of ASTM B117 exposure

GMW 14872 exposure of the 300M threaded parts present similar results to those found following salt fog exposure. Figure 16 through Figure 18 show the control and Gentoo treated parts after 272 cycles (6528 h) of GMW 14872 exposure. The parts were finally removed from testing due to the presence of red rust on the exposed threads of the control samples. Both control and Gentoo treated threads had white product accumulated on the exposed threads. The white product was unable to be removed by washing or wiping from the control samples and was a product of LHE ZnNi consumption. The white spots on the Gentoo surface, however, could be rinsed off with water, as displayed on the tips of the threads in Figure 17, or removed with a gentle wipe. During GMW 14872 testing, there are a series of salt sprays during ambient conditions. Due to the hydrophobic nature of Gentoo, the spray beads up on the surface of the exposed threads. When the water evaporates, it deposits the salt behind, providing a site for further sprays to build up and deposit along. Despite the salt build-up, Gentoo continues to provide an excellent barrier from the corrosion inducing material and the LHE ZnNi and underlying 300M HSS is unaffected. The excellent protection provided by the Gentoo treatment is also evident on the unexposed threads of the bolt and nuts. The Gentoo treated parts are shiny, grey and pristine, while the control parts are dark and contain many areas with red rust.



Figure 16

272 cycles of GMW14872 Exposure of control and Gentoo treated (blue box) LHE Zn-Ni 300M threaded components, as removed from testing

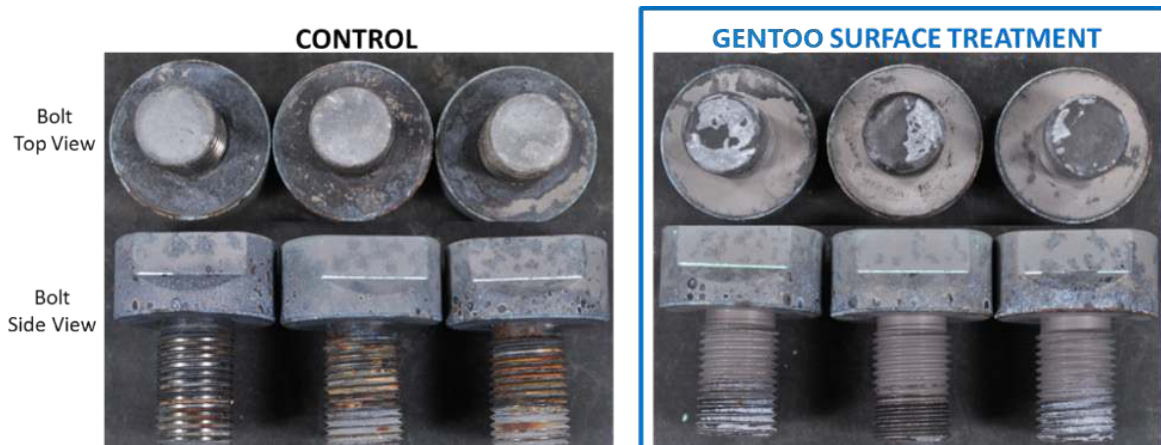


Figure 17

Plastic media stripped control and Gentoo treated (blue box) LHE Zn-Ni 300M bolts from 300M assemblies after 272 cycles of GMW14872 exposure

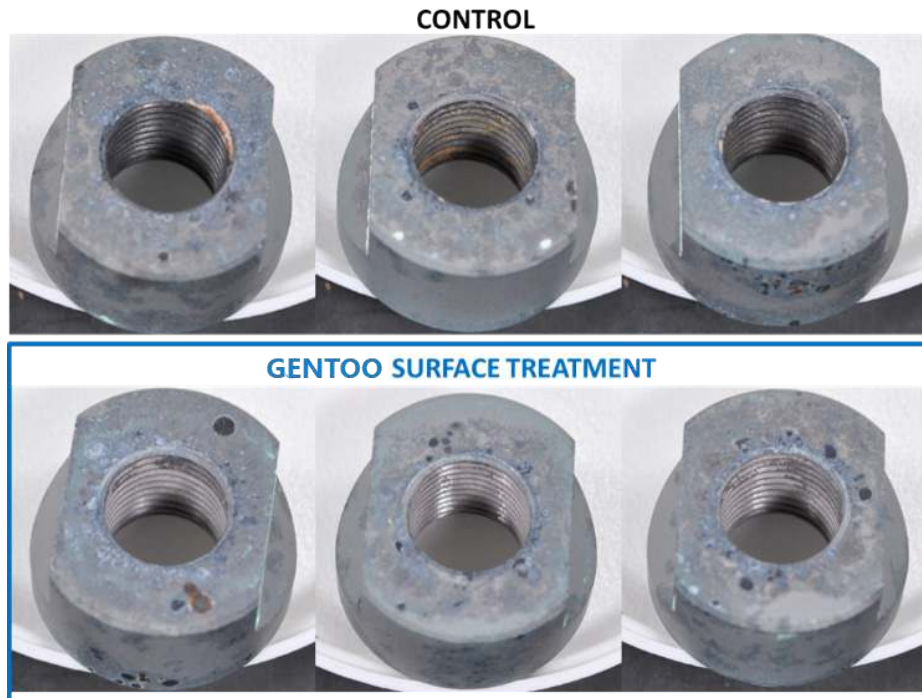


Figure 18

Plastic media stripped Control and Gentoo treated (blue box) LHE Zn-Ni 300M nuts from 300M assemblies after 272 cycles of GMW14872 exposure

Identical 300M threaded parts experienced 16 months of atmospheric exposure at Kennedy Space Center, Florida beachside. Images of the disassembled parts are displayed in Figure 19 and Figure 20. The exposed threads of the control assemblies show white LHE ZnNi consumption on the top and sides of the threads, while the Gentoo threads display minimal LHE ZnNi consumption. The inner threads of the Gentoo bolts are shiny and unchanged, while LHE ZnNi consumption down the threads toward the bolt head is obvious for the controls. Similarly, the inner threads of the Gentoo treated nuts are unaltered, while LHE ZnNi consumption is observed in the control threads.

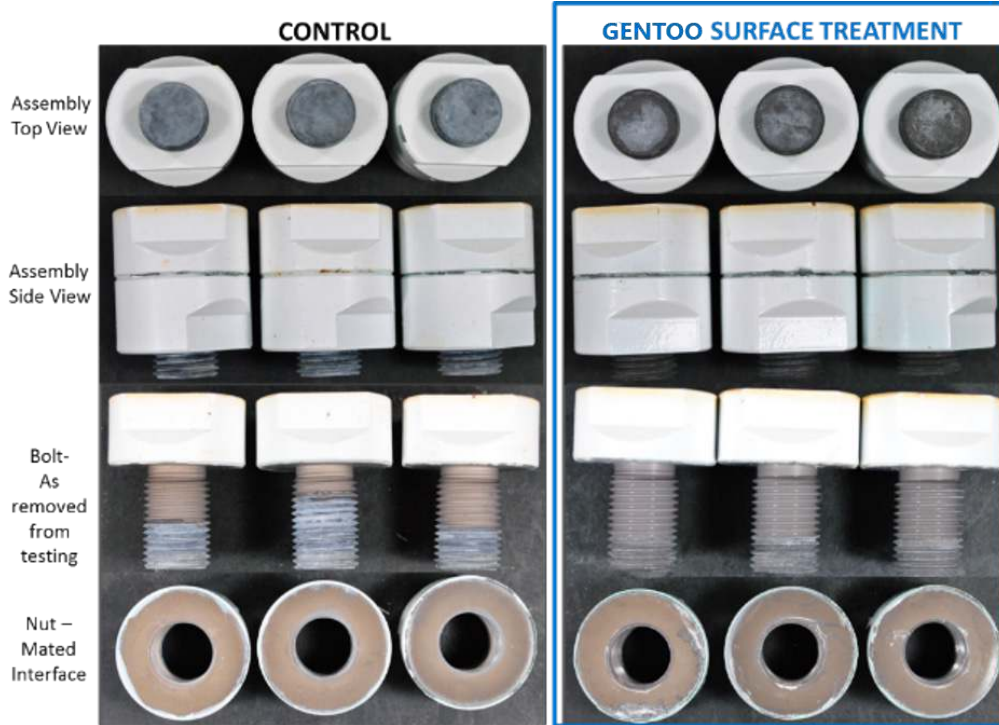


Figure 19

16 months of Kennedy Space Center, Florida beachside exposure of control and Gentoo treated (blue box) LHE Zn-Ni 300M threaded components, as removed from testing



Figure 20

Control and Gentoo treated (blue box) LHE Zn-Ni 300M nuts with a view of inner threads from 300M assemblies after 16 months of Kennedy Space Center, Florida beachside exposure



Table 7 highlights the best performers of the threaded parts for each of the test variables by test exposure method. Both galvanic and 300M-only parts were evaluated, along with assemblies with and without the joint corrosion inhibiting compound. The 7075-T6 aluminum in the galvanic assemblies was treated with a chrome-free adhesion promoter prior to painting. The threaded parts were tested according to ASTM B117 salt fog exposure, GMW 14872 cyclic exposure, and 16 month outdoor environmental exposure at Kennedy Space Center (KSC). The duration of exposure for each of the tests is also listed. Test removal time varied depending on the amount of corrosion product observed on the exposed threads. The Gentoo treated parts outperformed the control parts on all accelerated corrosion test methods, except for one that exhibited a similar performance. Atmospheric testing at KSC was recently concluded and performance differences are based on the condition of the exposed threads and initial impressions of the threads upon disassembly of the parts. The use of a corrosion inhibiting compound significantly delays the onset of corrosion in both accelerated and outdoor exposure testing. Long exposure times in accelerated testing resulted in noticeable differences between the Gentoo-treated and control parts. The short atmospheric exposure was likely not long enough to exhibit these differences.

Table 7
Top performers for comparison between control and Gentoo treated threaded part assemblies after completed accelerated corrosion and atmospheric exposure

Assembly Type	Galvanic		300M	
	Yes	No	Yes	No
ASTM B117 salt fog	Gentoo 3024 h	Gentoo 3024 h	Gentoo 3024 h	Gentoo 5040 h
Cyclic GMW 14872	Gentoo 272 cycles	Similar 272 cycles	Gentoo 231 cycles	Gentoo 272 cycles
Kennedy Space Center Atmospheric Exposure	Similar 16 months	Gentoo 16 months	Similar 16 months	Gentoo 16 months

Conclusions

The preparation and application of an abrasion and fluid resistant, hydrophobic Gentoo coating over plated high strength steel, anodized and pretreated aluminum, as well as on MIL-PRF-23377 epoxy primer with MIL-PRF-85285 polyurethane topcoated paints has been demonstrated. The Gentoo provides significant added corrosion protection over current protective coatings when evaluated with standardized accelerated corrosion test methods. Gentoo has demonstrated benefits for corrosion resistant applications through: i) increased barrier protection with orders of magnitude reduction in current density and reduced impedance loss following ASTM B117 exposure, ii) improved B117 corrosion resistant



performance against standard military aerospace coatings and metal surfaces (LHE Zn-Ni 4130 steel, anodized and unclad 7075-T6 aluminum), iii) 65-75% reduction in weight loss with Gentoo application to a galvanic fastener assembly, and iv) added accelerated environmental exposure protection following ASTM D 3170 Chipping Resistance testing. Gentoo also has many key coating application attributes: i) ability to be applied using currently employed High Volume Low Pressure (HVLP) spray methods, ii) inexpensive and scalable formulation, iii) excellent adhesion and compatibility with current MIL-Spec topcoats, plating materials and metal surfaces, and iv) thin, lightweight application (4-6 μm) resulting in little added weight. The hydrophobic nature of Gentoo provides excellent water shedding, which is capable of moving water, corrosion initiators and other liquids away from damaged areas resulting in a significant reduction in corrosion. Gentoo is durable, demonstrating impact resistance over current paint systems, and has excellent barrier properties, reducing penetration of corrosion initiating species. Finally, Gentoo provides added corrosion protection over painted and plated surfaces in both accelerated static and cyclic corrosion tests, as well as in actual atmospheric conditions This treatment exhibits a large operating temperature range, passing mandrel bend flexibility at -51°C to thermal stability up to 200°C , and is easily cleaned with no impact to the surface properties using standard cleaning methods.



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